QUESTION 108

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108

DAMS AND RESERVOIRS FOR CLIMATE CHANGE ADAPTATION

1. Dams for Pumped Storage: specific features, design, examples of implementation
2. Off-river dams for water storage and flood protection
3. Offshore dams and tidal power plant
4. Dams for recharge of aquifers and other new concepts
5. Floating solar on dam reservoirs – opportunities and risks

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BARRAGES ET RÉSERVOIRS : ADAPTATION AUX CHANGEMENTS CLIMATIQUES

1. Barrages et réservoirs par pompage : spécificités, conception, exemples de réalisation
2. Barrages hors rivière pour stockage d’eau et protection contre les crues
3. Barrages en mer et usine marée motrice
4. Barrages pour la recharge des aquifères et nouveaux concepts
5. Installations photovoltaïques sur les réservoirs : opportunités et risques

QUESTION 108

TABLE OF CONTENTS OF PAPERS

TABLE DES MATIÈRES DES RAPPORTS

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PAPERS ON QUESTION 108

RAPPORTS SUR LA QUESTION 108

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GRANDS BARRAGES
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SAND DAMS: THE CASE FOR GREATER COLLABORATION BETWEEN THE DAM INDUSTRY AND NON-GOVERNMENTAL ORGANIZATIONS (*)

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SPAIN

SUMMARY

An important strategy to address water scarcity in drylands is the provision of local storage solutions. Sand dams, a form of subsurface dam, capitalize on periods of relative excess to bridge the water supply gap during dry periods. Primarily constructed by NGOs, sand dams have transformed the lives of millions in drylands communities, and they comprise of a concrete wall which traps sand from floodwaters, eventually storing water within the sand particles that accrue behind the dam wall. They raise the groundwater level upstream to create a local aquifer, minimizing evaporation and protecting the population from water-borne diseases. However, their design and siting are complex, dynamic and require a multidisciplinary approach.

Based on the authors experience from the recent construction of Kithumba Dam in Kenya, the paper highlights the need for collaboration between NGOs, which are often under resourced, and larger organizations within the dam industry. Sand dams present systematic gaps and challenges from the planning stage, site investigations and design process, up to the construction and the operation of the dam.

**Barrages de sable : l'occasion d'une plus grande collaboration entre l'industrie des barrages et les organisations non-gouvernementales.*

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RÉSUMÉ

Une stratégie importante pour faire face à la pénurie d'eau dans les zones arides est la mise en place de solutions de stockage locales. Les barrages de sable, une sorte de barrage souterrain, profitent des périodes d'excès relatif pour combler le déficit d'approvisionnement en eau pendant les périodes de sécheresse. Principalement construits par des ONG, les barrages de sable ont transformé la vie de millions de personnes dans les communautés des zones arides. Ils sont constitués d'un mur en béton qui retient le sable des eaux de crue et stocke finalement l'eau dans les particules de sable qui s'accumulent derrière le mur du barrage. Ils augmentent le niveau des eaux souterraines en amont pour créer un aquifère local, minimisant l'évaporation et protégeant la population des maladies transmises par l'eau. Cependant, leur conception et leur implantation sont complexes et dynamiques, et nécessitent une approche multidisciplinaire.

Basé sur l'expérience des auteurs lors de la construction récente du barrage de Kithumba au Kenya, l'article souligne la nécessité d'une collaboration entre les ONG, qui manquent souvent de ressources, et les grandes organisations de l'industrie des barrages. Les barrages de sable présentent des lacunes et des défis systématiques depuis la phase de planification, l'étude du site et le processus de conception jusqu'à la construction et l'exploitation du barrage. La collaboration entre les ONG et l'industrie des barrages pourrait permettre de faire évoluer les barrages de sable de manière efficace et en gérant les risques.

1. INTRODUCTION

Sand dams are increasingly gaining recognition as resilient solutions for drylands communities contending with water scarcity and the unpredictable impacts of climate change [1]. Sand dams have been used in principle for millennia in Arid and Semi-Arid Lands (ASALs), known under various names including check dams, trap dams, sponge dams and desert water tanks [2]. Modern constructions can be traced back to the 1950's in Kenya, with recent estimates suggesting over 2,000 dams have been built worldwide. These dams are primarily constructed by Non-Governmental-Organizations (NGOs) who coordinate the fundraising, project management, dam design and siting, community engagement and construction of the sand dams around the world (see Figure 1) [3].

Whilst in principle sand dams offer a simple low-cost solution to water scarcity, in practice many challenges exist in achieving a successful sand dam. The geological, geomorphological, hydrogeological, hydraulic and climatic factors which govern the availability and storage of water in the dam, combined with the dynamic nature of these factors across different sand dam sites present complexities in the planning, design and execution of sand dams projects. Notably, these projects are often

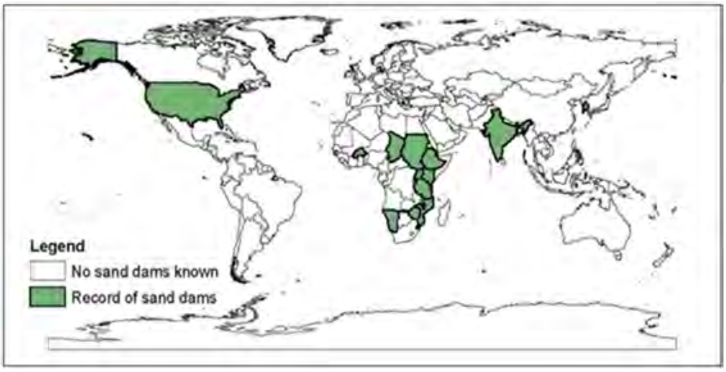

Fig. 1
Map of known sand dams constructed globally. Source: [3]
Carte des barrages de sable connus et construits dans le monde. Source : [*3*].

undertaken by NGOs with minimal funding, and construction is achieved with limited resources and technological capacity. Accordingly, whilst many sand dams have been constructed and successfully provided clean water to local communities, many have failed to provide a constant supply during the dry season [4]. In concentrated regions such as Kenya, failure rates have been reported as high as 50% [5,6].

This paper explores potential gaps across the various project phases from planning and site investigations to the design phase, construction phase and post-construction management of the dam, including a case study. Recommendations are proposed based on current engineering best practices and the authors own experiences with dam projects and humanitarian development.

2. CHALLENGES IN SITING, DESIGNING AND CONSTRUCTING SAND DAMS

Sand dams are formed from an impervious concrete or masonry structure built across an ephemeral riverbed. Whilst traditional dams and reservoirs store water above ground, sand dams store water within sand particles which accrue behind the dam wall or spillway (see Figure 2), raising the groundwater level upstream to create a local aquifer [1]. This offers several benefits over other forms of water storage, including minimizing evaporation losses and protecting the water supply from water borne diseases such as those carried by insects [7]. Initially, the dam wall sits above the surface of the riverbed, until subsequent flooding events lead to the level accumulation of material against the concrete retaining wall. This is known as the

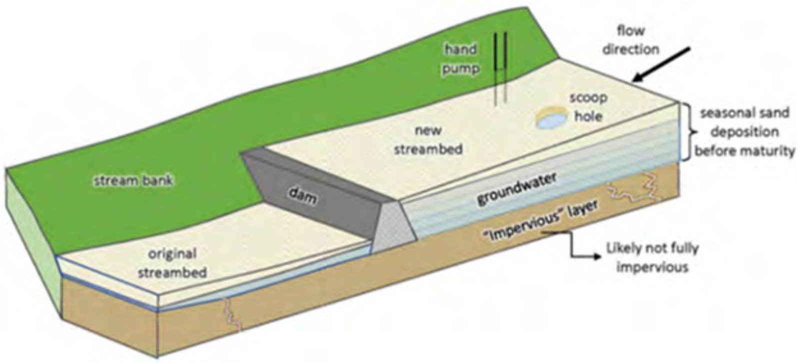

Fig. 2
Typical cross section of a sand dam. Source: [3].
Coupe transversale typique d'un barrage de sable. Source : [*3*].

maturation of the sand dam and can take anywhere between one season and 7 years, dependent on local erosion rates and flood patterns [8].

The material carried by the floodwater tends to be a mixture of sands, gravel, silts and clay, however upon passing across the dam the coarser sand settles upstream whilst the finer, lighter silts and clay particles pass downstream over the dam spillway [3]. Accessing the stored water requires the installation of shallow wells, pipes or the more rudimentary process of excavating scoop holes.

2.1. Hydrogeological considerations

Hydraulic properties of the sediments in the sand dam, largely influenced by particle size distribution, have significant impact on the dam's propensity to store, transmit and yield water. There is unanimous consensus within published research that for a sand dam to function effectively, it is necessary to predominantly accrue coarse-grained sands particles. There is strong evidence to suggest the majority of sand dam failures are indeed the consequence of fine sediments which are deposited during flood events [4,5]. This is because fine sediments decrease the water available to the community for abstraction by reducing infiltration through the sand, reducing the specific yield of the accrued sediments, and increasing evaporation losses [5,8,9].

2.2. Hydraulic processes

Flow velocities are crucial in influencing the fraction of fine sediments in the water column, with low flow leading to the adverse deposition of fine sediments [10].

The flow model in Figure 3 illustrates how flow velocities decrease substantially near the dam base, emphasising the need for dam designs and catchment characteristics that ensure baseflows are sufficient to maintain fine sediments in suspension. This is especially important considering the biophysical context of areas densely populated with sand dams, such as south-eastern Kenya, where rivers usually transport high quantities of clayey and silty sediments. [11]. Reducing the spillway height generally helps maximize the accumulation of the coarsest sediments, by facilitating higher flow energies [10]. However, lower dam heights and shallower reservoirs also exhibit limited storage and yield capacity, with higher vulnerability to evaporation [12]. Therefore, dam heights must be designed with specific attention to the regular flood levels associated with each individual site. This allows the maximum stage height to be achieved, whilst ensuring adequate flow velocities. However, predicting these flood levels with accuracy generally requires historical flood data, which is often unavailable given the difficult geographical and socio-economic context of many sand dam sites. Alternatively, there is evidence which supports the construction of the dam wall incrementally, only raising each stage after the previous one has accrued with coarse sand [5,10]. Whilst this maximizes baseflows and improves the likelihood of coarser sand deposits, the approach is not widely used by NGOs due to the increased construction costs and the logistical challenge of remobilizing the local community.

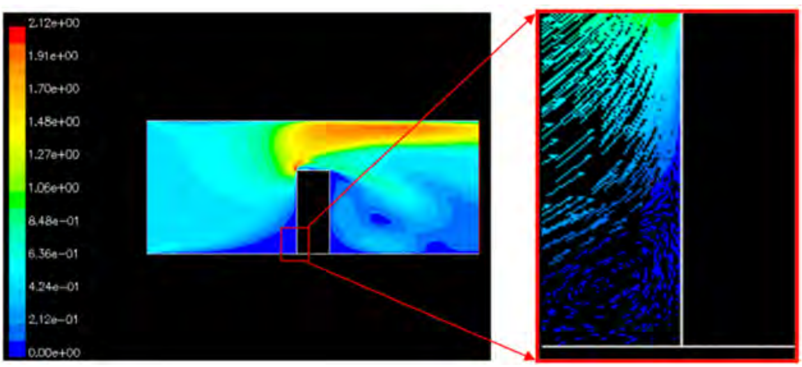

Fig. 3
Flow characteristics near the dam wall. Source: [10].
Caractéristiques de l'écoulement près du barrage. Source : [*10*].

2.3. Geological and geomorphological considerations

The geology and geomorphology of the proposed site must be considered to optimize coarse grained sediment and adequate baseflows. The most favorable parent rocks for coarse sand include coarse granite, quartzite, and sandstone, while basalts and rhyolites tend to produce less favorable sediments for the sand dam [13]. Optimal sites contain a degree of slope that aids the delivery of rainfall, and a valley shape which provides the necessary containment to prevent water from seeping through the sides of the dam. The dam should also be sited at a point on the river that ensures even the largest possible floods will still be directed across the dam spillway and avoids topographical arrangements that could lead to the dam being bypassed. Lastly, as with a regular water dam, the geological conditions of the dam foundation must comprise of strong impermeable bedrock with no fractures or defects. Failure to do so can lead to structural issues with the dam wall and seepage into the aquifer below.

2.4. Construction challenges

The majority of sand dams are constructed in rural areas with limited access to regular utilities necessary for construction works, such as power and water. Site access is often restricted by the absence of suitable roads, and there is limited availability of construction machinery such as earth moving equipment or concrete mixers. NGOs generally resort to construction methods which are labour intensive, such as hand-mixing concrete, and hence rely on the effective mobilisation of the community for which the dam is to supply water to. This mobilisation is seen as a key aspect facilitating low-cost construction and ensuring the community's interest in its success. However, given the importance of maintaining a high standard of quality in the construction of any dam project, the challenge lies in achieving a balance between low-cost community led construction and ensuring appropriate technical practices are applied during construction.

3. KITHUMBA SAND DAM CASE STUDY

This section discusses the site characteristics, design methodology, construction techniques and general practices employed to construct the Kithumba Dam. The findings are based on visual observations, photographs, discussions with the NGO representatives and excerpts from the technical guidebook used by the NGO to take a sand dam from concept to completion.

3.1. Site location

The construction of the Kithumba Sand Dam is located in Makueni County, South-East Kenya, approximately 130 km southeast of Nairobi (see Figure 4). Upstream from the Kithumba Dam at Point A, the following has been observed: At 1200 m upstream, there is another sand dam (B); At 1900 m upstream there is a sand dam river crossing (C); A water reservoir (D). Both (B) and (C) can be considered mature sand dams because they are full of sandy sediment until the dam overflow level.

3.2. Site geology

The regional geology upstream and slightly downstream of the dam wall consists of rock outcrops of fractured sandstone, layered in 0.2-0.5 m beds with the strike orthogonal to the dam wall and dip direction of 15-20° north-northwest parallel to the dam wall. This implies that when the sand dam matures with sand and is fully saturated, during the dry season water may leach through the sandstone layers away from the sediment accumulated upstream (see Figure 5). Some of this water may reappear on the surface just downstream of the concrete wall due to the difference of water pressure on either side of the wall.

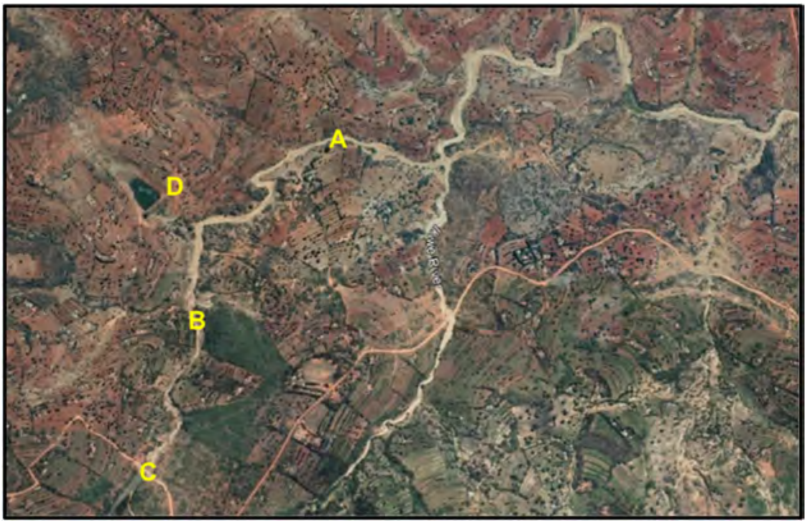

Fig. 4
Infrastructure in the same water catchment area of the Kithumba Dam
Infrastructure dans le même bassin versant que le barrage de Kithumba.

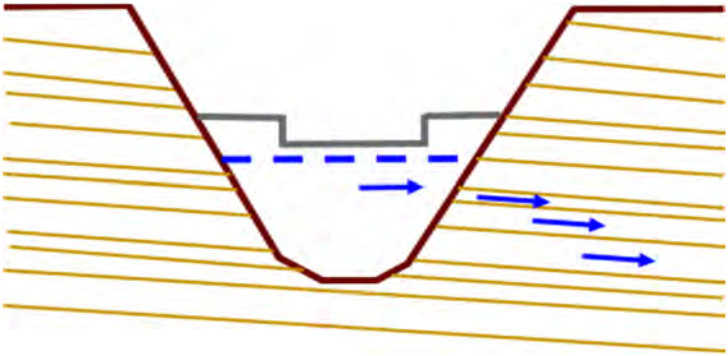

Fig. 5
Schematic hydro-geological situation at the concrete wall location.
Situation hydrogéologique schématique à l'emplacement du mur en béton.

All the area around the new sand dam is organized in benches parallel to the topographic contours for agriculture purposes with the presence of red silty sandy lateritic soil. Walking upstream from Point A in Figure 4, for around 400 m there are no consistent natural deposits of sand, until the stream drastically bends with an "S" shape, after which there are deposits of sandy sediments (see Figure 6).

Fig. 6
Left: Dry Stream bed with sandstone rock outcrops and scarce deposit of sandy sediments. Right: "S" shape of the stream course 400 m upstream the dam concrete wall location (A).
Gauche : Lit de ruisseau asséché avec des affleurements de grès et un dépôt rare de sédiments sableux. Droite : Forme en "S" du cours d'eau à 400 m en amont de l'emplacement du mur en béton du barrage (A).

The presence of this ‘S’ bend appears to reduce the speed of the water running in the stream, depositing coarse sandy sediments at this point and transporting the fine sediments towards Point A where the existing construction was planned.

3.3. Site Investigations and site selection

For the Kithumba Dam, the NGO managing the project received solicitations from the local community expressing their desire for a sand dam. The community proposed 3 potential sites, ranked in preferential order and, for these locations, the NGO conducted their investigations, using their local experience and the technical manual as a guide to decide the most suitable site.

In the case of Kithumba, the assessment of favorable site conditions was predominantly formed through the judgement of those familiar with sand dam constructions in the Makueni district. It is understood that in regions they are familiar with, or where the optimal site is clear, the NGO usually performs visual assessments and does not record the site characteristics of each site. In new regions, or instances where the optimal site is unclear, sieve analysis and water retention tests are conducted. Establishing historical flood characteristics and the frequency of rain events at Kithumba was primarily achieved through discussions with community elders. This is also common practice for most sand dams constructed by the NGO, due to the lack of available records in rural regions.

3.4. Dam design

Once the site was selected, the dam was designed according to the technical manual specifications and site-specific factors. Most importantly, this involved establishing the normal height of the river flow during the rainy season, used to define the height of the spillway. The height of the largest flood water level during a normal rainy season flood, termed annual flood flow, and the largest recorded flood height in 50 years or living memory were also used to determine the progression of the wing walls. The purpose of these wing walls is to ensure the riverbanks are not eroded during the largest recorded flood event in 50 years, which could cause the river to divert away from the dam. The degree of weathering of the bedrock was also visually assessed to determine whether the dam could be built to its maximum height.

In the case of Kithumba Dam, the spillway was designed to be around 3.5 m high. The dam thickness was designed to taper 0.3 m for every 1.0 m of height, with the base width designed to 2/3 of the chosen spillway height. The technical manual specifies the use of cyclopean masonry construction, with a recommended volume

Fig. 7
Reinforcement and barbed wire layout of Kithumba Dam.
Disposition des renforts et des fils barbelés du barrage de Kithumba.

of the dam to be 50–60% stone and the remainder a blend of sand and cement to the ratio of 4:1. As seen in Figure 7, the use of 20 mm ribbed bar set out in a staggered alternating pattern at 1.5 metre diagonal spacing and anchored around 0.15 m into the foundation bedrock was incorporated into the design of Kithumba Dam.

3.5. Construction methodology

Construction of Kithumba Dam was predominantly carried out by the local community members. These community members were volunteers and did not necessarily possess construction expertise. They were supported by skilled craftsmen funded by the NGO, and worked under the direction of the NGO's project manager and engineers, who were trained in sand dam design and construction. The remote nature of Kithumba Dam and limited funding for the project restricted access to heavy machinery and equipment that would normally be used for concrete dam construction. Particularly, there was no access to concrete mixing trucks, line pumps, earth moving equipment, cranage, concrete vibration tools or power tools. The only available equipment was a small tractor used to move sand from the nearby riverbed to the construction site, and a diesel water pump used to pump rainwater to the concrete mixing area. Accordingly, the majority of the construction work was labor intensive, involving the transport and mixing of hundreds of tons of cement, sand and water by hand, manual excavation of the foundations, shoveling of wet concrete into the dam with makeshift platforms and hand-relay systems, and the transport of heavy rocks by hand.

The general construction process for Kithumba Dam involved the excavation of the foundations down to the bedrock, and foundation treatment of fissures and cracks with mortar. The reinforcing bars were anchored into the bedrock. This was followed by the erection of shuttering, which allowed the hand mixed concrete to be shoveled into place. Over a week, the dam was formed incrementally in several layers of concrete progressing around 1 m high each day, with rocks placed in-situ as the concrete was poured and barbed wire used to provide horizontal stiffness. The wing walls were then formed and poured once the spillway reached the level of the first step, and finally the dam was levelled with a smooth finish using a string line and a float.

During the construction, several issues were identified, and are listed below:

- *Quality and consistency of the concrete mix*. The approach towards hand mixing the bags of sand, cement was widely inconsistent. In some instances, 50 bags of cement were mixed with sand in one large pile (Figure 8, Top Left). These large batches were impractical to mix, resulting in large patches of unmixed sand or cement which had to be dug up repeatedly and remixed.
- *Lack of quality control towards addition of water to the mix*. Often, the dam was flooded with water and the wet concrete resembled a liquid rather than its usual slurry form (Figure 8, Top Left). This led to segregation of the concrete mix resulting in variable quality throughout the concrete mass, and a tendency towards high shrinkage and subsequent cracking (Figure 8, Top Right). As a result of this wet concrete mix, and in tangent with poorly sealed formwork, a substantial portion of concrete was lost downstream with every pour (Figure 8, Bottom Right).
- *Reinforcement placement.* The placement of reinforcement was also inadequate in some instances, with positioning too close to the edge of the concrete leading to the bar splitting out (Figure 8, Bottom Left).

3.6. Quality management and data collection

Throughout the project, it was observed that there were insufficient systems in place to ensure effective quality management and standardized data collection across various phases of dam development. This was likely due to a combination of limited human resources, appropriate technologies, and funding. During the planning and design phases, it became apparent that most observations and data collected on potential sand dam sites, as well as the corresponding decisions regarding

Fig. 8

Issues identified during construction (Clockwise from top left): Large piles of sand and cement mixture, and waterlogged concrete mix in the dam; Transverse cracking through the concrete following curing; Concrete overflowing downstream; Reinforcement splitting out through upstream wall.

Problèmes identifiés lors de la construction (dans le sens horaire à partir du coin supérieur gauche) : Grands tas de mélange de sable et de ciment, et mélange de béton gorgé d'eau dans le barrage ; Fissuration transversale du béton après durcissement ; Débordement de béton en aval ; Séparation des armatures à travers le mur amont.

site selection and design, were not adequately documented by the NGO. Additionally, few records were kept of construction decisions made on-site or of environmental factors during construction.

Following construction, it is understood that community members are instructed to contact the NGO if they identify any issues with the dam. Several structural failures of previously constructed dams were acknowledged during discussions with the NGO, for which investigations were carried out and specific lessons adopted. The NGO also dispatches its engineers to visit constructed dams after heavy rains to make visual observations and assess recent flood levels. This practice is important for determining whether the dam height and wing walls are sufficient to contain floodwaters.

However, when it comes to non-structural failures, the NGO maintains minimal records. It was observed that no investigations were conducted to verify the accumulation of desirable coarse-grained sand sediments. Furthermore, there were no systems in place to assess the success of each dam in terms of water storage and levels of abstraction by the community.

4. RECOMMENDATIONS TO ADDRESS GAPS

Based on recognized good practice and the authors' experiences working with dam projects and humanitarian development, the following recommendations are provided to address the gaps identified.

For the Planning and Site Investigation Phase, the following is recommended:

- NGOs keep a clear record of all sites investigated during the planning phase, and the factors which made them suitable or unsuitable for further development.
- Record keeping is standardized to cover all critical factors, including geological, geomorphological, hydraulic, hydrogeological, climate considerations, cost factors and constructability.
- NGOs structure the investigations process in a manner that accommodates more quantitative methods and testing procedures which allow the collection of objective data.
- NGOs are proactive in identifying areas with high potential for sand dams rather than being reactive to community solicitations. Identification of such areas requires support from academia and/or the private sector.

For the Design and Construction Phases, the following is recommended:

- The technical manual used to construct sand dams is reviewed and updated by a suitable engineering organization with experience in dams engineering, providing geotechnical, hydraulic and structural engineering expertise.
- The review covers the dam design, including concrete to rock ratios, dam and wingwall dimensions, downstream slope angle, amount of rebar, rebar spacing, and anchoring to bedrock, among other issues.
- The review incorporates the construction process, including formwork design, foundation preparation, and concrete mixes, amongst other issues
- The review considers limitations to the budget, contextual factors, and resources available to sand dam projects, and acknowledges the importance of community involvement during siting and construction.

For the Post-Construction Phase, the following is recommended:

- Given the complex and unpredictable manner in which a sand dam matures with sediments, NGOs should monitor the deposition of sediments after each flood event to ensure the dam is filling with coarse sand as desired.
- Local community or NGO members follow standardized procedures following floods, such as capturing photos of the dam before and after each flood event digging scoop holes to observe the layering of sediments plus conducting granulometric curve distributions of the sediments accumulated by the dam at different depths and locations.
- A central database of sand dams is developed in partnership with industry or a research institution using Geographical Information Systems (GIS) to record the location and key details of all constructed dams. This should include at a minimum; construction dates, maturation times, photos before, during and after construction and maturation, costs, key personnel and partner organizations involved, and community members serviced by the dam. It should also incorporate any dam failures.
- Local community members should carry out regular visual inspections of the sand dams and keep track of them by means of dedicated checklists and record keeping. A minimum dam surveillance plan should be prepared and implemented.
- Local community members keep track of changes in dwellings downstream of existing sand dams to update the consequences assessment, in case of failure.

5. CONCLUSIONS AND OPPORTUNITIES FOR DAM INDUSTRY

With their demonstrated benefits and vast future potential to be scaled across ASALs, sand dams are positioned to play a critical role in addressing global water scarcity. As this paper has highlighted, the success of these sand dams depends on careful consideration of geological, hydraulic, and geomorphological factors, as well as the quality of design and construction practices. However, the challenges observed in the Kithumba Dam case study underscore the need for more robust quality control, data collection and evaluation, and post-construction monitoring processes.

Acknowledging the constraints facing NGOs operating in this space, the emphasis is on the dam industry to pursue greater collaboration with NGOs to help deliver solutions to the gaps identified. NGOs have the on-ground presence, practical experience and community engagement necessary for successful project execution, whilst the dam industry can provide technical expertise, best practices, and resources to enhance the planning, design, construction and operational phases of sand dam projects. Such collaborations can help bridge the gap between traditional engineering practices and the realities of implementing projects in remote, under-resourced areas.

By fostering partnerships between the dam industry and NGOs, there is potential to significantly improve the effectiveness of sand dams as a sustainable water resource solution. These collaborations can ultimately contribute to greater resilience against water scarcity and climate change impacts across the world's drylands.

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COMMISSION INTERNATIONALE DES
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VINGT-HUITIEME CONGRES DES
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CHENGDU, MAI 2025

SEDIMENT AND FLOOD MANAGEMENT AT A PLANNED MULTIPURPOSE RESERVOIR IN A PERIGLACIAL ENVIRONMENT (*)

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SWITZERLAND

**Gestion des sédiments et des crues dans un réservoir polyvalent dans un environnement périglaciaire*

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SUMMARY

With the retreat of glaciers following climate change, new sites for water resources management and storage are emerging in Switzerland, gaining importance due to the fading of natural storage that today's glaciers represent. Gornerli multi-purpose reservoir situated above Zermatt, a well-known Alpine ski resort in the south of Switzerland, is a newly planned reservoir formed by an arch dam to be constructed in the framework of the Swiss energy transition. With 650 GWh it has by far the largest storage capacity of 15 envisaged reservoir extensions or new constructions. Another prominent feature of this reservoir is its high-altitude, heavily glaciated catchment. Rapidly melting glacier ice due to climatic warming will lead to the formation of a natural lake in the coming years in a pronounced depression formed by the topography of the underlying bed rock, while flood peaks will increase substantially. In the long term, reservoir sedimentation represents a major challenge to maintaining the active storage capacity of such periglacial reservoirs.

This strategic reservoir dam project aims in particular at (i) increasing the security of Switzerland's winter energy supply and (ii) protecting Zermatt and the downstream Mattertal valley from flooding. An analysis of glacier retreat, sediment yield, and flood management confirmed the great potential of this location. After the planned completion of the dam in 2032, a substantial part of the reservoir volume will still be occupied by the retreating glacier snout for an additional 20 to 40 years. Despite considerable uncertainties, the sedimentation impact is supposed to be surprisingly small, with an estimated loss of less than 1 Mm^3 after 80 years of operation, representing 0.5% of the reservoir's active storage capacity of 152 Mm^3. This low value, despite considerable suspended sediment inflows, can be explained by the reservoir's geometry and the deep natural lake that will form, constituting a very large dead storage volume.

It can be further shown that an 80-hour flood hydrograph delivering 20 Mm^3 of water into the reservoir could be entirely retained by the dam for a freeboard of 5.6 m between full supply level and dam crest. The study underlines the importance of improving the mapping of the bedrock beneath the current glacier while giving recommendations on the elaboration of proactive studies, particularly on sediment particle size distribution, and the development of potential measures for the sustainable management of the sediments that will settle in front of the dam.

RÉSUMÉ

Avec le recul des glaciers en conséquence du changement climatique, de nouveaux sites de gestion et de stockage des ressources en eau apparaissent en

Suisse et gagnent en importance en raison de la diminution du stockage naturel que représentent les glaciers actuels. Le réservoir polyvalent du Gornerli, situé au-dessus de Zermatt, une station de ski alpine bien connue du sud de la Suisse, est un nouveau réservoir formé par un barrage-voûte dont la construction est prévue dans le cadre de la transition énergétique suisse. Avec 650 GWh, il possède de loin la plus grande capacité de stockage des 15 extensions ou nouvelles constructions de réservoirs envisagées au niveau national. Une autre caractéristique notable de ce réservoir est son bassin versant d'altitude, fortement glaciaire. La fonte rapide des glaciers due au réchauffement climatique entraînera la formation d'un lac naturel dans les années à venir, dans une dépression prononcée formée par la topographie de la roche sous-jacente, tandis que les pics de crue augmenteront considérablement. À long terme, la sédimentation du réservoir représente un défi majeur afin de maintenir la capacité de stockage active de tels réservoirs périglaciaires.

Ce projet stratégique de barrage-réservoir vise notamment à (i) accroître la sécurité de l'approvisionnement énergétique hivernal de la Suisse et (ii) protéger Zermatt et la vallée du Mattertal en aval contre les inondations. Une analyse du retrait des glaciers, de la production de sédiments et de la gestion des crues a confirmé le grand potentiel de ce site. Après l'achèvement prévu du barrage en 2032, une partie substantielle du volume du réservoir sera encore occupée par le museau du glacier en retrait pendant 20 à 40 ans. Malgré des incertitudes considérables, l'impact de la sédimentation est supposé être étonnamment faible, avec une perte estimée à moins de 1 Mm^3 après 80 ans d'exploitation, ce qui représente 0.5 % de la capacité de stockage active du réservoir, qui est de 152 Mm^3. Cette faible valeur, malgré des apports considérables de sédiments en suspension, peut s'expliquer par la géométrie du réservoir et le lac naturel profond qui se formera, constituant un grand volume de stockage mort.

Il peut également être démontré qu'un hydrogramme de crue de 80 heures délivrant 20 Mm^3 d'eau dans le réservoir pourrait être entièrement retenu par le barrage avec une revanche de 5.6 m entre le niveau de remplissage maximal et le couronnement du barrage. L'étude souligne l'importance d'améliorer la cartographie du toit du rocher sous le glacier actuel tout en donnant des recommandations sur l'élaboration d'études proactives, en particulier sur la distribution granulométrique des sédiments, et le développement de potentielles mesures pour la gestion durable des sédiments qui se déposeront devant le barrage.

1. INTRODUCTION

With the retreat of Gorner glacier upstream of the village of Zermatt (Farinotti *et al.*, 2012), a new dam is planned in the Gorner Gorge, at an altitude of 2'165 m.a.

s.l. The water volume of the reservoir is estimated to be over 150 Mm^3 after the complete melting of the glacier tongue that still occupies a substantial part of the basin. The structure would consist of a double-curved arch dam with a height of 93 m and a crest length of about 285 m. The construction of this reservoir has multiple objectives. On the one hand, the dam would protect the village of Zermatt and the Matter Valley from natural hazards, particularly floods resulting from extreme weather events and/or the outburst of proglacial lakes or ice-dammed lakes. On the other hand, it allows the seasonal storage of approximately 650 GWh of electricity to ensure hydropower production during periods of high demand, specifically during the winter season. Water from the reservoir will be directly pumped into an existing water transfer siphon up to an altitude of 2’443 m.a.s.l., from where it will flow by gravity to the Grande Dixence reservoir, the largest Swiss hydropower reservoir by volume. Over the entire year, an additional net production is estimated at 200 GWh. Moreover, the project offers certain advantages, including the supply of drinking water, irrigation water, and the production of artificial snow for the Zermatt ski resort.

The Gorner glacier is a contiguous glaciated area consisting of multiple glaciers merging into a glacier tongue with a maximum thickness of almost 400 m of ice. According to Holzhauser (2008), the glacier reached its last peak extent in 1859, when the ice almost reached the settlement of Schweigmatten, where it was clearly visible from Zermatt. For this reason, it is referred to in older literature as the “Grand glacier de Zermatt [Grand glacier of Zermatt]” (Agassiz, 1840) or “Grosser Gletscher vom Monte Rosa [Great glacier of Monte Rosa]” (Forbes, 1845). The water released by melting snow and ice from the Gorner catchment forms the Gornera river. From the glacier, the river flows through the Gorner Gorge towards an existing water intake. Further downstream, together with its confluence Zmuttbach from the Zmutt valley, it forms the Matter Vispa river. This river flows through the village of Zermatt and the entire Mattertal before merging with its namesake from the Saastal into the river Rhone at Visp.

This study investigates the spatial and temporal evolution of Gorner glacier and quantifies sediment input and accumulation in the planned reservoir lake. In addition, the reservoir’s capability to act as a flood protection measure for the village of Zermatt is assessed. The findings of this study may act as basis for the development of efficient sediment management strategies as well as for the identification of potential benefits of Gornerli dam as a multi-purpose project.

2. FUTURE GLACIER AND RESERVOIR EVOLUTION

In the context of climate change, various scenarios for the future evolution of the glacier have been modeled. Among the climate scenarios defined by the Swiss Confederation (CH2018, 2018) and based on the work of the Intergovernmental

Panel on Climate Change (IPCC, 2023), which considers different possible developments in future greenhouse gas emissions, three plausible scenarios have been studied in more detail for the Gornerli site. Each of these scenarios presents varying increases in greenhouse gas concentration and rates of temperature change, resulting from human behavior. With the implementation of all known mitigation measures, a sustainable reduction in greenhouse gas concentration is expected (Shared Socioeconomic Pathway SSP1-2.6). Conversely, if no measures are implemented, emissions will continue to rise (SSP5-8.5). The SSP2-4.5 scenario falls between these two extremes. Based on these greenhouse gas emission scenarios, a set of Global Circulation Models predict future changes in air temperature and precipitation that are utilized to force the Global Glacier Evolution Model (GloGEM, Huss and Hock, 2018). This model provides monthly glacier surface mass balance and runoff, as well as projections of the future change in ice surface geometry and thus glacier retreat. Figure 1 shows the situation of the dam and its reservoir, as well as projections of glacier extent at different points in time for SSP2-4.5. The bedrock topography beneath the glacier is the result of ground-penetrating radar surveys conducted in 2004 and 2008. Modelled future glacier extent clearly shows the formation of an ice block completely separated from the glacier's main branch.

On the one hand, it is a result of the retreat of ice in this region that the Gornerli project came into existence. According to the longitudinal profile (Figure 2), a

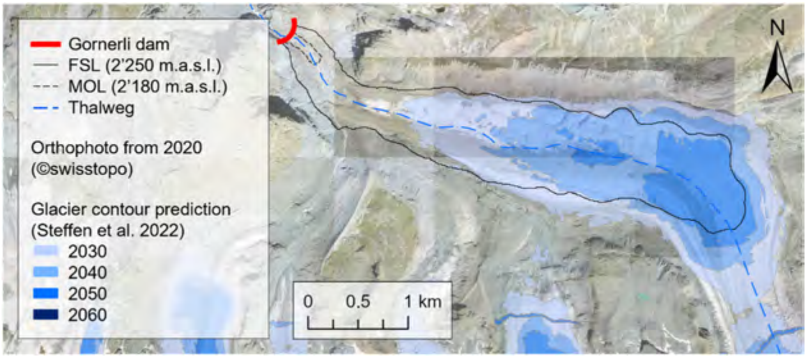

Fig. 1
Visualisation of the extent of the Gornerli reservoir following the construction of a dam (FSL = full supply level, MOL = minimum operating level). Modelled glacier extent according to Steffen *et al.* (2022) is shown with blue colors corresponding to SSP2-4.5.
Visualisation de l'étendue du réservoir Gornerli après la construction d'un barrage (FSL = niveau maximal de la retenue, MOL = niveau minimal d'exploitation). L'étendue des glaciers modélisée selon Steffen *et al.* (2022) *est représentée par des couleurs bleues correspondant à SSP2-4.5.*

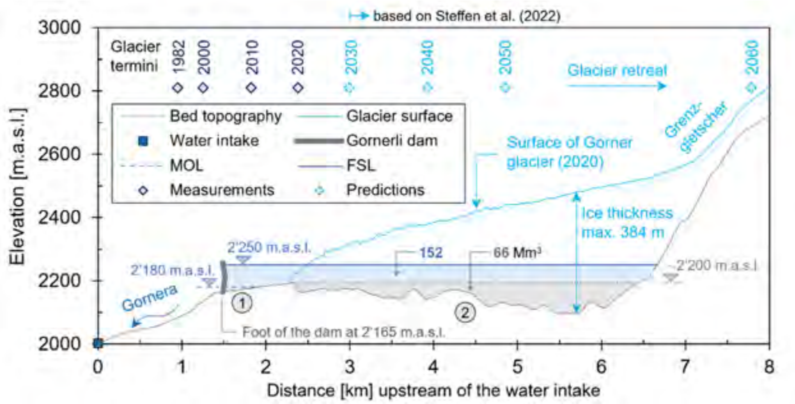

Fig. 2
Longitudinal profile of the Gornerli reservoir, including the water levels of the new dams, as well as the lake level of a natural lake forming after deglaciation. The position of modelled glacier termini (Steffen *et al.*, 2022) is shown as dots corresponding to SSP2-4.5.
*Profil longitudinal du réservoir Gornerli, incluant le niveau maximal de la retenue artificielle ainsi que le niveau du lac naturel se formant après le retrait du glacier. La position des terminus des glaciers modélisés (*Steffen *et al.*, 2022*) est représentée par des losanges correspondant à SSP2-4.5.*

topographical depression or overdeepening exists beneath the current glacier tongue. With glacier retreat, a natural lake will form and will partially become visible in the coming years. There is a legend in Zermatt about this topic: according to the history passed down from generation to generation, the people of Zermatt are aware of the existence of a large lake in this valley. It was likely ice-free for the last time about 1'000 years ago. On the other hand, various challenges related to energy supply and flood protection are driving the planning of an engineered reservoir, making use of this natural lake at the toe of the Gorner glacier.

The longitudinal profile in Figure 2 follows the estimated thalweg outlined with blue dashed lines in Figure 1. The first depression (1) is located close to the planned dam site. At an altitude of approximately 2'200 m.a.s.l., this depression is being delimited upstream by a rock sill dividing the entire reservoir into two distinct sections. The sill is near the present glacier terminus. In addition, the different glacier termini, measured and estimated according to the intermediate greenhouse gas emission scenario are shown for SSP2-4.5 in Figure 2 (Steffen *et al.*, 2022). Upstream of the sill, the bottom of the reservoir plunges, forming a large depression (2) descending to an elevation of 2'100 m.a.s.l. This means that the lowest point of the reservoir is not the toe of the dam at 2'165 m.a.s.l., but rather the bottom of depression (2). In terms of volumes, depression (1), filled up to the rock sill at approximately 2'200 m.a.s.l., amounts to 2 Mm^3, while depression (2), filled to the same elevation, represents a substantial dead storage volume of 66 Mm^3.

It is important to highlight the uncertainty of measurements of the bedrock topography beneath the glacier. The ground-penetrating radar method used in 2004 and 2008 estimates the glacier bed from the glacier surface, and thus the ice thickness, with a vertical accuracy of $\pm$10 m. Between different measurement lines, ice thickness was interpolated by a model-based approach (Grab *et al.*, 2021), leading to potential ice thickness deviations within the reservoir ranging from $-$32 m to +47 m from the actual value. This also applies to the exact altitude of the rock sill. Concerning the reservoir's volume estimations described above, this uncertainty in the course of the bedrock represents a considerable unknown.

With the gradual retreat of the glacier and the formation of the natural lake upstream of the rock sill, the impoundment of the dam will be fed by the overflow from the natural glacial lake where the fresh water will be in contact with the ice up to an elevation of approximately 2'200 m.a.s.l. Above this elevation, the water level in the reservoir can be further raised up to full supply level (FSL = 2'250 m.a.s.l.) impounding an active storage capacity of 152 Mm^3 (Figure 2). The evolution of the storage capacity as a function of the three glacier retreat scenarios considered is shown in Figure 3. Full active storage capacity should be reached between 2050 and 2072 for the SSP5-8.5 and SSP1-2.6 scenarios, respectively. During the

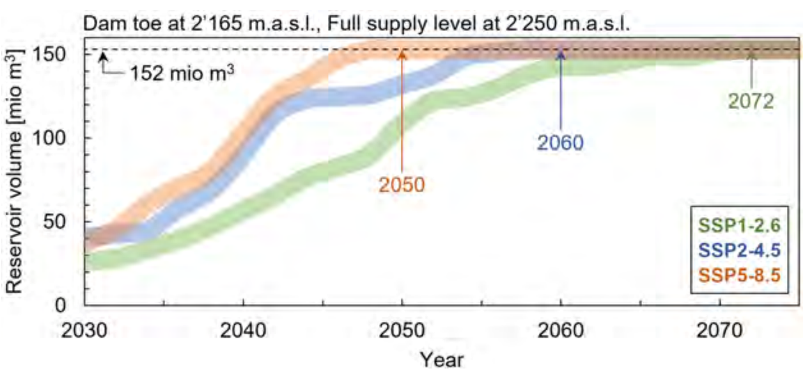

Fig. 3
Evolution of the active storage capacity of the reservoir according to the climate scenario considered, depending on the melt-down of remaining glacier ice in the reservoir
Evolution de la capacité active de stockage du réservoir en fonction des différents scénarios climatiques considérés et de la fonte de la glace de glacier restante dans le réservoir

impoundment of the Oberaar (1953) and Gries (1966) dams, both in Switzerland, the reservoir lakes were also in contact with their upstream glaciers. In such situations, the effect of lake impoundment on the rate of ice retreat generally appeared to be relatively small. This is also confirmed by observations at the Rhone glacier. There has been a lake at its glacier tongue for almost 20 years, but the retreat of the glacier snout has hardly been accelerated by the lake. This is related to the relatively low water temperatures in such lakes considering the reservoir's elevation and the fact that the water mainly originates from ice melt. A major issue that could affect the dam's operation involves rock/snow avalanches or glacier break-offs that, upon contact with the reservoir lake, would generate a wave moving towards the dam. In such situations, an assessment of impulse waves generated in the reservoir is required for the concession application, as was done by VAW commissioned by the Oberhasli power plants (KWO) for a similar reservoir project at the foot of the Trift glacier in the Canton of Bern (Evers *et al.*, 2018; Evers & Boes, 2022).

3. SEDIMENT YIELD AND ACCUMULATION

This section addresses the sedimentation of the future Gornerli reservoir. Firstly, the data from previous sediment transport and suspended sediment concentrations measured in the Gornera river are presented. To assess the sediment input into the future reservoir, the selected erosion models are then briefly introduced. In the following, the amount of derived sediment transported (in suspension and as bedload) in the future reservoir is estimated. By considering the reservoir as a large desanding basin and an assumed particle size distribution, the quantity of fine sediment settling in front of the dam is derived. The last part addresses the consequences for the current dam project.

3.1. Previous measurements

To quantify the amount of sediment transported through the Gorner watershed, various seasonal measurement campaigns were conducted at the existing Gornera water intake downstream of the future dam (Bezinge, 1987; Collins, 1989, 1996; Delaney *et al.*, 2018). Between 1972 and 1990, Bezinge (1987) and Collins (1989) determined the suspended sediment concentration (SSC) by gravimetric analysis of water samples collected at hourly intervals throughout the day from May to September, i.e. the glacier melting period. From measurements in the summers of 1973 and 1974, Bezinge & Aeschlimann (1989) reported maximum SSC values of 15 to 20 g/l. This order of magnitude was also reported by Collins (1989), who measured a maximum SSC of 15.4 g/l in the spring of 1987 and related this value to drainage events of an ice-dammed lake. Delaney *et al.* (2018) also determined the SSC during similar melt seasons in 2016 and 2017, using turbidity measurements taken every 5 seconds at approximately 1 m below the water surface. These turbidity measurements were calibrated by taking 90 sediment-laden water samples. The mean SSC in 2016 and 2017 was 0.25 g/l and 0.37 g/l with maximum concentrations up to 5.04±0.79 g/l and 3.27±0.73 g/l, respectively. These maximum concentrations can be related to ice-dammed lake drainage in 2016, as well as to a substantial precipitation event in 2017. Based on actively initiated flushing at the existing Gornera water intake, the volume share of bedload was estimated to 6 to 12% of the total transported sediment volume. Differences in the above-stated SSC values may be attributed to incongruences between instrumentation and measurement techniques (Delaney *et al.*, 2018).

3.2. Erosion models

For the entire operational life of the future Gornerli reservoir, i.e. over a typical concession period of 80 years, the sediment supply from the catchment was determined using three different empirical erosion models as a function of discharge as well as, for one approach, temperature. As input, we use modelled daily runoff from the lake's catchment area until the end of the century based on the Glacier Evolution Runoff Model (GERM, Huss *et al.*, 2008; Farinotti *et al.*, 2011). Three scenarios of greenhouse gas emission (Representative Concentration Pathways RCP) were used and glacier retreat and daily runoff was modelled between 2020 and 2099 based on results from various regional climate models (8 for RCP2.6, 17 for RCP4.5, and 22 for RCP8.5). These results were then used as inputs for the empirical equations of the erosion models outlined in the following.

Gurnell *et al.* (1996) derived an empirical equation for determining the annual volume of suspended sediment yield V_{ss} for a given annual discharge volume V_w. The empirical parameters of the model were calibrated using observations of 72 glacier catchments. Based on the annual discharge volume derived by integrating daily discharge data from the runoff model, the amount of suspended sediment input into the reservoir was estimated until the end of the century. For this estimation, the density of suspended sediment was assumed to 1'500 kg/m^3 (Delaney *et al.*, 2018).

For the mobilization of deposited sediment in the catchment, the hydraulic regime and thus sediment transport capacity are important. To enable a more detailed analysis than in the previous approach, Delaney *et al.* (2018) applied runoff data at daily temporal resolution. For an annual estimate of the volumes of transported sediments based on the mean annual flow, the peaks in discharge linked to precipitation, eventually cumulated with the melting of the glacier, are not well considered and the total volume of transported sediments should be underestimated. In fact, the greater the discharge, the more sediment is mobilized and transported. Based on an empirical relationship established by Müller & Förstner (1968) between discharge Q_w [m^3/s] and SCC [kg/m^3], Delaney *et al.* (2018) used average daily discharge values to obtain a better correlation between modelled and observed suspended sediment concentrations.

Where data is available on the sediment transported by rivers, it is possible to introduce a catchment erosion factor or *denudation rate r*, often expressed in mm/year. This factor, which can then be applied to similar catchments to estimate the order of magnitude of its annual rock erosion, considers uniform erosion over the entire surface of the basin. Schlunegger & Hinderer (2003) stated from suspended sediment load measurements collected by the Swiss Federal Hydrological Service in 1993, 1995, and 1997 that the denudation rate of Swiss Alpine core catchments in the Central Alps are in the order of 0.5 mm/year. Wittmann *et al.* (2007) reached a similar conclusion, demonstrating from their own samples a mean denudation rate of the order of 0.9$\pm$0.3 mm/year (95% interval) for the crystalline Central Alps. For the future Gornerli reservoir, three different factors were taken from Delaney *et al.* (2018), i.e., the minimum, average, and maximum values of the erosion factor (r_{min} = 0.15, r_{mean} = 0.47, r_{max} = 0.82 mm/year) and multiplied with the catchment size of 76.6 km^2 at the dam site. To allocate the total annual sediment supply between bedload and suspended sediment, the mean distribution ratio according to Delaney *et al.* (2018) (9% bedload, 91% suspended sediment) was used.

3.3. Sediment yield

In Figure 4, the solid lines are the result of estimates of annual suspended sediment yield derived from the three empirical models. The above intervals show the total sediment load estimated using the distribution range given by Delaney *et al.* (2018) for this catchment (between 6-12% of total sediment volume is bedload). The approach of Gurnell *et al.* (1996) appears to overestimate the sediment supply compared with Delaney's empirical equation and the calculation using the denudation rate. Note that these models do not account for morphological changes of the catchment due to glacier retreat including morphological connectivity, e.g., the formation of temporal lakes above the future reservoir, as presented by Steffen *et al.* (2022).

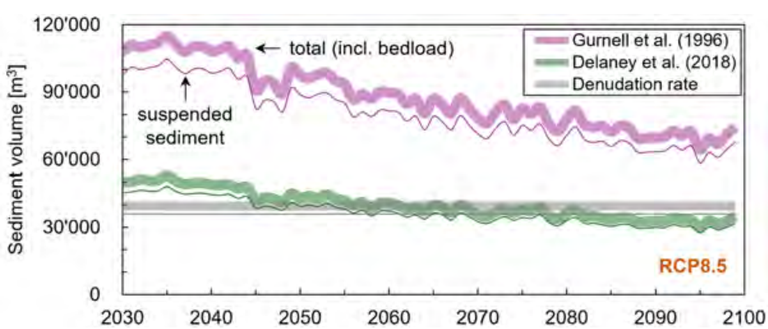

Fig. 4
Annual sediment input into the Gornerli reservoir for RCP8.5
Apport annuel de sédiments dans le réservoir du Gornerli en considérant le scénario RCP8.5

3.4. Settling velocity and diameter of critical particles

Based on the estimated input of sediment load into the future Gornerli reservoir, it was assumed that the bedload would deposit in the first major depression of the reservoir (left in Figure 5). Given its bathymetry, the question arises as to the quantity of sediment transported in suspension with the flow that could settle in the second depression just in front of the dam (right in Figure 5). These fine sediments could reach the dam and, by settling, obstruct the various water intake structures (low-level outlet and water intake). In the absence of a computational fluid dynamics (CFD) modelling of the reservoir, a simplified approach based on the idea of the reservoir acting as a very large desander basin was investigated. The calculation procedure involves the following steps:

1. The capacity inflow ratio (CIR) is calculated for each year between 2032 and 2111 (80 years of concession). The evolution of this coefficient which is defined by the ratio between the reservoir volume (increasing with glacier retreat, see Figure 3) and the annual volume of incoming water. The CIR allows for estimating the residence time taken for the flow to cross the lake and reach the dam.
2. By dividing the distance between the river inlet into the reservoir and the dam by the residence time of the water in the reservoir (= CIR · 365 days), the averaged horizontal flow velocity in the reservoir is estimated.
3. Accounting for the reservoir bathymetry, it is necessary for the reservoir level to exceed 2’200 m.a.s.l. so that the fine particles can settle in the depression in front of the dam. During an analysis of reservoir operations, the daily fill level has been determined over the entire concession period. The number of days per year that the lake level exceeds this critical threshold of 2’200 m.a.s.l. is therefore counted. The lake was conservatively assumed to be completely full, reaching its FSL of 2’250 m.a.s.l. on these days.
4. The critical settling velocity of a particle is determined based on the equation developed by Ferguson & Church (2004) by dividing the vertical distance between the FSL and the rock sill, i.e., 50 m, by the time determined in step 3.
5. As the length and therefore the capacity of the reservoir increases each year with the retreat of the glacier, the water remains in the reservoir for longer. Therefore, with the critical settling velocity calculated in step 4, a fine particle entering the reservoir may not be able to reach the rock sill. In fact, given the time required to cover the distance between the river inlet and the sill, the particle will have sunk more than 50 m. The simplified assumption here is that the particles do not rise, but always continue to sink in the reservoir before settling. Therefore, the critical settling velocity is revised downwards by dividing the 50 m difference by the time taken for the particle to reach this rock sill from its entry into the reservoir. This time is determined beforehand using the horizontal flow velocity determined in step 2 and the distance to be covered by a particle between the river inlet and the barrier.
6. The lowest critical settling velocity determined in steps 4 and 5 is selected.

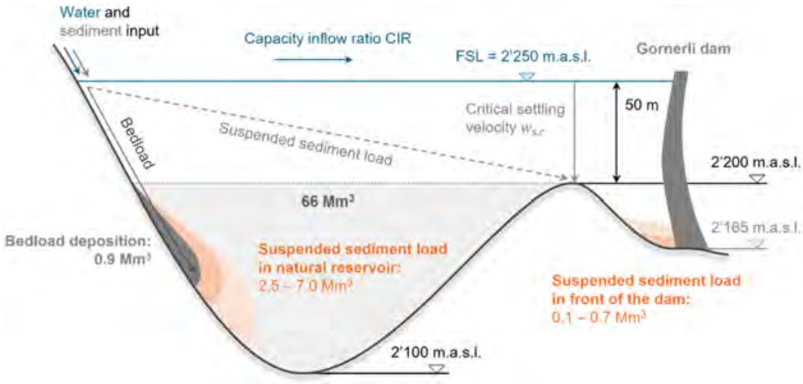

Fig. 5
Schematic representation of the reservoir in the context of sedimentation and results of the analysis
Représentation schématique du réservoir dans le contexte de la sédimentation et résultats de l'analyse

Based on this calculated settling velocity, the diameter of the critical particle that will settle close to the dam is determined. The density of the suspended sediments considered in this analysis plays a key role in the calculation of the diameter of critical particles. For suspended sediments, Delaney *et al.* (2018) assume a density of 1'500 kg/m^3. This value seems low compared with the 2'650 kg/m^3 specified as sediment particle density by Paschmann *et al.* (2022) for the design of desander facilities. As this is a crucial parameter, a sensitivity analysis was carried out. For the lowest sediment density assumed, these critical particles have a diameter of between 3.1 and 4.7 μm, while for a density of 2'650 kg/m^3, the diameter varies between 1.7 and 2.6 μm.

3.5. Particle size distribution

After having estimated the largest diameter of the particles settling in front of the dam, the quantity of sediment from this fraction can be calculated if the particle size distribution (PSD) of the sediment in the reservoir is known. Ehrbar (2018) analysed the behaviour of suspended sediments in three Alpine reservoirs in Switzerland (Griessee, Lac de Mauvoisin, and Gebidem) located in watersheds with ice-covered regions. It was found that generally, 80 – 100% of suspended sediments in this type of reservoir are clayey or silty (with a diameter smaller than 63 μm), while the remaining portion (usually less than 10%) is composed of sand.

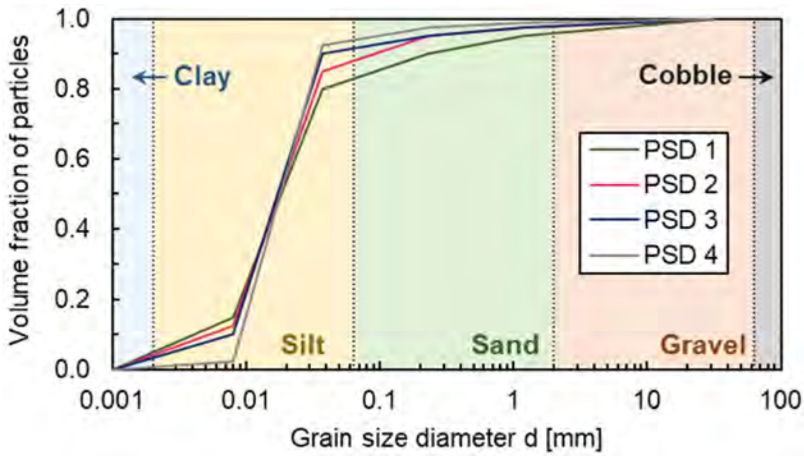

Fig. 6
Particle size distributions considered in the sedimentation analysis
Distribution granulométrique des particules considérée dans l'analyse de la sédimentation

The median diameter d_{50} of suspended particles varies between 10 and 100 μm, with the maximum observed at 200 μm. As the fraction of suspended sediment appears to be very high for this catchment according to measurements by Delaney *et al.* (2018) at the existing water intake, the conclusions of Ehrbar (2018) regarding the distribution of suspended sediment in the potential reservoir are retained. For the Gorner catchment and in the absence of measured data, four grain size distributions were estimated as shown in Figure 6.

3.6. Trap efficiency

According to the observation of Brune (1953), not all sediment is necessarily retained in the reservoir. Some particles remain in suspension and exit the reservoir directly through the power intakes or outlet structures. Brune (1953) established a correlation between the reservoir's trap efficiency and its capacity-inflow ratio (CIR) with three curves, one for fine-grained, another for medium-grained, and the last for coarse-grained sediments. These curves were expressed through equations by Ehrbar (2018). For the volumes estimated using the PSD and the CIR evaluated for each year, the equation for fine particles is applied.

3.7. Sedimentation rate at the dam

The annual volume of sediment deposited in front of the dam is estimated by multiplying for each approach and year (2032 – 2111) considering:

(1) the volume of suspended sediment entering the reservoir [m^3/year],
(2) the volumetric fraction of suspended sediment deposited in the reservoir [%], and
(3) the trap efficiency of the reservoir [%].

With a reservoir beginning at the dam toe at 2'165 m.a.s.l., considering minimum and maximum sediment densities a sediment accumulation height of between 15 and 20 m (Gurnell *et al.*, 1996), 11 and 15 m (Delaney *et al.*, 2018), and 11 and 14 m (denudation rate) can be estimated after 80 years of operation, if no measures against sedimentation are taken. The sedimentation rate is highly dependent on the volumetric capacity of the reservoir. At the very start of reservoir impoundment, the lowest layers of the reservoir are filled more quickly, whereas as the sediment level rises, the surface area increases and so does the volume available for sedimentation. The volume of sediment to be managed (i.e. immediately upstream of the dam) is in the order of 0.1 to 0.7 Mm^3. The loss of active storage capacity after 80 years is therefore estimated to be considerably less than 1 Mm^3, amounting to around 0.5% of the active storage capacity of 152 Mm^3.

4. FLOOD MANAGEMENT AT THE GORNERLI DAM

The hydrological analysis of the catchment area carried out by the public utility Alpiq provides the design flood and safety check flood hydrographs to be considered for the planned Gornerli dam (shown in blue and red, respectively, in Figure 7). The presented design flood hydrograph has a statistical return period of 1'000 years according to the Directive C2 of the Swiss Federal Office of Energy (SFOE) on the safety of water retaining facilities (SFOE, 2018).

The current discharge capacity of the Matter Vispa river in the village of Zermatt is of the order of 75 m^3/s, representing currently an approximately 30-year flood. However, in summer 2024, Zermatt has already been inundated by two major flood events as the river's discharge capacity was exceeded. One of the main objectives of the future Gornerli dam is to protect the site against higher floods. To this end, an additional storage volume allowing a 1000-year flood to be fully retained (design flood in Figure 7) is added to the active storage capacity of the dam. Considering the extended hydrograph of the design flood and a lake level at its FSL at the start of the event, the spillway elevation must be set at 2'255.61 m.a.s.l. or

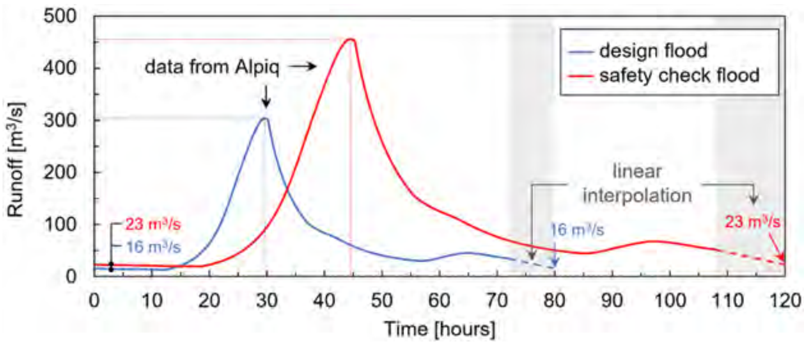

Fig. 7
Hydrographs of the design and the safety check flood considered for the Gornerli project
Hydrogrammes de la crue de dimensionnement et de la crue de sécurité envisagée pour le projet Gornerli

higher so that the reservoir can fully retain the 20 Mm^3 of this 1000-year event (ordinary flood retention area according to DIN 19700-11 :2004-07).

For a structure of this type, extreme loading situations must also be considered. For new facilities, SFOE defines a safety check flood discharge based on the design flood by increasing both the inflow and the event duration by 50% (SFOE, 2018). This is what was followed to obtain the red curve in Figure 7. By applying the extended hydrograph to a full reservoir (FSL) at the onset of the event, the water in the reservoir reaches a maximum elevation of 2'257.28 m.a.s.l. (Figure 8). With a crest level at 2'255.61 m.a.s.l., the spillway goes into operation 45 hours after the start of the event, i.e. 1 hour after the flood peak was reached. Maximum overflow water depth and peak discharge are estimated at 1.67 m and 148 m^3/s, respectively, 11 h after the spillway comes into operation (Figure 8). An exceptional flood retention volume (according to DIN 19700-11 :2004-07) is therefore created to evacuate the excess water that cannot be retained. Note that the damping effect would decrease the peak outflow to about one third of its inflow value only even for such an extreme flood event.

The spillway is planned to be composed of six individual uncontrolled overflow weirs, each 6 m wide, placed in the middle of the dam crest. With an overflow coefficient μ = 0.65, and applying the Poleni equation with a 3 m head, the discharge capacity is 360 m^3/s. For an extreme event spanning over 5 days (120 h), the ordinary retention volume fills up during the first 2 days. Then the spillway goes into operation for just over 4 days to evacuate the excess water present in the exceptional flood retention volume before equilibrium (inflow = outflow) is reached. Moreover, from the maximum overflow depth, the Swiss federal directive C2 on

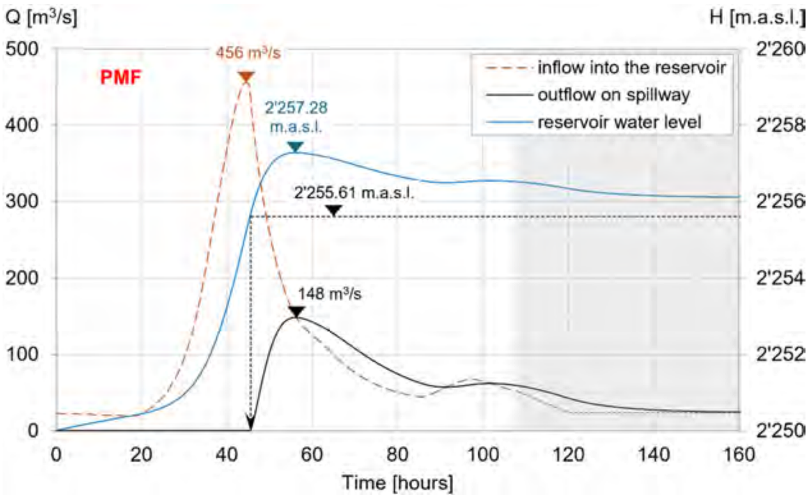

Fig. 8
Reservoir routing calculation for the safety check flood (shaded area: extrapolated flood data)
Comportement du réservoir et de l'évacuateur de crue durant la crue de sécurité considérée (zone ombrée : données de crue extrapolées)

flood safety and lowering the reservoir water level of water retaining facilities specifies that a minimum safety freeboard of 1 m must be observed for concrete structures over 40 m in height (SFOE, 2018). To meet this requirement, the minimum elevation of the dam crest is determined to be 2'258.28 m.a.s.l. The dam therefore rises to a height of 93.3 m above ground level.

5. CONCLUSIONS

In this contribution, we analyzed the spatio-temporal evolution of the Gorner glacier in connection with a planned proglacial water reservoir. Between 2050 and 2072, the ice is expected to have completely retreated from the planned reservoir area of the Gornerli dam, allowing for the use of the total operational volume for energy storage purposes. This volume will be used to store 650 GWh of electricity and will play a very significant role in ensuring a secure energy supply for Switzerland, particularly during the winter season. The evolution of the runoff and the capacity of the reservoir show that from 2045 onwards, all the water (except for environmental flow) will be used for energy production, meaning that there will be no more annual losses due to overflow.

Although the three approaches used to estimate the amount of sediment filling the reservoir differ, they all provide general insights into the expected order of magnitude. According to the assumptions, calculation approaches, particle size distributions, and sediment densities considered, between 85 and 98% of the material entering the reservoir is deposited in the natural lake formed by the first large depression of the engineered reservoir. Over the 80-year period of the concession, this corresponds to a volume between 2.5 and 7.0 Mm^3, slightly reducing the dead volume of 66 Mm^3 (Figure 5). Only a minority of these particles are transported beyond the rock sill and settle in the depression in front of the dam. The volume of sediment to be managed (i.e. immediately upstream of the dam) is in the order of 0.1 to 0.7 Mm^3. The loss of active storage capacity after 80 years is therefore estimated to considerably less than 1 Mm^3, amounting to around 0.5% of the active storage capacity of 152 Mm^3.

The existing discharge capacity of the river flowing through the village of Zermatt is some 75 m^3/s. Considering the hydrographs provided by Alpiq, the volume to be provided for retention purposes was calculated based on the design flood with a return period of 1’000 years. For flood protection purposes, it was assumed that all the water from such an 80-hour event with a peak discharge of 300 m^3/s would be stored in the reservoir, although this protection level is largely in excess of the common Swiss target level of a 100-year flood for the protection of settlements and residential areas. Assuming a full reservoir and therefore reaching its FSL at the onset of the event, the dam should offer an additional height between FSL and dam crest of 5.6 m to store the 20 Mm^3 of water entering the reservoir. For the safety check flood, which is 50% larger in terms of peak inflow (450 m^3/s) and duration (120 h), the spillway, comprising six unregulated weir bays located just below the dam crest, goes into operation 45 h after the start of the event. At peak, the maximum spillway discharge is estimated at 148 m^3/s.

Finally, it is important to remember the uncertainties surrounding these analyses. On the one hand, the topography beneath the glacier, measured by ground-penetrating radar in 2004 and 2008, has an uncertainty of at least $\pm$10 m. This range is particularly significant for the elevation of the rock sill behind which the natural lake will form. Indeed, this peak separating the two main overdeepenings of the reservoir has a major influence on the volume of active storage, as well as on the quantification of sediment settling just in front of the dam. On this point, the grain size distribution assumed in this analysis based on measurements in other Valais reservoirs also contributes to the uncertainties associated with the quantification of these deposited materials.

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WILDFIRE IMPACT ON DAM AND RESERVOIR LANDSLIDE SAFETY RISKS CONSIDERING FUTURE CLIMATE (*)

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SUMMARY

Wildfires can cause immediate disruptions to dam operations and commonly lead to minor damage with short-term disruption; however, post-wildfire erosion and landslides around the reservoir rim triggered by subsequent extreme rainfall, can cause far greater long-term impact to the operation and safety of the dam.

Where vegetation above soil is observed to have undergone moderate to high severity burning following a wildfire, the annual probability of a landslide is considered to be higher until the vegetation restores itself.

Current landslide hazard assessment practice typically does not consider the short-term increase in landslide susceptibility following wildfire. Climate change is expected to increase the frequency and severity of wildfires due to warming

**Impact des incendies de forêt sur les risques liés à la sécurité des barrages et des réservoirs, compte tenu du climat futur*

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temperature, increased severity of drought factor, increased intensity of rainfall, and a greater occurrence of thunderstorms.

For dams in wildfire prone areas, the future increase in annual probability of wildfire, driven by climate change, can have significant impact to operational and safety considerations. This paper suggests an enhancement to traditional abutment and reservoir rim stability considerations for dams by including the impact of wildfires and climate change. It builds on traditional risk assessment frameworks to integrate climate change by assessing variable temporal risk states (current, current with wildfire, post-wildfire, and future climate).

RÉSUMÉ

Les incendies de forêt peuvent provoquer des perturbations immédiates dans l'exploitation d'un barrage et entraînent généralement des dommages mineurs avec des perturbations à court terme ; cependant, l'érosion et les glissements de terrain qui se produisent après l'incendie de forêt autour du réservoir et qui sont déclenchés par des précipitations extrêmes ultérieures peuvent avoir un impact à long terme beaucoup plus important sur la sécurité du barrage.

Lorsqu'on observe que la végétation au-dessus du sol a subi des dégâts d'intensité modérée à élevée à la suite d'un incendie de forêt, on considère que la probabilité annuelle d'un glissement de terrain est plus élevée jusqu'à ce que la végétation se rétablisse.

Les pratiques actuelles d'évaluation des risques de glissement de terrain ne tiennent généralement pas compte de l'augmentation à court terme de la vulnérabilité aux glissements de terrain à la suite d'un incendie de forêt. Le changement climatique devrait accroître la fréquence et la gravité des incendies de forêt en raison du réchauffement des températures, de l'augmentation des facteurs de sécheresse, de l'intensité accrue des précipitations et de l'augmentation de la fréquence des orages.

Pour les barrages situés dans des zones sujettes aux incendies de forêt, l'augmentation future de la probabilité annuelle d'incendies de forêt, due au changement climatique, peut avoir un impact significatif sur les considérations opérationnelles et de sécurité. Cet article propose une amélioration des considérations traditionnelles sur la stabilité des culées et du bord du réservoir pour les barrages en y ajoutant l'impact des incendies de forêt et du changement climatique. Il s'appuie sur les cadres classiques d'évaluation des risques et intègre le changement climatique en évaluant des états de risque temporels variables (actuel, atuel avec feu de forêt, après le feu de forêt et climat futur).

1. INTRODUCTION

A landslide is a geological phenomenon where a mass of rock or soil moves down a slope under the influence of gravity. Typical types of landsliding include rockfall, debris flows, rotational slides, and translational slides. The consideration of landslides in the abutments, reservoir rim and broader catchment are integral to dam operation and safety risk assessments. Landsliding can impact dam operation and safety in many ways including:

- Damage from direct impact to the dam and appurtenant structures from landslide.
- Generation of seiche wave impacting the dam wall.
- Blockage of spillways leading to scour or overtopping of the dam.
- Changes in the watershed infiltration rates that could either increase or decrease the likelihood of landslides and flood hydrology.
- Landslide debris forming dams in the catchment upstream, which upon dam break generated a flood wave causing cascade failure (or other impacts) of the dam.

The 1963 Vaiont reservoir landslide was a turning point in emphasis given in hydropower and dams projects to reservoir slopes [11]. Engineering geologists and Engineers in line with current practice today are now obliged to consider landslide hazards to new dams or under dam safety reviews.

Wildfires can significantly increase the likelihood of debris flow and rockfall landslide hazards by removing stabilizing vegetation, altering soil stability, changing hydrological patterns, physically weakening rocks, accelerating and weathering processes. The likelihood of landslide post-wildfire triggered by subsequent rainfall, increases over a period while the vegetation recovers. In Australia, authors have proposed an order of magnitude increase in likelihood with moderate to severe wildfire for a 5-year period following a wildfire [15].

In addition, wildfires can impact water supply infrastructure reservoirs [6]. The ‘Black Saturday’ fires in Victoria Australia of February 2009 highlighted the need for owners and managers of catchments, dams and associated infrastructure to better understand and plan for the potential impacts of fire. For the 2009 Victorian bush-fires, a modified paired catchment method that considers the partial effect of annual precipitation differences was used in eight catchments with burned areas and found that evapotranspiration declined by 33 $\pm$ 20 mm/yr (mean $\pm$ standard deviation) and streamflow increased by 68 $\pm$ 32 mm/yr during the post-fire decade. Averaged for the post-fire decade, there seems to be an overall decline in terrestrial water storage for burned catchments relative to unburned catchments [21].

Climate change is expected to worsen the situation due to warming temperature, increased drought severity, a greater occurrence of lightning from thunderstorms, and increased intensity of rainfall [3,4]. In particular, these factors can increase the likelihood of wildfires and subsequent debris flow landslides following intense short duration rainfall events [5].

To address landslide hazard to dam operation and safety risk assessments, an understanding of abutment, catchment, and reservoir rim slope stability is required (e.g. the likelihood or annual probability of a landslide hazard of a certain type and size will feed into the risk assessment and implemented with the use of event trees).

Current state of practice follows methodologies, like the one put forward by the Australian Geomechanics Society [2], to estimate the probability of landslide trigger (i.e. rainfall event) and probability of landslide travel to the element of interest. The approach is typically static, in the sense that it considers current slope and climate conditions, and the probability of landslide does not change over the design life of the dam or until the next dam safety review is undertaken. It does not typically consider the short-term (i.e. 5 to 10 year) increase in landslide susceptibility following wildfire or long-term (i.e. within design life) changes to the rainfall trigger events from climate change.

With climate change, the approach where climatic triggers on landslide likelihood are assumed to be static over the dam design-life is not adequately expressing the hazard and therefore the dam safety and operational risk. This paper collects several historical case studies to propose the development of a methodology that includes climate change influenced bushfire impact on dam and reservoir safety risks, notably debris flow and rockfall landslides.

2. BACKGROUND ON CLIMATE CHANGE AND WILDFIRES

Driven by unabated global greenhouse gas emissions, changes in climate are now being observed in every region of the world and across entire Earth systems [13]. According to the Sixth Assessment Report (AR6) released by the Intergovernmental Panel on Climate Change (IPCC), the climate has warmed at a rate that is unprecedented in thousands of years. In Australia, the 2023 the national mean temperature 0.98 °C warmer than the 1961–1990 average [4]. Although climate change is now an “established fact” [13], there is still significant uncertainty around the future climate.

Although decarbonization and mitigation efforts are critical to limiting further climate change, it is equally important to understand, prepare, and adapt to the changes in climate that are already locked in. According to the Sixth Assessment Report released by the Intergovernmental Panel on Climate Change even under the most optimistic scenario with the lowest greenhouse gas emissions, global surface temperature is expected to rise by up to 1.7°C by 2040 and potentially 2°C within the next 40 years (i.e., by 2060) (both temperatures as compared to pre-industrial levels from 1850–1900) [13].

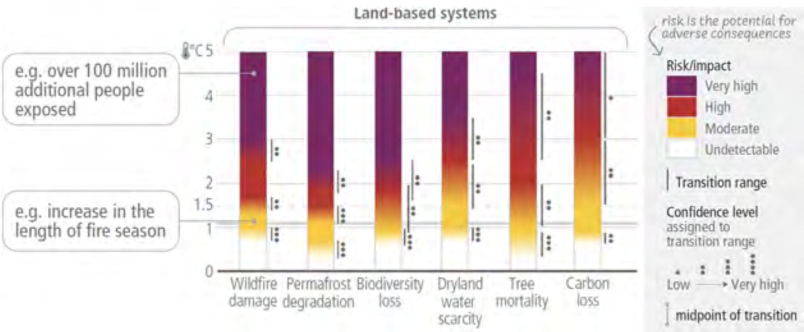

Fig. 1
Increase of risks with every increment of warming, including wildfire damage. Adapted from [13]
Augmentation des risques avec chaque augmentation du réchauffement, y compris les dommages causés par les incendies de forêt. Adapté de [*13*]

For example, the New South Wales (Australia) climate has already changed, driven by a rate of warming faster than the global average. Since the pre-industrial period, NSW has warmed by 1.4–1.6°C which is 1.4 times higher than the global average of 0.8–1.1°C. This has contributed to more frequent and extreme weather events, such as wildfires and extreme rainfall. In Victoria (Australia), peak hourly and peak daily rainfalls have increased with the rate of increase in sub-daily durations [1,4,7,8,18].

Wildfires can have significant impacts on the occurrence and frequency of landslide in several ways:

- Loss of Vegetation: Wildfires often burn away vegetation that holds soil and rocks in place on slopes. Without this root system to stabilize the soil and rocks, there is an increased likelihood of rockfalls and debris flow.
- Loss of Soil Stability: The heat from wildfires can alter soil properties, making it more prone to erosion and destabilization.
- Changes in Hydrological Patterns: Wildfires alter the infiltration rate of a catchment. This can lead to increased erosion and can change the catchment flood hydrology.

- Changes to Rock Mass: Intense heat from wildfires can cause thermal stress and expansion in rocks, leading to fractures and weakening of rock.
- Increased Weathering Processes: Wildfires can accelerate weathering processes including chemical weathering from altered soil conditions and physical weathering from increased freeze-thaw cycles.
- Post-Fire Debris Flows: After a wildfire, the increased runoff and sediment transport can lead to debris flows.

The increase in landslide susceptibility, particularly debris flow, following wildfire where vegetation above soil is observed to have undergone moderate to high severity burning, is well known [5]. Moderate severity corresponds to the fire consumption of all understory plants and pre-fire organic soils and high severity additionally includes the destruction of canopy trees.

Studies in Australia have estimated the likelihood of a landslide to have increased by one order of magnitude [15] in the short-term after a wildfire by an order of magnitude higher than the “base case” (i.e. vegetated). This increase in the likelihood of landslides, and changes in other parameters such as evapotranspiration or streamflow, seems to be short-term in the next 5 to 10 years until vegetation returns [15,21], and creates a temporal change to the landslide hazard probability.

Considering climate change in the future, say 2070, the annual probability of a wildfire will increase in the future from warming temperature and an increase in intensity of rainfall in many areas around the world. The compounded impacts of increased probability of wildfire and rainfall could increase the overall landslide likelihood within a design life of 100-years, perhaps up to an order of magnitude ($\sim$10x), though this impact needs to be quantified and justified case by case.

3. WILDFIRE INLUFENCE LANDSLIDE DAM SAFETY CASES

Within the last decade, a number of significant wildfires and subsequent landslides have highlighted concerns to dam operation and safety. In these cases, the dam itself was not directly damaged. Three case studies where dams or their appurtenant structures were damaged are presented below, involving debris flows and rockfall.

3.1. Wenner lakes dam breaches and hawkins dam

In mid-July 2014, lightning started several forest fires that eventually combined to form the Carlton Complex Fire which eventually burned more than

1,036 km^2 in Washington State (USA). The burned area included most of the Finley Canyon watershed and the downstream Benson Creek Watershed. Upstream in Lower Finley Canyon, high runoff flows in conjunction with spillway blockages resulted in overtopping of the dams at Wenner Lake Nos. 1 through 4.

Fig. 2
Rabel Dam (Wenner Lake No.4) spillway blocked by debris flow during the 2014 wildfire and rainfall event. Source: [17]
Le déversoir du barrage Rabel (Wenner Lake n° 4) bloqué par une coulée de débris lors de l'incendie de forêt et des précipitations de 2014. Source : [17]

At Rabel Dam (Wenner Lake No. 2), a debris flow from the hillside blocked the spillway, but fast action by the owners reopened the spillway in time to prevent further damage [17]. At Hawkins Dam, a debris flow from the hillside above the right side of the dam may have partially blocked the spillway, but there was no indication that the dam overtopped. Erosion in the Hawkins Dam unlined spillway chute scoured a channel 110 m long, ranging in width from 5.5 to 14 m and ranging in depth from 2.4 to 5.5 m deep, with an estimated volume of about 5,050 m^3 within the spillway chute.

Apart from the debris flow that caused damages, an interesting fact is that rainfall calculations by the National Weather Service (NWS) Spokane office and by the Department of Ecology's Dam Safety Office (DSO) indicate the rainfall on Finley Canyon and the Benson Creek watershed was on the order of only a 5-year event. These results were then compared to a pre-fire watershed model and the estimated flows from the fire event were 7 to 8 times larger than the predicted flows from a 1000-year local storm event. The pre-fire surface infiltration rates ranged from 45 to 49 mm/h, while the post-fire surface infiltration rates used in the model ranged from 2 to 5 mm/h, that is approximately a 10-fold reduction in infiltration. As a result of this flood and the failure of Hawkins Dam, the Washington State DSO developed recommended dam safety protocols for burned watershed hydrology calculations [19].

3.2. Burrinjuck dam

The Burrinjuck Dam and reservoir are located within a deep valley of the Murrumbidgee River, NSW Australia. It is an area where wildfire have occurred on average every 16-years for the last 66-years [3].

Fig. 3
Burrinjuck Dam in Australia, with downstream buttresses incorporated in the 1950's and a raised crest in the 1990's. Picture source: The Area News, 2022.
Barrage de Burrinjuck en Australie, avec des contreforts en aval incorporés dans les années 1950 et une crête surélevée dans les années 1990. Source de l'image : The Area News, 2022.

A major fire in December 1972 destroyed the vegetation cover on the slopes and following rains caused a considerable quantity of boulders and debris to wash down the steep gullies into the right spillway channel and in the workshop area. Later, on 29 August 1974, a rockfall occurred downstream of the right spillway during the second largest flood event recorded at the site. The rock-fall carried away a 40 m length of the DN 2.16 m penstock to the No. 1 Power Station and triggered an uncontrolled release of water.

A reported wildfire every 16 years is a 6.25% annual probability of wildfire. Assuming that post-wildfire the likelihood of landslide is an order of magnitude greater than “normal” conditions and it takes 5-years to recover, the combination of a 6.25% annual probability of wildfire and a 5-year recovery period shows that the long-term likelihood accounting for wildfire hazard is approximately 30% increase in annual probability. Climate change is expected to increase the likelihood of wildfires in many regions and the consideration of this increased likelihood of landslides following a wildfire suggests that climate change may eventually increase the landslide likelihood and therefore, risk for dams.

3.3. Glenmaggie dam

Glenmaggie Dam is a 37 m high concrete gravity dam that was originally commissioned in 1926 to store 132 million m^3 in the Macalister River basin, with a catchment area of 1,891 km^2. After World War II, it was raised 3.6 m by installing 14 radial gates to increase its capacity up to 177 million m^3, whereas in 1987, the dam was further upgraded to withstand major floods and earthquakes by means of 70 post-tensioned anchors.

Significant flood events took place in June 2007 in the Gippsland region (Victoria, Australia) following severe wildfires experienced during the previous summer (beginning of 2007), and major damage was reported at Glenmaggie Dam. The flood event introduced a record peak inflow of 250 million m^3 in one day and tested Southern Rural Water emergency management procedures to deal with a swift rise in storage volumes, the loss of upstream warning gauges, the development of water release strategies, the communication with the local community, and notably, the accumulation of large volumes of debris.

The hydrology review included a flood frequency assessment which showed that the magnitude of the Glenmaggie flood was in the order of a 1:200 AEP (Annual Exceedance Probability) event, which was disproportionate to the rainfall event frequency assessed as having a 1:50 AEP, when averaged across the catchment [10].

Fig. 4
Glenmaggie Dam in Australia. Picture source: Girt By, 2023 (https://www.girtby.com/blog/2023/1/21/lake-glenmaggie).
Barrage de Glenmaggie en Australie. Source de l'image : Girt By, 2023 (https://www.girtby.com/blog/2023/1/21/lake-glenmaggie).

4. CLIMATE CHANGE WILDFIRE IMPACTS ON DAM AND RESERVOIR LANDSLIDE HAZARD ESTIMATIONS

Currently, methodologies to estimate the likelihood of landslides consider the present climate conditions (either based on prescribed annual return periods or annual frequency). However, consideration of wildfire and climate change requires consideration of additional temporal states.

4.1. Temporal states when analyzing wildfire and landslide hazards

Temporal states should reflect the design lives of the infrastructure asset components, typically the current year or 2030 to represent the current climate state for assets with shorter operating lives, and future states (i.e. 2070 or 2090) to inform the design of remediation or ‘fixed’ asset components with longer operating lives. The four key temporal states are the following:

- Current Climate (i.e. Baseline): Current hazard state of a slope where vegetation is grown.
- Current Climate with Wildfire: Current hazard state with an increased likelihood of subsequent landslide considering and annual probability of wildfire.
- Post-wildfire: Hazard over a few years immediately following a wildfire with an increase in likelihood (i.e. 10x estimated for post-wildfire slopes in eastern Australia) due to the removal of vegetation from the slope and changes to soil permeability. The post-wildfire increase in probability should be short-term, as the probability returns to pre-wildfire levels with vegetation regrowth within a few years.
- Future Climate: Future hazard state considering climate change with both wildfire probability and rainfall intensity increased, thus increasing landslide likelihood.

4.2. Annual probability of wildfire hazards

The estimation of annual probability of wildfire for any location is beyond the scope of this paper. This is a multi-disciplinary approach which draws upon the knowledge of fire scientists. However, some high-level guidance, based on published literature and project experience, is provided below.

The Forest Fire Danger Index (FFDI) is a numerical scale based on a combination of different weather conditions known to influence the risk of dangerous wildfire conditions in Australia, including temperature, rainfall, humidity, and wind speed [3].

One approach to estimate annual burn probability is outlined for a national wildfire risk assessment for Portugal [16], as well as a case study which follows a similar procedure [14]. This methodology integrates susceptibility factors (vegetation landcover and topography) with historical wildfire data, to estimate an annual burn probability for a location.

This approach is exemplified by a study commissioned by Infrastructure Victoria wherein an area in rural Victoria was considered in context of an annual wildfire which burnt 50% of the area of the 2019/2020 wildfire season [1]. In Victoria (Australia), the historical wildfire data showed that the average area burnt each year due to unplanned wildfires over a five-year period (2018-2022) was approximately 350,000 hectares, equivalent to approximately 0.15% of the state’s total area [9]. In addition, a literature review of historical records identified five significant wildfires had occurred in the region since the early 19th Century. Using these parameters, the annual probability of wildfire (i.e. annual burn probability) in this area was estimated to be 3% under current climate conditions in 2022 [1].

However, as noted before, more frequent and severe wildfire weather will be driven by hotter and drier conditions. To estimate annual probability of wildfire under future climate conditions (i.e. climate in 2070), based on a greenhouse gas Representative Concentration Pathway (RCP – the prediction of greenhouse gas concentration in the atmosphere based on future human activities) of RCP8.5, the current burn probability of 3% is scaled proportionally to the projected change in number of severe fire danger days from the baseline to 2070. Severe fire danger days are represented by the number of days with FFDI greater than 50. In the rural Victoria example (as per Table 1), the baseline average number of severe fire danger days is 3.6 days, increasing to 7.1 days by 2070 under RCP8.5 [12]. Therefore, for this area in Victoria the annual probability of wildfire will double from current probability of 3% in 2022 to future probability of 6% in 2070.

4.3. Future annual probability of extreme rainfall events

While New South Wales and Victoria (Australia) are projected to likely receive less overall total rainfall in the future with extended periods of drought, extreme storms and rainfall intensity are likely to increase. For the Victorian example, peak rainfall intensity in 2070 under RCP8.5 has been determined using a 14% increase using the Australian Rainfall and Runoff Guidelines [7] and this rainfall increase will vary for different storm durations [18].

4.4. Combined wildfire-landslide hazard likelihood

The landslide hazard likelihood needs to be estimated for each significant temporal state. To estimate the landslide hazard, both the annual probability of wildfire under current climate conditions and under future climate conditions should be considered, in addition to the subsequent rainfall landslide triggers. Therefore, the likelihood estimation is modified to include a probability of wildfire (to create conditions for a landslide) and an increase in landslide likelihood (triggered by rainfall). As mentioned before, this post-wildfire increase in landslide likelihood is short-term and returns to pre-wildfire levels with vegetation regrowth in a few years (5 to 10 years).

An example of how landslide likelihood changes in the temporal risk states is presented below, considering a hypothetical case in Victoria and using the approach for assessing annual burn probability in [16], where the current annual probability of wildfire is assessed at 3%. The likelihood of a landslide for a given slope, following wildfire, is assessed to be increased up to an order of magnitude (i.e. 10x) for a

5-year period following the fire, that is a high to very high increase. Combining the annual probability of wildfire with the increase in likelihood of landslide results in an approximately 2.35 increase in the combined wildfire-landslide likelihood (for the current condition), which could be defined as a low increase.

The estimation of revised landslide likelihood integrates the probability of landslide without wildfire with the probability of an increase in landslide hazard post-wildfire using the probability of a wildfire occurring over the design life. For example, a given slope has a 10^{-3} annual probability of landslide in its current state without a recent wildfire, but there is a 3% annual probability that a wildfire will occur and temporarily increase the annual probability of landslide up to 10^{-2} for a period of five years over a 50-year design life.

In the future climate (i.e. 2070) for this Australian region, the annual probability of wildfire rises to 6%. When combined with the landslide likelihood increase in a five-year period, the overall, combined likelihood is increased by a factor of around 3.7 times. Consideration of the approximate 14% increase in extreme rainfall events in the future climate increases this factor up to more than 4 times for the combined wildfire-landslide likelihood, which could be qualified as a medium to high increase (see Table 1).

Table 1
Examples of changes in combined wildfire-landslide likelihood for different temporal risk states in Victoria (Australia).
Exemples de variations dans la probabilité combinée d'incendies de forêt et de glissements de terrain pour différents états de risque temporel dans le Victoria (Australie).

TEMPORAL RISK STATE	LANDSLIDE LIKELIHOOD	COMMENTS
Current climate	CURRENT LIKELIHOOD	Baseline value
Current with wildfires	LOW INCREASE	With 3% annual probability of wildfire
Post-wildfire	HIGH TO VERY HIGH INCREASE	Within 5 years of wildfire (up to an order of magnitude increase depending on the specific circumstances)
Future (2070) with wildfires	MEDIUM TO HIGH INCREASE	With 6% annual probability of wildfire and increase in rainfall intensity

5. CONCLUSIONS ON DAM AND RESERVOIR LANDSLIDE SAFETY RISKS CONSIDERING CLIMATE CHANGE

In principle, the potential landsliding in the abutment, reservoir rim, and catchment are credible hazards to dam safety and operations. The safety and risk implications of major landslides involving a volume of over 400 000 m^3 always calls for dedicated surveillance and monitoring systems [20]. The increased likelihood of landslide, under post-wildfire conditions compounded by time for post-fire vegetation/soil recovery may be significant enough to include it in risk assessments for dams.

The combined effects of climate change on increased wildfire probability and increase in extreme rainfall intensity may have a compounded impacts on probability of landslides. For the wildfire case, a dam with an existing safety/operational issue from landslide/debris/rockfall from the reservoir rim could experience an increase in the overall landslide likelihood accounting for the combined climate change, wildfire and rainfall event likelihoods.

This paper has introduced concepts to consider climate change influenced wildfire impact on dam and reservoir safety risks considering future climate by looking at variable temporal states of hazard. The dam industry is encouraged to share case studies to further develop and refine the likelihood estimates and impact of wildfires on the overall dam and reservoir safety levels.

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GRANDS BARRAGES
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TOWARDS FRCOLD GUIDELINES FOR THE REALIZATION OF FLOATING PV PLANTS ON DAM RESERVOIRS (*)

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SUMMARY

To address the challenges of decarbonizing energy production, making territories more resilient to the effects of climate change and preserving biodiversity, it is essential to explore solutions for developing reservoirs and hydraulic structures that can respond to these issues. The installation of floating photovoltaic power plants on dam reservoirs is an effective solution to this problem [7]. France has a significant potential for installing such plants, with numerous projects currently in development. These projects often appear to be far from the safety standards expected with regards to dam safety. In light of this, the FRCOLD has created a working group with the objective of producing technical recommendations for floating photovoltaic (FPV) power plants projects on dam reservoirs. The aim is to improve the quality of FPV projects and guarantee the safety of the dams. This article outlines the initial findings of the working group, which included a survey of current projects and identified the gaps for improvement in the field of floating photovoltaic power plants on dam reservoirs.

**Vers un guide CFBR de recommandation pour la réalisation de centrales PV flottantes sur les réservoirs de barrages*

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RÉSUMÉ

Face aux enjeux de la décarbonation de la production d'énergie, de la résilience des territoires face aux impacts du changement climatique, et de la préservation de la biodiversité, il est essentiel d'explorer les solutions d'aménagements de réservoirs susceptibles de répondre à ces sujets. Les centrales photovoltaïques flottantes sur retenues de barrages répondent à cet objectif [7]. La France dispose d'un potentiel d'installation de centrales photovoltaïques flottantes important, et de nombreux projets émergent. Ces projets apparaissent, pour nombre d'entre eux, loin des standards de sécurité attendus vis-à-vis de la sécurité des barrages. Devant cette situation, le CFBR a créé un groupe de travail visant à produire des recommandations techniques pour les projets d'installation de centrales photovoltaïques flottantes sur les retenues de barrage, de manière à améliorer la qualité des projets tout en garantissant la sécurité des barrages. Cet article rend compte de la première phase de travail de ce groupe qui a établi une enquête de retour d'expérience des projets en cours et des manques pour la profession des centrales photovoltaïques flottantes et des barrages.

1. INTRODUCTION

Floating photovoltaics on dam reservoirs constitute one of the solutions to enable the energy transition and the decarbonization of energy production. It is experiencing significant development throughout the world and the dam profession has been interested in these subjects for several years now. In this area, the Solar-Hydro conferences present the vast potential and prospects of hybridization technology and floating solar energy (FPV) [8,9].

France has a strong potential for equipping dam reservoirs with floating hydro photovoltaics, with a few floating photovoltaic power plants already installed [5]. Furthermore, an increasing number of floating photovoltaic (FPV) projects on dam reservoirs are being studied, developed, or considered. In south-west France alone, for example, several dozen projects are in gestation or preparation. Some of the proposed projects are far from the safety standards expected for dams and may pose real safety problems. In addition, floating PV technology is still evolving, with no clearly established technical benchmark, and the techniques are yet to be stabilized.

For other projects, engineers may propose misaligned and sometimes excessive design criteria, while regulators may issue unfavorable opinions without a clear understanding of the risks involved. In fact, there is a real difficulty in proving the reliability of the planned FPV installations in relation to the regulatory requirements and recommendations of the dam sector, particularly for flood evacuation systems, but also for other potential risks (fire, etc.). In general, there is a real difficulty in demonstrating risk control to maintain dam safety levels. This makes the development process complex for both FPV developers and dam operators [1].

In this context, the French Committee on Large Dams (CFBR) has decided to set up a working group with three key objectives [3]:

1. Provide keys to understand the administrative process for permitting and developing a floating PV power plant in France,
2. Establish the state of the art of floating PV technologies and techniques and propose design criteria,
3. Propose a risk analysis approach for evaluating floating PV projects.

The deliverables of the working group are aimed at both the dam industry (operators, engineering companies, authorities) and the floating PV industry.

The working group gathers CFBR members: engineering offices, dam owners, governmental authorities, regional administration, floating PV developers; and work closely with the ICOLD Committee T [6]. Under the direction of Marine BERNICOT (ISL), Nicolas GERARD (EDF CIH) and Laurent PEYRAS (INRAE), the composition of the working group is the following: Gaetan BAYART (EDF - Renouvelables), Gaëtan DAUTOIS (ARTELIA), Laurent DEL GATTO (EDF CIH), Anthony DOLS (EDF - Renouvelables), Nicolas FRAYSSE (BRLI), Yohann GRISARD (SCP), Jean Marc LABRUE (DREAL), Tarik OUSSALAH (PoNSOH), Samuel RENAUD (TRACTEBEL).

Fig.1
Lazer FPV Plan in France @EDF
La centrale FPV de Lazer en France @EDF

The working group commenced its activities in mid-2023. A survey covering the three objectives of the working group was carried out on projects currently underway in France, in order to collect initial feedback from floating PV power plant projects developed on dam reservoirs. This article focuses on this survey and preliminary lessons learnt from it, which constitute the first deliverable of the working group. For further information, please refer to the full report [3].

2. APPROACH AND DATA COLLECTION [3]

2.1. Typology of dams and main features of the floating PV projects

Data from 18 floating PV projects was collected from the members of the working group: 12 in France and 6 abroad. For each project are given the location, the planned capacity and its status in 2023, split into the 4 main stages of the life of a project: development, authorization, construction and operation: [3]

Fig. 2
Main stages in the progress of a project
Principales étapes du déroulement d'un projet

In 2023, floating PV projects on dam reservoirs in France are mainly in development phase (69%). Only one project is in operation, and two others have been authorized. One project has not been authorized by the authorities.

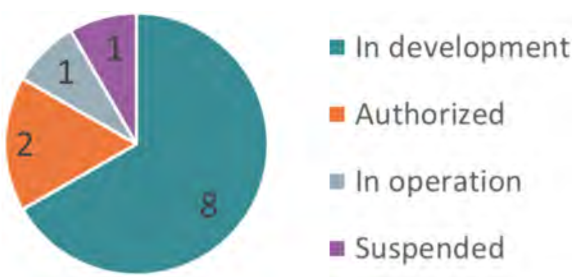

Fig. 3
Status of the floating PV projects on dam reservoir
Statuts des projets de centrale PV flottantes sur retenue de barrage

The dam reservoirs envisaged for floating PV power plant projects (in France) are primarily dedicated to irrigation (7), followed by hydroelectricity (3). Two projects involve reservoirs used for drinking water supply or low-water support.

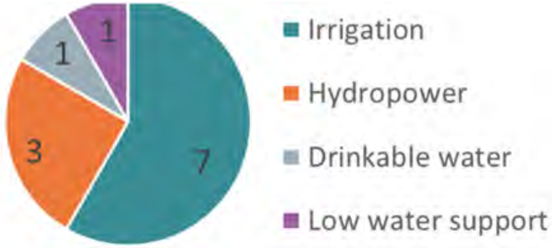

Fig. 4
Use of dams hosting floating PV plants
Usage des barrages accueillant des centrales FPV

The dams considered for floating PV projects (in France) are predominantly medium sized to small structures, mostly class B (58%), followed by class C (33%) dams. Only one class A dam is reported at this stage.

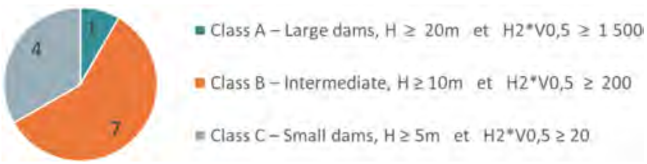

Fig. 5
Dam sizes hosting floating PV plants
Taille des barrages accueillant des centrales FPV

The main technical characteristics of the floating PV projects analyzed are as follows:

- **Installed capacity in MWp**: [3.7; 45] - Average 14.8

This analysis shows a wide range of project sizes, from small installations to large-scale projects. It should be noted that there are no projects with large installed capacities in France, unlike some of the international projects studied, which exceed 80 MWp.

- **PV panel area [ha]**: [2.1; 27.7] - Average 12.7

Also, the various projects examined were widely dispersed.

- **% impoundment coverage at Normal Water Level:** [20%; 70%] - Average 40%.

The planned coverage rate seems to be quite homogeneous and high, attesting of projects installed on small to medium-sized reservoirs. It should be noted that the survey did not always accurately specify the area considered for the panels and that for the reservoir.

3. THE ADMINISTRATIVE DEVELOPMENT PROCESS IN FRANCE

3.1. General framework – the environmental authorization

Some hydraulic structures are of public safety concern for downstream populations. In application of the French Environmental Code, these structures are subject to technical regulations designed to guarantee their resistance and suitability for use. A floating PV power plant on a dam reservoir, because of its potential interaction with the hydraulic structure, must be designed in compliance with these regulations.

Depending on the size of the dam and its reservoir, maximum annual probabilities of dam failure due to the failure of the floating PV plant have been set by the supervisory authorities, and project developers must prove the conformity of their projects at different stages of administrative authorizations, the first one being the “Environmental Authorization”.

Reservoir size (H = height, V = volume)	Maximum annual probabilities of dam failure due to the failure of the floating PV plant
Classe A : H >= 20 et $H^2*V^{0,5}$ >= 1 500	10^{-4}
Classe B : H >= 10 et $H^2*V^{0,5}$ >= 200	3×10^{-4}
Classe C : H >= 5 et $H^2*V^{0,5}$ >= 20	10^{-3}

Fig. 6
Maximum annual probability of dam failure due to floating PV system failure in French regulation
Probabilité annuelle maximale de rupture de barrage due à une défaillance du système photovoltaïque flottant dans la réglementation française

3.2. Survey feedback

An analysis of the case studies shows that, although the administration is structuring itself, there is currently no uniformity in the way Regulators and Supervision authorities analyze projects to deliver the "Environmental Authorization". At the time of the analysis, it can be seen that project applications for hydroelectric reservoirs are more detailed than those for other types of reservoirs. This is however due to the financial implications involved, associated with the agreement between the owner-operators of the hydraulic structure and the PV plant.

It should be noted that the supplier and therefore the technology chosen for the floats/anchors is generally not known at the preliminary design stage. Technical solutions, as well as the final layout and number of islands, may then change after the authorization.

Developers also report how important it is for them to control costs (and therefore the level of detail of studies) in the project development phases, i.e. before obtaining authorization.

One of the difficulties faced by Regulators and Supervision authorities is thus to base their opinions on relevant, non-evolving elements. In particular, the following points are mentioned:

- Design criteria or hypothesis note, instead of technical solutions that may evolve after authorization,
- Level of maintenance and inspection requirements for floats and anchors (anchor points and mooring lines),
- Division of responsibilities between the dam operator and the floating PV plant operator (floating PV instructions, consistency with the dam operator's organization),
- Definition of the expected minimum level of geotechnical knowledge.

If a classified dam is not safety compliant prior to the floating PV project, the latter may be an opportunity for the dam manager to finance compliance work. The level of requirements and the timeframe between the development of the floating PV project and the compliance of the dam need to be addressed. One question is how to handle cases where the floating PV project would contribute to improving the safety of the dam without achieving full compliance in areas unrelated to the PV project.

4. FLOATING PV TECHNOLOGIES & TECHNICS

4.1. Floating PV accidentology

Communications on hazards or accidents are rare, which does not necessarily mean that there are none. Two significant incidents have been reported:

A significant accident occurred in September 2019 on the Yamakura Dam reservoir, during a typhoon (Fig. 7). The reservoir is a water reserve for industrial and agricultural uses. It is not a hydroelectric facility. The dam is a 23m high, 1460m long embankment dam. The reservoir stores 5.1 hm3 and covers an area of 61ha. The solar power plant occupies 30% of the reservoir (18ha), for a total capacity of 13.7MWp. An electrical fault on the solar power plant was detected remotely by the plant's monitoring system and an alarm was transmitted to the on-call staff, who noticed the detachment and rupture of elements of the floating system. They proceeded to an emergency shutdown of the electrical equipment. A few hours later, a fire then broke out. It was brought under control in a few hours. The solar power plant did not disintegrate into a multitude of floating bodies. The accident had no

Fig. 7
Yamakura FPV Plant in Japan, during a typhoon in 2019 [8]
La centrale PV flottant de Yamakura au Japon suite au typhon 2019 [8]

consequences on the operation of the flood spillway. The review concluded that the stress concentration on some mooring anchors was the trigger for the accident. This stress concentration was caused by the complex shape of the floating structure. Once failure occurs for some anchors, the balance of forces is reorganized and the loads can increase at adjacent points, causing a kind of chain reaction of failure. If the shape of the floating structure had been simpler (rectangular), the stress concentration would have been mitigated. Following this accident, floating solar systems have seen their shapes simplified and their surface area reduced (several medium-sized islands rather than a single large island). It was also recommended to introduce a safety factor at the anchor/foundation soil interface.

In April 2024, the world's largest floating solar plant in Madhya Pradesh's Khandwa district (India) was damaged by a storm (Fig. 8). The plant, built on the backwaters of Omkareshwar Dam, was under construction. It seems that a large section of FPV about to be connected and moored to the other sections and anchorages drifted away under the wind gusts loads (only around 50 kmph), but little precise information is available. It seems other parts of the project, definitively moored, did not suffered any problem.

In France, we can report an electrical incident occurred on a floating solar power plant installed on a gravel pit in January 2022 (Piolenc site), in the Rhone Valley. The incident occurred during a strong wind episode, but the incident is not

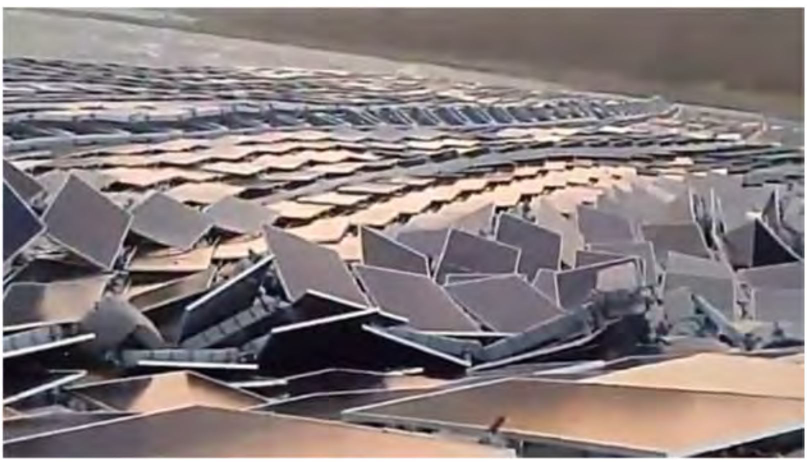

Fig. 8
FPV plant in Madhya Pradesh Yamakura damaged by a storm in April 2024 @X/Nandini K Oza
La centrale PV flottant de Madhya Pradesh Yamakura endommagée par une tempête en avril 2024 @X/Nandini K Oza

directly linked to this strong wind episode. Investigations have identified that under the effect of the choppy water regularly observed on the body of water, the repeated friction between the internal electrical cables of the island and the structures of the cable trays that support them led to degradation of the insulation of the conductors, causing a short circuit. The electrical protection system did indeed cause the installation to be disconnected, but some floats supporting the cable tray ignited and took on water.

4.2. Sizing : Pratices

The technologies and techniques being considered or implemented for floating PV power plants are in a state of flux, with no clearly established technical benchmark, and the techniques are not yet fully stabilized or mastered. In March 2021, the DNV-GL organization published recommendations on the subject "DNVGL-RP-0584 -Design, development and operation of floating solar photovoltaic systems" [4], which give general design principles for floating PV. In these recommendations, we note, for example, that the levels of stress considered for the design of these installations (loads, associated hazards and return periods, design criteria, etc.) are significantly lower than those taken into account for dam design. However, it should be remembered that these recommendations remain recommendations and do not have the force of a standard. The design guidelines remain rather general, and most of the time call for compliance with applicable national regulations, especially with regards to natural hazards.

The information gathered by this WG on dimensioning shows that the recommendations issued by the DNVGL (DNVGL-RP-0584-2021) are mostly known [4]. For France, natural hazards and load combinations as defined in the Eurocodes are generally considered in the design. Furthermore, the technologies and techniques envisaged or implemented for floating PV power plants are often little or not at all known to the dam industry, which is therefore generally rather unprepared to support the engineering of these installations.

This study [3] provides a state-of-the-art review of the technologies and techniques being considered or implemented for floating PV power plant projects, based on the information gathered during the survey.

4.2.1. *Natural hazards*

WIND: Eurocode reference wind speeds are usually given in the data sheets. This reference wind speed (10-minute average speed at 10 m height, with a 50-year return period) is sometimes reduced to the height of floating structures, which is much less than 10 m. The determination of gust winds is rarely mentioned. When it is, it seems to be used to verify the dimensions of the elements used to attach the photovoltaic panels to the floats.

For international projects, the criteria follow the applicable national standards. Wind is well recognized as an important dimensioning element and its assessment is often carried out at the earliest stages of project development.

WAVES: Waves are not systematically determined. Wave studies are quite variable: often absent for small reservoirs $<$ 25 ha, they are sometimes very thorough, especially for large projects, located on very large reservoirs, and moreover in typhoon zones (but this is also not systematic). The models used range from simple formulas (based on fetch, wind speed and duration) to complex wave propagation models applied to the project site (such as SWAN models). For large reservoirs, wave studies should be carried out fairly early during the development studies, as they can lead to the implementation of mitigation or protection measures that are prohibitive to the financial equilibrium of a project.

CURRENT: Current velocities are generally low. Depending on the site location and water inflow, current velocity is sometimes considered negligible. This may also be the case for very large reservoirs. Depending on the context, specific hydraulic studies may have been carried out (although this is rare). Of the French projects studied, none is located on a reservoir directly fed by a major watercourse that could generate significant currents. Floods (and their return periods) are not systematically considered.

SNOW: The action of snow is largely neglected in the projects studied.

ICE: The action of ice is never considered in the projects studied.

SEISM: Only one project mentions seismic considerations in the design, due to the anchoring system technology (vertical piles).

4.2.2. *External hazards*

The external hazard most frequently mentioned and considered in the projects examined is the risk of floating debris. The characterization of this risk from a design perspective is generally vague. One of the projects assumes a fixed force on the upstream solar island but does not specify how the value of the force was assessed. For the vast majority of projects, this risk is considered negligible, as most of the selected water bodies appear to be relatively unaffected by the arrival of floating objects.

Vandalism and personal protection are sometimes mentioned. Countermeasures vary and may include partial fencing or other devices to keep swimmers or small boats at a distance. It should be noted that most of the projects surveyed are developed on reservoirs where swimming or boating is not permitted. In some large international projects, floating lines are sometimes installed around the periphery of the islands.

With regards to grounding (partial or total), little information is available beyond the identification of the hazard. Qualitative criteria are sometimes mentioned (nature and geometry of the seabed). In the case of several projects, we note that the area selected for the floating PV project corresponds to the zone that remains in the water at the lowest water levels.

4.2.3. *Fire hazard*

Although international (and more recently national) feedback points to the possibility of fire outbreaks within the islands of floating PV power plants, this risk is hardly mentioned in the data sheets, and it does not appear that specific counter-measures are planned in the project stage. Nevertheless, it is likely that this risk will be better taken into account in the developers' dossiers, as the SDIS (in charge of fire and rescue) is consulted during the administrative assessment of floating PV projects. In this respect, the SDIS of Gironde in France produced a document in 2021 entitled "Centrales photovoltaïques flottantes - prescriptions et recommandations du SDIS" ("Floating PV plants – prescriptions and recommendations").

4.3. Operational monitoring – maintenance

Monitoring aspects (in operation and/or maintenance) were largely left unspecified in the questionnaire responses. This may be explained by the fact that most projects are at the development stage, and these considerations are integrated at a later stage. Operation/maintenance arrangements are to be dealt with by the developer of the floating PV plant: during appraisal, the Regulators and Supervision authorities requires the preparation of an organization document for the floating PV plant explaining the interaction with the operation/maintenance of the hydraulic structure. The organization document for the hydraulic structure must also be updated.

Projects generally include quarterly or annual visual inspection rounds, and sampling for larger projects. Monitoring of production data is sometimes mentioned as a means of detecting failures. We note that one of the larger projects plans to implement comprehensive monitoring to track the behavior of the structures and their evolution over time. In some cases, monitoring of anchor behavior is mentioned, particularly in the early years of the structure.

5. RISK ANALYSIS AND SAFETY ISSUES FOR THE DAM

5.1. Assessing the intrinsic risks of a floating PV plant

The survey revealed that the majority of projects (75%) were subject to an intrinsic risk assessment.

The methodologies used to address intrinsic risks are mainly the Eurocodes for stress determination and anchorage calculation. DNV recommendations [4] are cited twice in the survey.

The detailed analysis of the case studies qualifies the production of a true intrinsic analysis. In fact, in the first case study examined, the intrinsic safety of the floating PV plant is not established as it is considered that its reliability cannot be accurately assessed. Therefore, in the interest of safety, the risk analysis does not introduce the intrinsic safety of the floating PV plant, and only assesses the scenarios related to the failure of the floating PV plant. The second case study evaluates the inherent safety of the floating PV system considering the project risks taken into account in the design. Among these, wind is one of the main hazards, and is evaluated based on the Eurocodes with a 50-year return period, which allows the sizing of the panel mounts on the floats. For the wave hazard, the CFBR references are considered, considering the hydrodynamic forces of a thousand-year flood concomitant with a fifty-year wind. Ultimately, the intrinsic safety of the installation is determined by the occurrence of the reference wind, and the probability of failure is between 10^{-2} and 10^{-1} per year.

In summary, this feedback highlights the real difficulty of assessing the intrinsic safety of floating PV plants, all the more as the calculation notes focus essentially on anchors and cables, without necessarily taking into account the connecting elements between the main components, which can be points of weakness. In any case, and given the assumed loads (from Eurocodes or DNV), the project hazards correspond to rather high probabilities of occurrence (typically for wind, the reference return period is T = 50 years), leading to rather low intrinsic safety. A first partial conclusion is therefore that in most situations, the intrinsic failure of the photovoltaic installation has a probability greater than 10^{-3}, 3.10^{-4} and 10^{-4} respectively for class C, B and A dams (the levels of safety imposed by French regulation), which requires the analysis of global dam failure scenarios involving the failure of the PV installation.

5.2. Risk analysis methods used to evaluate projects

A detailed analysis of the case studies highlights the use of risk analysis methods as practiced in dam hazard and risk assessment studies: Preliminary Risk

Analysis to identify failure modes, scenario modeling using fault trees, semi-quantitative safety assessment using probability interval grids. This practice appeared to be complete and appropriate.

5.3. Overall risk assessment

The environmental elements considered are mainly:

- the dam spillway and the risk of obstruction by floating PV panels,
- the water level variations of the reservoir with respect to the anchoring and grounding of floating PV panels,
- the maintenance and protection of the watertightness of dams or basin for structures with artificial waterproofing with respect to the anchoring of floating PV panels.

A detailed analysis of the two case studies confirms that environmental factors were considered in the risk analyses. These included the risk of damage to the basin by the anchors, which could lead to internal erosion mechanisms; the risk of obstruction of the spillway by the panels; the risk of obstruction of other hydraulic devices, such as sluice gates, the risk of tidal movements of the reservoir at the power plant; and the risk of floating debris impacting the plant, which could lead to additional stress on anchors and cables. This practice appeared to be complete and appropriate.

5.4. Specific risk control or reduction measure

The survey revealed that the majority of projects were subject to specific risk control or mitigation measures.

These include specific safety barriers (4) such as floating barriers or log booms, oversized anchors, or electrical cables to prevent fire hazards (2). It is worth noting that one case study uses the floating PV project to upgrade its spillway in response to the need for risk control.

A detailed analysis of both case studies shows the choice of two different options. The first case study presents a generously dimensioned spillway capable of accepting without failure a significant percentage of obstruction due to floating debris from detached floating PV panels. The risk analysis then focuses on this demonstration, supported by hydraulic flow modelling in the spillway, without including any specific risk control measures. In the second case study, the hydraulic capacity of the spillway is insufficient to evacuate the project flood with an obstructed spillway, and the project requires the installation of a log boom. This is considered in the risk analysis as a safety barrier, which effectiveness is evaluated based on the criteria of independence, effectiveness, response time and maintainability.

6. PERSPECTIVES

These issues should be further detailed in the upcoming work of the working group, which aims to produce a best practice guide for the development of floating PV projects on dam reservoirs.

As shown on the diagram below, the reflection will start from the risk analysis in order to define precisely the elements required to achieve the desired level of safety. This will lead to the definition of design, construction and monitoring recommendations, which can ultimately be used to define appropriate procedures to meet the needs of regulation and control.

In more detail, the content of the best practice guide will be for the "Risk Analysis and safety assessment" part (Fig. 9) the following:

– Assessment of the intrinsic reliability of a floating PV power plant, taking into account natural hazards (frequency and intensity): wind, current, tidal range, mooring, etc., which can lead to pulling out, drift,
– Assessment of the intrinsic reliability of a floating PV power plant, taking into account other failures: failure of the plant's main components (cables,

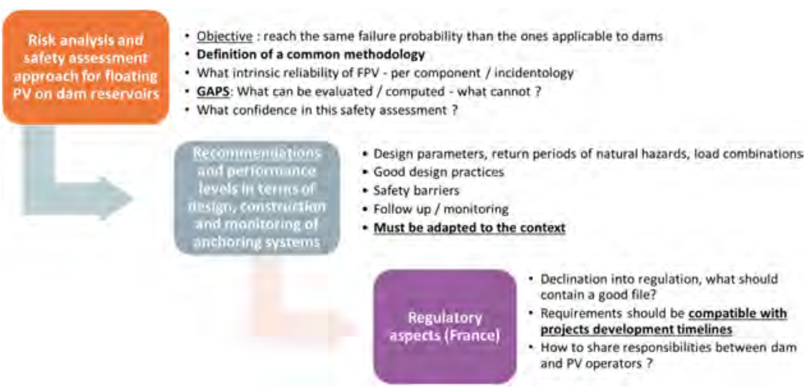

Fig. 9
Organization for the work of the 2nd phase of the FRCOLD working group
Organization du travail de la 2ème phase du groupe de travail du CFBR

supports), failure of other components linking the main components, failure of the ears, internal failure of the floating structure, fire, long-term durability/ maintenance,
- Risk analysis methodology and definition of failure probabilities for floating PV plants. An example of risk analysis could be developed,
- Definition of the initiating events to be considered in FPV risk analysis: massive break-up of an island or island sub-element, unhooking of a sinking PV module (impact on bottom drain),
- Proposal of risk analysis methodology(ies) and assessment of the probability of failure of a dam and its spillway conditioned by the failure of the floating PV power plant, depending on the configuration of the development: geometry of the reservoir, currentology, constitution and performance of the flood evacuation devices, prevailing winds, etc. Examples of good practice could be proposed,
- Assessment of the performance (Confidence Level) of safety barriers, possible countermeasures and redundancies: dromes, combs, other anti-jamming devices, and their inclusion in the risk analysis,
- Maintenance, monitoring and inspection of floating PV power plants to ensure long-term reliability: principles, organisation, resources and means.

For the “Recommendations in terms of design, construction and monitoring” part (Fig. 9), the content will be:

- Set the wind hazard in accordance with the Eurocode in the absence of more detailed specific studies,
- Recommend that the Eurocode be followed when determining the design wind (type of wind, occurrence, depending on the structures under consideration),
- Consider producing a flow chart to guide the return periods to be considered, depending on the sensitivity of the structure,
- Calculation of waves on the basis of the reference wind,
- Design criteria (return time, etc.),
- Have suppliers specify the permissible stresses and minimum resistances required by the plastic and connecting components. Data to be provided on ageing to feed into a maintenance plan,
- General recommendations on the design of solar islands following the REX (simple geometric shapes, no re-entrant angles),
- Specify the load cases/conditions to be taken into account for Limit-State combinations. Specify the notion of redundancy on anchor lines (accidental load cases with one or more broken lines),
- Specify the flow rate reduction criteria to be considered for the operation of the various types of spillways,
- Qualification of the type of anchor using pull-out tests,
- Checking the strength of anchors during construction, particularly for acceptance operations (% of anchors to be checked),
- Maintaining monitoring systems for hydraulic structures,
- Distribution of responsibilities between players,

- Temporary anchoring arrangements,
- Recommendations for checking or even preventive replacement of equipment (anchors, lines, chains, floats, etc.) during the operating phase,
- Countermeasures to be taken in the event of grounding and slack lines,
- Variability / erodibility of the seabed,
- Elastomer feedback,
- Transposition of natural hazards into stresses (verification of manufacturers' data),
- Fire (electrical insulation protection).

For the "*Regulatory aspects*" part (Fig. 9), the content will be:

- Content and level of detail of a file for the safety aspects of the environmental authorization,
- Definition of the relevant elements, for example:
  - Proposed sizing criteria or note of assumptions rather than description of a technical solution,
  - Level of requirements for maintenance and inspection of the anchoring system (anchor points and mooring lines),
  - Division of responsibilities between the dam operator and the floating PV plant operator (floating PV instructions, consistency with the dam operator's organization),
  - Definition of the minimum level of geotechnical knowledge expected.
- Definition of the technical elements that need to be fixed at the authorization application stage,
- Definition of the post-authorization stages,
- End of farm operation and restoration procedures.

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COMMISSION INTERNATIONALE DES
GRANDS BARRAGES

VINGT-HUITIEME CONGRES DES
GRANDS BARRAGES
CHENGDU, MAI 2025

ÉTANCHÉITÉ DES BARRAGES ET RÉSERVOIRS DE STEP : SPÉCIFICITÉS, CONCEPTION ET RETOURS D'EXPÉRIENCE (*)

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SUMMARY

Watertightness is a major challenge of Pumped-Storage Plants (PSPs). This is more specifically the case of closed-loop PSPs where water becomes a rare and costly resource. The current paper presents three types of solutions to achieve the watertightness of a part or of the entire reservoir of a PSP. The first series of examples describe the use of rigid facing of the embankments which can cover the entire reservoir when the lakebed does not reach the project watertightness criteria. This series of examples benefits from a significant feedback (∼50 years of operation) and allows a detailed evaluation. These generally satisfactory experiences demonstrate the value of this solution. Specific design principles for PSP basins are proposed, in particular to facilitate monitoring and maintenance of the waterproofing and drainage elements, and thus optimize asset management and limit shutdown. The second topic focuses on the management of the watertightness of dams by using good workability RCC. This type of RCC is a rather recent evolution of this

Watertightness of dams and reservoirs of PSPs: specific features, design, and feedbacks

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material which allows an overall watertightness and strength parameters equaling or even exceeding those of Conventionally Vibrated Concrete. The paper describes the main principles which allow to produce such RCC, mainly consisting in optimizing the aggregate skeletal structure. A few constructed examples are used to illustrate the approach and the feedback of a PSP dam under first impounding and allow to draw the preliminary conclusions which seem to confirm the suitability of this type of RCC for PSP reservoirs. Finally, the last part of the paper deals with the use of geomembranes, a flexible material, as a liner for PSP reservoirs. The inherent requirements and the advantages of its use are reminded, and three recent examples of application on an earth embankment, on a small particles rockfill embankment and on a rockfill embankment are described. The required specific adjustments relating to the use of the SIBELON® solution in the above cases are illustrated and the consideration of wind in the design in highlighted. The first conclusions from the ongoing filling tests are drawn and show the required specific care at the connection with rigid structures but also highlight the very good capacity of the solution to accommodate differential displacements.

RÉSUMÉ

L’étanchéité est un enjeu principal des Station de Transfert d’Energie par Pompage (STEP). C’est en particulier le cas des STEP en circuit fermé où l’eau peut alors représenter une ressource limitée et couteuse. Le présent article présente trois typologies de solutions pour assurer l’étanchéité d’une partie ou de la totalité du réservoir d’une STEP. La première série d’exemples décrit les solutions d’étanchéité par un masque amont de béton de ciment ou béton bitumineux pouvant couvrir la totalité du réservoir lorsque le fond de cuvette n’atteint pas une étanchéité suffisante. Cette série d’exemples bénéficie d’un retour d’expérience conséquent ($\sim$50 ans) et permet de dresser un bilan détaillé. Ces expériences globalement satisfaisantes démontrent l’intérêt et les limites de cette solution. Des principes de conception spécifiques aux bassins de STEP sont ainsi tirés et proposés, notamment pour faciliter la surveillance et la maintenance de l’étanchéité et du drainage, et ainsi optimiser la gestion du patrimoine et maintenir la disponibilité de l’aménagement. Le deuxième sujet se concentre sur la maîtrise de l’étanchéité du barrage par l’utilisation d’un BCR à bonne ouvrabilité. Ce type de BCR constitue une évolution relativement récente de ce matériau qui permet d’atteindre une étanchéité dans la masse et des résistances qui atteignent voire surpassent celles du béton conventionnel vibré. L’article décrit les principes généraux qui permettent de réaliser ce type de BCR qui réside surtout dans l’optimisation du squelette granulaire de la formulation du béton. Quelques exemples réalisés illustrent l’approche et le retour d’expérience d’un barrage de STEP en cours de mise en eau et permettent de tirer les premières leçons qui semblent confirmer la bonne appropriation de ce type de BCR aux réservoirs de STEP. Enfin, la dernière partie de l’article se concentre sur l’utilisation des géomembranes, un matériau flexible, pour assurer l’étanchéité des barrages et réservoirs de STEPs. Il rappelle les exigences et les atouts de son utilisation et décrit trois exemples récents d'application sur un support de remblais en terre, en petits enrochements et en grands enrochements. Les ajustements spécifiques nécessaires à l'application de la solution SIBELON® à ces différents cas sont illustrés et la prise en compte du vent dans le dimensionnement des solutions est mise en évidence. Les premières leçons tirées d'essais de mise en eau en cours montrent un point d'attention nécessaire au droit des connexions avec les ouvrages rigides mais aussi une très bonne capacité à accepter les déplacements différentiels.

1. INTRODUCTION

La principale fonction d'un barrage étant de retenir l'eau, la question de son étanchéité, fondation et cuvette comprise, est évidemment fondamentale. Aucun ouvrage ne peut prétendre être parfaitement étanche. La performance de l'étanchéité se mesure alors par son débit de fuite, dont la limite acceptable dépend des enjeux associés : sûreté, économiques, environnementaux. Pour un projet de réservoir lorsqu'une étanchéité artificielle est nécessaire, de multiples technologies sont disponibles. La conception optimale dépendra des contraintes du site. Ce rapport aborde en particulier l'étanchéité des barrages et des réservoirs des projets de Station de Transfert d'Energie par Pompage (STEP), avec leurs conditions d'exploitation spécifiques : marnage fréquent et rapide, fortes exigences quant à la performance de l'étanchéité (notamment pour les systèmes fermés) à cause des coûts et contraintes de remplissages notamment. Plusieurs références avec différentes techniques d'étanchéité sont développées ci-après, avec des éléments de conception, de performance, et des retours d'expérience.

Le présent article présente trois typologies de solutions pour assurer l'étanchéité d'une partie ou de la totalité du réservoir d'une STEP. La première série d'exemples décrit les solutions d'étanchéité par un masque amont rigide des digues. La deuxième série d'exemples se concentre sur la maîtrise de l'étanchéité du barrage par l'utilisation d'un BCR à bonne ouvrabilité. Enfin, la dernière série d'exemples traite de l'utilisation des géomembranes, un matériau flexible, pour assurer l'étanchéité des barrages et réservoirs de STEPs.

2. ETANCHÉITÉ PAR MASQUE AMONT RIGIDE

L'utilisation d'un masque amont rigide (béton de ciment, béton bitumineux, ou plus rarement brai-vinyle) comme organe d'étanchéité du barrage est une technique courante, qui a fait l'objet de nombreuses publications, notamment le bulletin 141 [1] pour les barrages en enrochements à masque en béton de ciment, le bulletin 114 [2] pour les barrages en remblais à masque en béton bitumineux pour n'en citer que deux.

2.1. Etude de cas

La Coche 1975, Revin 1977, Montézic 1982, ces trois Stations de Transfert d'Energie par Pompage (STEP) française en service depuis bientôt cinq décennies, utilisent ces matériaux pour leur bassin supérieur. Après une brève description de leur conception, des éléments de retour d'expérience sont apportés, puis une réflexion est proposée pour identifier quelques bonnes pratiques de conception.

2.1.1. *Barrage de la coche (STEP de la coche)*

Construit entre 1972 et 1975, l'aménagement hydroélectrique de La Coche est une STEP située près de Moutiers, en Savoie (France). Les projeteurs avaient eu leur attention attirée par l'existence d'une dépression naturelle, dont la situation topographique était idéale pour être utilisée dans un aménagement de pompage. En effet, juchée à 900 m au-dessus de l'Isère, elle se trouvait à moins de 2,8 km en distance horizontale du réservoir existant du barrage d'Aigueblanche (non abordé dans cet article), servant de prise à la chute de Randens. Cette dépression dont le fond était à la cote 1348, était constituée par un verrou naturel calé à la cote 1367. En aménageant les formes de la cuvette, et en surélevant le verrou à la cote 1400, il était possible ainsi de créer une capacité de 2,1 hm^3 permettant une exploitation en pompage hebdomadaire. La figure 1 schématise l'implantation du barrage sur le verrou naturel.

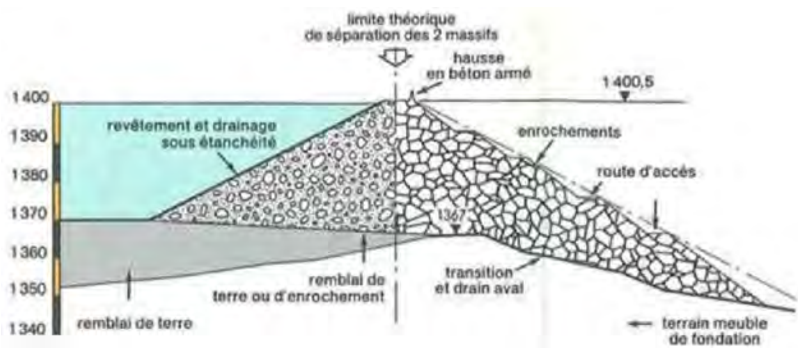

Fig. 1
Coupe type du barrage de la Coche, bassin supérieur de la STEP
Typical cross section of La Coche dam, upper reservoir of PSP

Ce site, topographiquement intéressant, fut néanmoins examiné en détail quant aux caractéristiques géologiques des fondations. La cuvette était en effet située sur un sillon profond (90 m au niveau du barrage), remplis de terrain quaternaire. La perméabilité de la fondation, et le risque de génération de tassement par des circulation d'eau ne permettaient pas de compter sur l'étanchéité naturelle de la cuvette.

Une conception de la cuvette avec une étanchéité 100 % artificielle a été adoptée, avec l'option innovante (au moment de la construction) d'une double étanchéité drainée (Fig. 2).

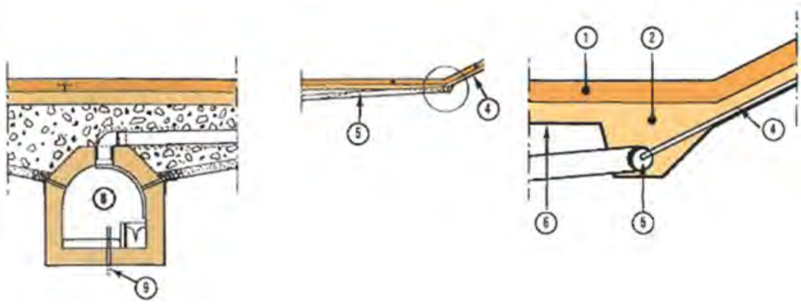

Fig. 2
Conception de la double étanchéité drainée du barrage de La Coche
Design of the double drained seal of La Coche dam
1. Etanchéité primaire (dalles en béton armé) / Primary sealing (reinforced concrete slabs) , 2. Drainage (béton poreux) / Drainage (porous concrete), 4.& 5. Collecteurs de drainage / Drainage manifold, 6. Etanchéité secondaire (géomembrane PVC-P armé) / Secondary sealing (PVC-P reinforced geomembrane), 8. Galerie de drainage / Drainage gallery, 9. Piézomètre / Piezometer

Une conception de la cuvette avec une étanchéité 100 % artificielle a été adoptée, avec l'option innovante (au moment de la construction) d'une double étanchéité drainée, voir Figure 2.

L'étanchéité primaire est assurée par des dalles en béton armé, dont les bords sont équipés de joints noyés en caoutchouc type « water stop ». Les dalles reposent sur un important drainage, composé d'un béton poreux et d'un réseau de collecteur, compartimenté (Fig. 3) et aboutissant dans une galerie de drainage permettant une surveillance quantifiée et localisée des fuites. Enfin une étanchéité secondaire est réalisée par une géomembrane PVC-P armée avec des fils de nylon.

La cuvette a été mise en eau partiellement en 1975 puis totalement en 1978, et est toujours en exploitation à ce jour, soit 50 ans d'exploitation. L'étanchéité de la cuvette a été globalement bonne en partie « courante », en revanche des fuites ont été constatées essentiellement autour des zones singulières de la prise d'eau et du débouché de la galerie d'adduction amont. Ces fuites avaient pour origines des fissurations des dalles, et des défauts de certains joints « water-stop », générés par des tassements différentiels excessifs liés à la présence locale d'une structure en béton massive entourée de formations meubles. Des réparations des étanchéités ont été réalisées lors de différentes campagnes par des techniques locales (calfatage des défauts avec différents produits, ciment ou polymère), mais aussi globale au niveau de la zone prise d'eau, qui a été couverte en 2018 par une géomembrane PVC-P posée de manière non adhérente et drainée (qui constitue ainsi une troisième étanchéité).

La conception double étanchéité drainée sur cet ouvrage permet une détection et une quantification précise des fuites, mais aussi une localisation grâce aux compartiments du drainage. Cette surveillance fine permet d'apprécier la performance de l'étanchéité, et optimiser la maintenance en ciblant les zones à réparer. Enfin, le niveau de fuite est considérablement réduit à l'aval de l'étanchéité secondaire (grâce à cette conception, mais aussi la possibilité de maintenance localisée), ce qui peut être déterminant pour les projets où les fuites sont associées à de forts enjeux (sûreté de l'aménagement, mais aussi fonctionnel, environnementaux, économiques ...).

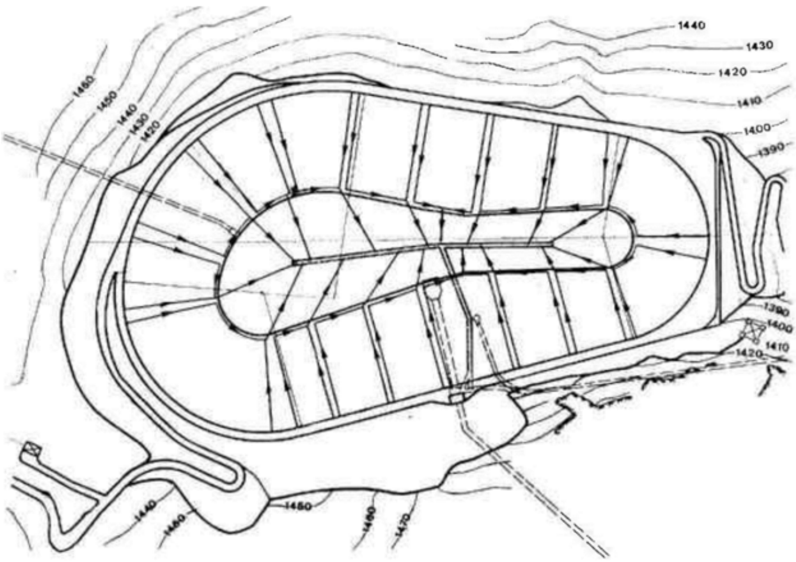

Fig. 3
Vue en plan du barrage et bassin supérieur, détails sur le réseau de drainage et ses compartiments, représentation du débouché de la galerie d'adduction amont et de la prise d'eau et de la galerie d'amenée de la centrale, et galerie de drainage (en pointillés)
Plan view of the dam and upper reservoir, details of the drainage network and its compartments, upstream outlet, water intake to the plant, and drainage gallery

L'état de la géomembrane secondaire en PVC-P a pu être contrôlé localement : il est bon et la membrane accomplit encore très bien sa fonction d'étanchéité après 50 ans d'exploitation. Ce REX positif, rare pour une si longue durée, s'explique notamment par la position couverte de la géomembrane, qui assure une protection mécanique et contre le rayonnement solaire.

2.1.2. *Barrage des marquisades (STEP de Revin)*

L'aménagement hydroélectrique de Revin, en service depuis 1977, est une STEP située dans le massif des Ardennes (France) comportant deux retenues dénivelées d'environ 230 m. Le bassin de Whitaker, généré par le barrage de Saint Nicolas sur le cours naturel de la Faux, constitue la retenue inférieure. Il ne sera pas abordé dans cet article.

La retenue supérieure (dit bassin ou barrage des Marquisades) est un bassin 100 % artificiel qui a été réalisé en arasant le sommet du plateau au niveau du fond du bassin et en créant, avec le déblai ainsi obtenu, une digue en remblai qui constitue une ceinture de 4200 m de longueur et de 9 à 18 m de hauteur. Le marnage total est de 11,75 m et le volume utile est de 7 millions de m^3.

Les digues et les fondations (Limons et schistes) étant sensibles à l'eau et non parfaitement imperméables, une étanchéité artificielle a été installée sur la totalité de la surface du bassin supérieur (Fig. 4 et 5). Deux techniques ont été utilisées. Pour le radier, il s'agit d'un corroi argileux couvert par une épaisseur granulaire (schistes brisés). Les digues ont été étanchées par un masque amont bicouche bitumineux imperméable, reposant sur une couche de béton bitumineux drainant (binder drainant), reposant lui-même sur une couche de béton bitumineux filtrant (binder filtrant). Un important système de drainage et de collecteurs permet de collecter les fuites, rabattre les éventuelles sous-pressions, et surveiller le comportement hydraulique de l'ouvrage.

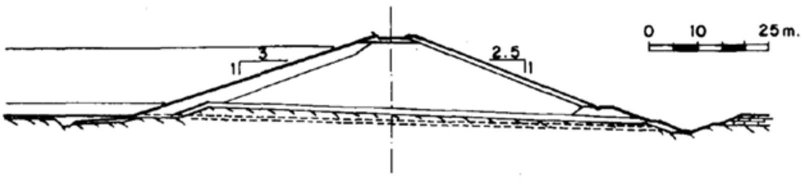

Fig. 4
Profil en travers type de la digue de fermeture du bassin des Marquisades : limons (partie centrale) et schistes (recharges)
Typical cross section of the dike of Marquisade reservoir: silt (central part) and shale rock (shoulder)

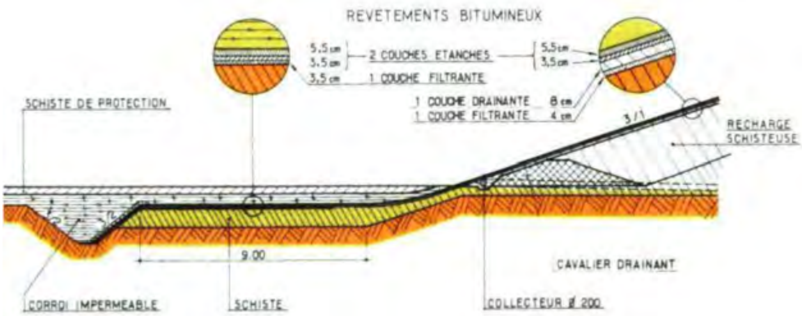

Fig. 5
Conception des étanchéités du bassin : talus, radier, et raccordement
Sealing design of the reservoir: slope, raft and connection

L'aménagement est toujours en service après presque 50 ans d'exploitation. L'historique de comportement et de maintenance du bassin a été marqué par :

- une étanchéité dans l'ensemble satisfaisante en partie « courante » ;
- des défaillances régulières de l'étanchéité au niveau de certains points singuliers. Notamment la zone de raccordement avec les structures en béton armé de la prise d'eau, mais qui semble désormais traitée durablement grâce à une modification de la conception (ajout d'une géomembrane PVC-P non adhérente et drainée) ;
- un drainage, dont l'efficacité diminue (colmatage) localement dans le temps, mais qui est régulièrement restauré par hydro-curage, grâce notamment à des trappes d'accès dans les bassins qui permettent d'atteindre les parties des drains non accessibles depuis l'aval (à cause de l'impossibilité de passer les coudes du réseau de conduite).

Quelques signes de vieillissement des revêtements commencent à être observés. La surveillance (auscultation et examens visuels) permet de les détecter, et des réparations sont réalisées avec des techniques locales. Des recherches sont en cours pour anticiper plus finement l'apparition de ces phénomènes de vieillissement et optimiser ainsi les opérations de maintenance, pour réparer seulement ce qui est nécessaire, le plus tard possible mais avant l'apparition de défaillances.

La conception avec une étanchéité drainée simple (mais avec des digues et une fondation peu perméable), permet d'apprécier et surveiller finement le comportement hydraulique de l'ouvrage, cibler la maintenance, et atteindre un niveau global de fuite faible.

2.1.3. *Barrages de monnès et de l'etang (STEP de montézic)*

L'aménagement de Montézic est une STEP située dans le département de l'Aveyron (France), mise en exploitation en 1982. La retenue supérieure de Montézic est fermée par notamment deux barrages (Fig. 6) de même conception : remblais zonés avec partie centrale en gore sableux (gore très altéré et plutôt fin) et recharges en enrochements (granite sain) avec masque amont en béton de brai de vinyle (820 m de longueur pour le barrage de Monnès, 680 m pour celui de l'Etang, Fig. 7 et 8).

Fig. 6
Vue générale de la STEP de Montézic
General view of Montézic PSP

La fondation, en-dessous de la terre végétale de surface, est constituée par un granite présentant, en descendant, tous les stades de décomposition, irrégulièrement, du gore jusqu'à une roche très saine entre 5 et 30 m de profondeur. Les digues sont ainsi fondées sur du granite d'altération variable mais toujours importante. La fondation a été étanchée par différentes techniques superficielles (retrait des formations de surface impropres, mur parafouille, ...), ou profondes (écran étanche, injections, ...)

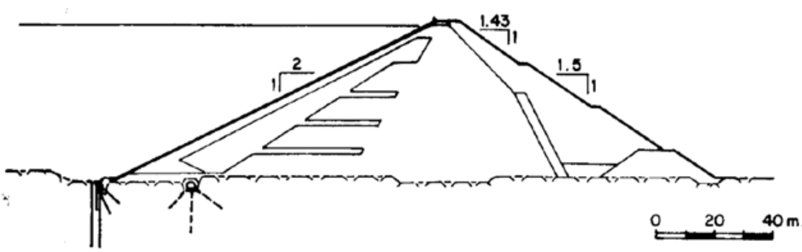

Fig. 7
Coupe type du barrage de Monnès
Typical cross section of Monnès dam

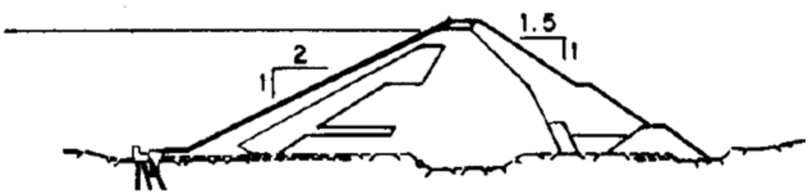

Fig. 8
Coupes type du barrage de l'Etang
Typical cross section of Etang dam

Le masque amont, d'une surface totale de 75 000 m^2 pour les deux digues, est constitué en partie courante : une couche de reprofilage imprégnée d'une émulsion, un béton de brai de vinyle poreux de 6 cm d'épaisseur, servant d'enclume pour le compactage et assurant le drainage de la couche étanche, un béton de brai de vinyle étanche dosé à 10 % de liant, de 8 cm d'épaisseur.

L'aménagement est toujours en service après plus de 40 ans d'exploitation. L'historique de comportement et de maintenance du bassin a été marqué par :

- une étanchéité dans l'ensemble satisfaisante en partie « courante » ;
- des défaillances régulières de l'étanchéité au niveau du pied du barrage, dans la zone de raccordement entre le masque en partie courante, et la longrine de fondation en béton armé, qui ont fait l'objet de nombreuses réparations ;
- une tendance générale et lente, à la baisse de l'efficacité de l'étanchéité et du drainage (notamment en pied de parement amont, sous le revêtement étanche mais aussi des collecteurs), malgré les opérations de maintenance. Cela a conduit à une hausse de la ligne piézométrique dans les barrages, entre le masque et la partie centrale en gore sableux peu perméable. Ce comportement hydraulique oblige à limiter la vitesse d'abaissement de la retenue à cote basse, pour éviter le risque de soulèvement du masque amont, et à charger localement le masque avec une recharge granulaire.

2.2. Analyse

Ces trois références de bassin de STEP, exploités depuis 50 ans, permettent de tirer les enseignements suivants quant à la conception de l'étanchéité et du drainage avec un masque rigide :

1) La technologie masque amont en béton bitumineux, béton de ciment, ou brai vinyle est une solution qui a démontré son efficacité à l'épreuve du temps, pour les ouvrages fortement sollicités comme les STEP.
2) En partie courante, le retour d'expérience est très bon. Les difficultés se concentrent pour l'essentiel sur les zones singulières : zones de tassements

différentiels, zones de jonction ou de raccordement. Un soin particulier (conception et réalisation) est indispensable pour bien les traiter. L'utilisation des géomembranes pour ces zones singulières semble efficace pour surmonter ces difficultés.

3) La capacité et la pérennité du drainage est particulièrement importante pour les bassins de STEP, soumis à des marnages rapides et fréquents, pour éviter les conséquences de sous-pressions en aval du masque dont le rabattement ne suivrait pas la vitesse d'abaissement de la retenue. Il est prudent de prendre en compte une baisse d'efficacité de l'étanchéité et du drainage dans le temps, afin de ne pas pénaliser la disponibilité et la durabilité des ouvrages. Il semble intéressant d'intégrer dans la conception du drainage :
   (a) Une capacité de drainage supérieure aux barrages avec marnage moins fréquents et rapides (mensuelles ou saisonnières) ;
   (b) La possibilité de visiter le drainage sur sa totalité (par exemple avec des trappes d'accès depuis l'amont, ou mieux par des galeries de visites accessibles depuis l'aval), et au besoin de le nettoyer et régénérer par hydrocurage ;
   (c) Un dispositif de surveillance de la pression en plus du débit dans le drainage, pour une évaluation plus fine du comportement et des risques.
4) Afin d'augmenter la durabilité et la disponibilité de l'ouvrage, il est utile de mettre en œuvre une surveillance du vieillissement des revêtement, afin d'optimiser la stratégie de maintenance : repousser le plus tard possibles les réparations ou les remplacements, avec des risques maîtrisés, cibler uniquement les zones nécessaires, anticiper les opérations pour les planifier de façon optimale pour l'exploitation de l'aménagement.
5) L'option double étanchéité drainée est très efficace pour les projets où les enjeux des fuites sont particulièrement importants, pour des raisons de sûreté, environnementales, fonctionnelles ou économiques. Elle permet d'atteindre des niveaux d'étanchéité records, grâce à une surveillance fine des fuites de l'étanchéité primaire (détectables, quantifiables et localisables), permettant des réparations ciblées, et enfin autorisant la récupération totale des fuites pour une éventuelle revalorisation. La technologie de l'étanchéité secondaire n'est pas nécessairement identique à celle de la primaire.

Les masques d'étanchéité amont en béton bitumineux ou béton de ciment présentent de nombreux avantages, notamment :

- Lorsqu'une barrière étanche convenablement drainée est située sur le parement amont, le remblai peut être conçu sans tenir compte de la pression interstitielle en situation durable d'exploitation, et donc sans effet d'une percolation permanente ou d'une vidange rapide.
- Un autre avantage offert par un masque amont est qu'il est facile à inspecter et réparer le cas échéant, à sec, mais également sous l'eau ce qui limite le besoin de vidange pour la surveillance et la maintenance.

- Les masques en béton bitumineux (mais également les géomembranes) ont l’avantage d’offrir une certaine souplesse, particulièrement à jeune âge, pour s’adapter aux faibles tassements différentiels des remblais sous-jacents.
- Les masques rigides associés à une surveillance et maintenance précoces, présentent enfin l’avantage qu’en cas de fuite, le débit est contrôlé par la taille du défaut (au moins dans un premier temps) ce qui peut empêcher le développement exponentiel de phénomènes d’érosion interne dans le corps du barrage ou de sa fondation.

3. ÉTANCHÉITÉ PAR LA MAÎTRISE DE L’OUVRABILITÉ DU BCR

Le principe historique du Béton Compacté au Rouleau (BCR) est de mettre en œuvre à la manière d’un remblai géotechnique le béton d’un barrage. Le procédé de mise en œuvre est par conséquent simplifié par rapport à celui d’un Béton Conventionnel Vibré (BCV). En dehors de tout contexte sismique, la sollicitation en compression d’un béton de masse de barrage est faible. Dans le cas d’un BCV, la hauteur de levée de bétonnage excède généralement 1 m et peut atteindre 2.5 m. Pour ne pas ralentir le chantier, la résistance du béton au bout de quelques jours doit par conséquent être suffisante pour supporter la poussée associée à cette hauteur. Cet aspect peut alors dimensionner la teneur en liants d’un BCV de barrage (de l’ordre de 250 kg/m^3 dont au moins 50% de clinker). En comparaison, le BCR se construit généralement par couches successives de 30 cm de hauteur, avec une cadence d’une couche environ par jour. Au décoffrage, souvent par hauteurs de 1.20 m à 2.40 m, seules les couches supérieures n’ont pas encore atteint un degré de maturité suffisant. Il est donc possible de réduire significativement les objectifs de résistance et par conséquent la teneur en ciment par rapport à un BCV avec une teneur en liants de l’ordre de 80 à 120 kg/m^3. Il en découle un coût mais aussi une chaleur d’hydratation réduits. Le BCR traditionnel utilisant l’approche dite « séparée » au sens de [6] est un béton raide (indice Vebe modifié supérieur à 25s), sec, sensible à la ségrégation, nécessitant 8 à 12 passes de rouleau compacteur de 12 tonnes pour atteindre la densité cible, poreux, perméable et à faible résistance à long terme (rarement supérieur à 12 MPa). En particulier, la résistance à la traction et au cisaillement de ce type de BCR est gouvernée par les joints de reprise de bétonnage. Dans ces conditions, l’étanchéité amont doit souvent être assurée par un matériau différent du BCR, pouvant générer une lenteur à la construction, réduisant l’avantage économique de la solution, voire compliquant la gestion contractuelle du chantier. Par ailleurs, pour éviter un gradient hydraulique trop élevé, cette étanchéité peut être prolongée dans la masse du BCR sur une certaine distance à partir du parement amont par l’intermédiaire de traitement inter-couches à l’aide de mortier d’environ 3 cm d’épaisseur dosé en ciment à environ 400 kg/m^3.

Cette technologie traditionnelle est désormais supplantée par un BCR moderne, avec une ouvrabilité améliorée (indice Vebe modifié de 12 à 20s). La principale condition d’obtention de cette bonne ouvrabilité est l’optimisation de la granulométrie et de la géométrie des granulats pour limiter l'indice des vides. Cette bonne ouvrabilité peut nécessiter une plus forte teneur en liants (supérieure ou égale à 150 kg/m^3) qui peut paraître contraire à la philosophie initiale du BCR mais malgré l'augmentation de la teneur en liants, la teneur en clinker du liant reste souvent faible (30% en masse) et le liant est complété par des matériaux pouzzolaniques à moindre coût. La chaleur d'hydratation de l'ensemble reste bien plus faible que celle d'un liant à forte proportion de clinker. Par ailleurs, le besoin d'augmentation de la teneur en liants est d'autant plus réduit que l'optimisation vis-à-vis de l'indice des vides et de la densité du squelette granulaire est réussie. Il en découle un BCR non sensible à la ségrégation, nécessitant 4 à 6 passes de rouleau compacteur de 10-12 tonnes pour atteindre la densité cible, étanche dans sa masse, dont la résistance égale voire surpasse celle d'un BCV. En effet, par l'optimisation de son squelette granulaire, la pâte (liant + fines $<$75 microns + eau + air) du béton frais arrive à remplir le vide des granulats du béton. Cette pâte rend le BCR frais ouvrable et donc sensible à une réorganisation granulaire lors du compactage (Fig. 9). En contrepartie, cette réorganisation granulaire chasse la pâte vers la surface qui devient alors une pâte excédentaire. Lorsque cette pâte n'a pas encore démarré sa prise lorsque la couche sus-jacente est compactée, elle joue le rôle de colle par pénétration des granulats de la couche suivante dans la couche inférieure. Il n'y a donc pas besoin de traitement inter-couches et les joints de reprises de bétonnage deviennent imperceptibles, contrairement au cas des barrages en BCV. La construction du barrage rentre alors dans un cercle vertueux autour de la vitesse de la construction, qui est de nature à réduire la durée et par conséquent le coût du chantier. Dans le cas de ce type de BCR à ouvrabilité améliorée, l'utilisation d'adjuvant retardateur de prise est une bonne pratique permettant de garantir la bonne pénétration des granulats entre deux couches successives. Enfin, cette

Fig. 9
Comparaison des états de surface de BCR compacté traditionnel (à g.) et moderne (à dr.) : moule essai Vebe (haut) et sur site (en bas)
Comparison of surface finish between compacted traditional (left) and modern (right) RCC: Vebe test (top) and on site (bottom)

réorganisation granulaire au compactage rend le BCR moderne peu sujet au retrait endogène et au fluage au jeune âge, en particulier lorsque des cendres volantes sont utilisées comme matériau pouzzolanique supplémentaire du liant.

Le BCR moderne devient alors une solution auto-suffisante pour atteindre les critères de performance demandés pour un barrage de STEP au moins pour les deux raisons suivantes :

- Il est étanche dans la masse et permet par conséquent d'atteindre des critères souvent exigeants en débit de fuites autorisé ;
- Sa bonne résistance couplée à un retrait net final à long terme faible permettent d'espacer les joints de retrait qui sont un point de faiblesse des barrages en BCR d'un point de vue de l'étanchéité.

3.1. Optimisation du squelette granulaire et teneur en liant

Le récent bulletin B177 de la CIGB [6] définit les fuseaux granulométriques recommandés pour les granulats à utiliser pour la réalisation d'un mélange de BCR à bonne ouvrabilité.

Ce fuseau idéal permet de garantir l'absence de ségrégation, un BCR compacté cohésif (par opposition à pulvérulent) et la remontée d'une pâte excédentaire à l'issue du compactage avec une teneur en liant maîtrisée. Si la granulométrie sort significativement de ce fuseau idéal, une compensation par augmentation du volume de pâte pourra être nécessaire pour atteindre les performances voulues.

Ce fuseau demande la présence de fines non plastiques dans le mélange, à hauteur de 12% des granulats fins ($<$5 mm). Par ailleurs, un effort particulier doit être accordé à la géométrie des particules des granulats grossiers pour limiter la teneur en particules plates et allongées à 25, voire 20% au sens du BS 812 Partie 105. L'expérience montre que l'utilisation de concasseurs à impact augmente les possibilités d'atteindre ces critères de géométrie.

Trois exemples qui démontrent le rôle fondamental joué par cette granulométrie sont illustrés sur la figure 10. Les trois barrages ont été conçus par les équipes d'ARTELIA en tant que Maître d'œuvre ou en tant que bureau d'études du groupement d'entreprise chargé de la construction.

Le cas du BCR du barrage de Janneh et celui du barrage d'Umti sont considérés comme étant deux cas « extrêmes ». L'étude de formulation du BCR du barrage de Janneh a démarré de manière tardive pour des raisons contractuelles. Les différentes formulations sur la planche d'essai ont montré des critères de géométrie non respectés mais également une granulométrie tirant davantage vers les granulats fins intermédiaires (0.3-2 mm). De même, la stabilité du comportement du mélange vis-à-vis du retardateur de prise nécessitait encore davantage d'ajustements. Pour des raisons de planning, il a été décidé de démarrer le chantier avec l'unique formulation qui donnait satisfaction, impliquant une teneur en liant de 220 kg/m^3 et 128 L/m^3 d'eau. En revanche, il y avait une bonne confiance pour retrouver une teneur en liant de l'ordre de 160 kg/m^3 dont 48 kg/m^3 de clinker après une optimisation du squelette granulaire. Sur la planche d'essai, cette dernière formulation a montré des joints chauds de reprise de bétonnage difficilement perceptibles et une résistance moyenne à la traction directe dépassant 1 MPa y compris dans les joints. La perméabilité mesurée sur carottes au laboratoire (y compris dans les joints) a été de l'ordre de 10^{-11} à 10^{-12} m/s, confirmant une très bonne étanchéité dans la masse du BCR.

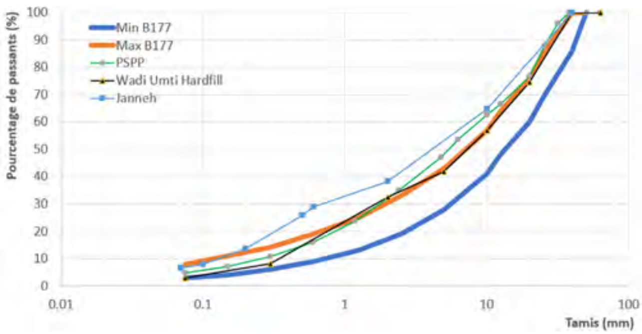

Fig. 10
Fuseau granulométrique recommandé par le Bulletin 177 pour un BCR à bonne ouvrabilité et quelques exemples de cas réels
Gradation ranges recommended by Bulletin 177 for a good workability RCC with a few real cases

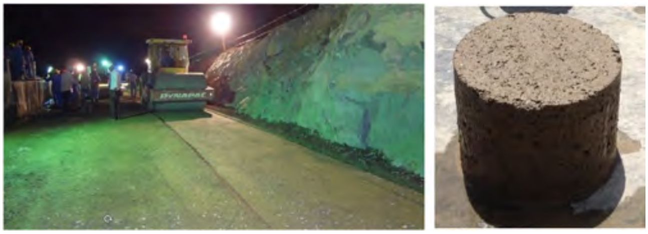

Fig. 11
Etat de surface du remblai dur compacté du barrage d'Umti : sur site (à g.) et au laboratoire (à dr.)
Surface finish of the compacted hardfill of Umti dam: on site (left) and from laboratory (right)

La courbe granulométrique des alluvions de fond de rivière du barrage d'Umti respectait naturellement les critères définis par le bulletin 177 de la CIGB. Le barrage étant de type remblai dur, le critère de résistance demandé est faible, 4 MPa à 90 jours. Avec uniquement 60 kg/m^3 de clinker et 110 L/m^3 d'eau, le béton frais obtenu est cohésif (Fig. 11), présente une certaine quantité de pâte excédentaire et la résistance à 90 jours a pratiquement atteint le double du critère. En particulier, la densité mesurée sur site a atteint une valeur supérieure à 2400 kg/m^3, soit une valeur légèrement supérieure à 98% de la valeur théorique sans air avec seulement 6 passes de compactage à l'aide d'un rouleau de 12 tonnes.

Le cas d'une STEP en cours de construction peut être considéré comme un cas intermédiaire. Les granulats intermédiaires (3 à 12 mm) sont en excès par rapport au fuseau recommandé. Néanmoins, il a été possible d'obtenir une formulation très satisfaisante avec une teneur en liant de 185 kg/m^3 dont 65 kg/m^3 de clinker et 125 Lm^3 d'eau. Avec un indice à l'essai Vebe modifié variant de 11 à 14 s en fonction de l'utilisation de glace pour remplacer l'eau de gâchage afin de maîtriser la température du béton frais, l'ouvrabilité de la formulation est très satisfaisante. Il en résulte un BCR avec des joints chauds imperceptibles et une résistance moyenne à la traction directe dépassant 1.5 voire 2 MPa. Les essais de perméabilité au laboratoire sur la base de carottes extraites de la planche d'essais montrent une valeur moyenne de 10^{-11} m/s, confirmant également une très bonne étanchéité dans la masse.

Enfin, le cas particulier d'un barrage français ayant nécessité l'utilisation de BCR est également d'intérêt. Lors de la mise au point de la formulation du BCR à la planche d'essai, la fraction de fines dans le mélange est bien plus faible que ce que requiert le bulletin 177 de la CIGB. Malgré l'utilisation de 180 kg/m^3 de liants et 130 L/m^3 d'eau, le BCR obtenu a nécessité plus de 8 passes de rouleau compacteur pour atteindre la densité théorique cible. Par ailleurs, il a montré de réelles difficultés pour mettre en œuvre le BCR enrichi au coulis des parements puisque le coulis ne remontait pratiquement pas à la surface après une longue durée de vibration (Fig. 12). En contrepartie, les trois exemples précédemment cités ont permis une réalisation aisée de BCR enrichi au coulis, y compris le remblai dur du barrage de Wadi Umti.

Fig. 12
BCR enrichi au coulis : remontée difficile du coulis dans le cas d'un barrage français (à g.), rendu de surface durcie du barrage de Wadi Umti (à dr.)
Grout-Enriched RCC: grout hard to bring to the surface in the case of a French dam (left), and finish surface of hardened RCC of Umti dam (right)

3.2. Dispositions constructives spécifiques des barrages de STEP

Dans le cas particulier des STEP, l'eau est souvent une denrée considérée rare et des critères de fuite exigeants sont demandés par le Maître d'Ouvrage. C'est le cas de la STEP en cours de construction ou un critère de fuite en situation stabilisée d'exploitation de 15 L/min est exigé. Ce critère couvre les fuites à travers le barrage de 70 m de hauteur et de 210 m de longueur en crête ainsi que les drains en fondation forés depuis les galeries du barrage.

Les joints de retrait des barrages en BCR modernes sont induits par insertion d'une feuille mince en PEHD à l'aide d'une lame vibrante dans le béton fraichement compacté. Ils sont généralement espacés de 20 m. Proche du parement amont, chaque joint est rendu étanche par l'intermédiaire d'un double joint waterstop tendu au préalable et déroulé par un tuteur mécanique au fur et à mesure de la montée du béton.

Ce double joint waterstop étant placé très proche du parement amont (dans les 80 cm depuis l'amont) et par la présence même du système de support, le BCR qui l'entoure ne peut pas être compacté au rouleau. Le compactage est réalisé par l'intermédiaire d'aiguille vibrante, par ajout très souvent de coulis dans le BCR. Cette procédure constitue un point de faiblesse puisque la garantie d'un parfait contact entre les joints waterstop et le BCR enrichi au coulis est faible sur toute la hauteur du barrage. Par ailleurs, il arrive souvent que la fissure de retrait contourne ce dispositif amont malgré l'utilisation de plaque raides en PEHD qui induisent la fissure dans l'axe des joints waterstop. Cela explique la redondance du dispositif : deux joints waterstop avec très souvent un drain central ou aval raccordé aux galeries du barrage et qui permettent d'identifier les défauts d'étanchéité et le cas échéant d'injecter les zones de fuites (Fig. 13).

Fig. 13
Système de double joints waterstop à l'amont d'un joint de retrait de BCR
Double waterstop joint system on the upstream of induced contraction joint of RCC

Pour se donner toutes les possibilités d'atteindre les critères de débit de fuite, il a été décidé d'espacer au maximum les joints de retrait dans ce cas. Cette décision assistée de près par plusieurs simulations numériques a été motivée par les résistances élevées atteintes par le BCR, combinée au faible retrait endogène et fluage au jeune âge de la formulation. Ces derniers paramètres ont été mesurés par plusieurs jauges de déformation à longue base et à correction thermique intégrée qui ont été installés dans la planche d'essai et dans le BCR même du barrage. Dans la planche d'essai, les valeurs mesurées de retrait net total ont été très faibles, proche de 0. Dans le BCR même du barrage, une valeur maximale de 70 microns a été atteinte, incluant probablement une part de retrait de dessication compte tenu du climat très aride et de l'exposition prolongée du barrage avant le premier remplissage. Cette valeur a été prise en compte par mesure conservative dans les calculs. Elle est conforme aux recommandations du bulletin 177 de la CIGB.

Les calculs ont été réalisés en adoptant les hypothèses recommandées par le bulletin 177 de la CIGB : le module d'Young n'évolue pas avec le temps et le retrait net final est pris en compte à la fin de la construction. Ce retrait net final se rajoute au retrait/dilatation thermique lié à l'écart entre la température à une date donnée de chaque élément du modèle et la température de placement du BCR de l'élément. Le calcul ne nécessite pas une construction mécanique couches par couches. Bien que contre intuitif, il s'agit de la méthode qui a permis la meilleure reproduction de la réalité [8].

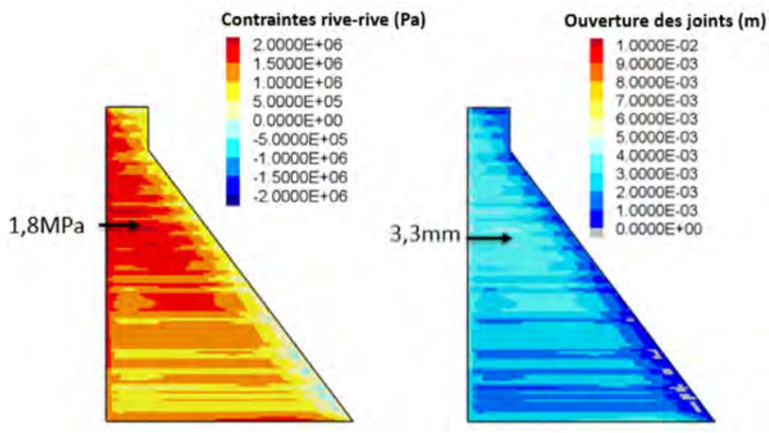

Fig. 14
Contraintes rive-rive (à g.) et ouverture des joints de retrait (à dr.) après dissipation de la chaleur d'hydratation du béton – zoom sur les 37 m supérieurs du barrage
Bank-to-Bank stresses (left) and opening of the contraction joints (right) after dissipation of concrete hydration heat – zoom on the upper 37m of the dam

Les essais au laboratoire réalisés sur les carottes de sondage montrent une résistance à la traction par fendage de l'ordre de 2 MPa à long terme. Cette méthode d'essai est jugée plus représentative de la résistance à la fissuration transverse du barrage compte tenu des couches horizontales du BCR. Les simulations numériques montrent que la contrainte maximale de traction dans la direction rive-rive attendue entre deux joints de retrait espacés de 30 m est de 1.8 MPa à long terme. Par ailleurs, l'ouverture maximale des joints de retrait est de 3.3 mm (Fig. 14). Les joints waterstop utilisés dans les barrages acceptent des valeurs de l'ordre de 5 mm. Néanmoins par prudence, entre deux joints de retrait, un système de double joints waterstop tel que montré sur la figure 13 a été implanté sur les 17 m supérieurs du barrage, sans prolongement par un réel joint de retrait à l'aval. L'objectif est de maîtriser le départ d'une fissure naissante si elle venait à se déclencher, même si les calculs indiquent qu'une telle situation ne devrait pas se produire.

3.2.1. *Eléments de retour d'expérience de première mise en eau*

La première mise en eau du réservoir est en cours à la date de rédaction de cet article avec un niveau d'eau à 5 m sous la retenue normale pour la STEP dont le BCR du barrage est décrit. Aucune fissure n'a été finalement visible à l'aval des double joints waterstop intermédiaires décrits dans le paragraphe précédent.

Le débit de fuite total collecté à travers le barrage et sa fondation est pour le moment de l'ordre de 34 L/min avec une cote de réservoir ascendante avec une faible vitesse. Le débit de fuite collecté dans les galeries en excluant les drains de fondation est d'environ 8 L/min. Le réservoir étant amené à marner de l'ordre de 25 m de manière quotidienne. Il y a une bonne confiance sur l'atteinte des critères à long terme puisque le critère de débit de fuite s'applique sur une valeur moyenne pendant la période de garantie du barrage.

8 points de fuites suintantes sont rencontrés dans les galeries de drainage. La moitié provient des joints de retrait. L'autre moitié provient de fissures, de la niche abritant les pendules et forée a posteriori vers l'amont depuis la galerie, maximisant le gradient hydraulique et enfin le long des réseaux/câblages électriques. Ces fuites sont néanmoins mineures avec un débit majoritairement déclinant malgré l'augmentation de la cote de retenue. La calcification est une explication apparente de cette baisse de fuite. C'est un comportement souvent rencontré dans les bétons à forte teneur en cendres volantes.

Enfin, deux points de fuite sont rencontrés à l'aval : un premier en rive gauche le long du contact béton / rocher, probablement dû à une petite bande de cisaillement dans le rocher qui n'a pas été traitée et cumulant environ 19 L/min, un second probablement le long d'une reprise de bétonnage (Fig. 15). Ce dernier montre un débit faible, difficilement mesurable.

D’une manière générale, l’étanchéité du béton du barrage est très satisfaisante. Des injections à la résine flexible dans le béton sont prévues pour les deux fissures les plus marquées, bien que faiblement débitantes. Compte tenu de l’étanchéité du béton dans sa masse, cette procédure s’est avérée très efficace pour la correction des fuites résiduelles dans des cas similaires [9], [10].

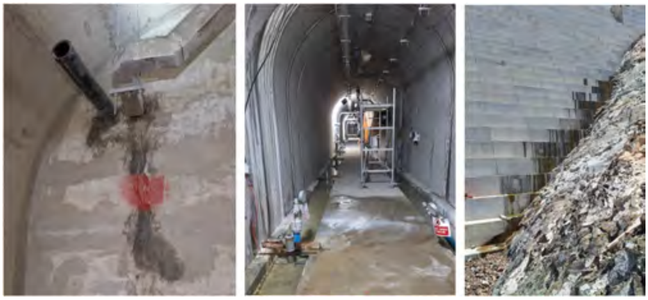

Fig. 15
Quelques fuites mineures à travers ou proche du BCR : le long de réseaux (à g.), au droit de fissure de la galerie avec calcification évidente (au milieu) et au contact béton / rocher (à dr.)
A few minor leakages through or close to the RCC: along embedded pipes (left), at gallery cracks with obvious calcification (middle) and at the concrete / rock contact (right)

4. ETANCHÉITÉ PAR GÉOMEMBRANE

4.1. Quelques données historiques

L’utilisation de géomembranes dans les STEPS a commencé au début des années 1990, comme solution de réparation pour les parements amont ou les joints de barrages formant l’un des deux réservoirs, dont l’étanchéité avait été compromise par un procès de vieillissement « physiologique » ou « précoce », ou par une pathologie particulière. Jusqu’au milieu des années 2010, il n’y avait qu’un seul cas, en 2003, avec masque en géomembrane sur un nouveau barrage : le barrage BCR d’Olivenhain aux Etats-Unis, formant le réservoir supérieur de la STEP de Lake Hodges en Californie, près de la faille de San Andreas.

La première, bien que non traditionnelle, STEP ayant un système de géomembrane comme masque d’étanchéité est certainement l’ensemble constitué par les 18 bassins d’économie d’eau du nouveau jeu d’écluses du projet d’élargissement du Canal de Panama, étanchés par Carpi en 2016. Par son fonctionnement très exigeant, cet aménagement dont les bassins sont remplis et vidés 5 à 6 fois par jour, est comparable à une STEP.

Le premier projet réalisé pour une STEP proprement dite est celui de Pico da Urze sur l'île de Madère au Portugal, où une géomembrane constitue le masque d'étanchéité du réservoir supérieur. Construit en 2019, le réservoir de Pico da Urze a été connecté au réservoir existant formé par le barrage de Calheta, ainsi créant la STEP de Calheta, combinant énergie éolienne et hydroélectrique. Dès lors, à partir de 2020, les dispositifs d'étanchéité par géomembrane ont constitué le masque d'étanchéité des deux réservoirs. Dans les projets cités, les géomembranes ont été installées en position exposées.

4.2. Masques amont par géomembranes : exigences et atouts

Les trois projets ci-dessous sont représentatifs des défis et des avantages qu'un masque souple offre.

A Olivenhain, les défis étaient l'ampleur du séisme de conception et la fonction critique du barrage, qui devait fournir l'eau en cas d'urgence. Les critères de sélection du masque en phase de conception ont mis l'accent sur la stabilité sismique et le contrôle des infiltrations. Les atouts techniques du masque en géomembrane se sont avérés être son étanchéité, sa fiabilité notamment au niveau des joints de dilatation, la présence d'un système de drainage au niveau du parement amont, évitant les infiltrations d'eau dans le corps du barrage, et la stabilité du système en cas de séisme, i.e., la capacité de pontage des fissures existantes ou nouvelles s'ouvrant en cas d'un fort tremblement de terre [1].

Dans le cas des bassins du Canal de Panama, les défis principaux étaient des tassements horizontaux prévisionnels de 100 mm et des déplacements différentiels de 120 mm entre remblais et ouvrages en béton [2]. Les variations du niveau de l'eau induisant une vitesse moyenne de 0.5 m/s et une vitesse de pointe de 1.5 m/s, les vitesses de vent de 115 km/h côté Pacifique et de 140 km /h côté Atlantique, étaient dimensionnantes également. La résistance à des surfaces agressives était aussi essentielle compte tenu du support. Enfin, la durée de vie requise pour le masque était de 100 ans.

A Pico da Urze, la conception intégrant un remblai en enrochement compacté de 31 m de hauteur avec des granulométries variables et une inclinaison de 1,4H/1V, les défis étaient principalement liés aux tassements estimés à 670 mm en phase de construction, 54 mm au premier remplissage, et environ 50 mm au niveau du couronnement en phase d'exploitation. Des couches de support agressives (granit et brèche altérées), et des vitesses du vent estimées à 120 km/h, ont été prises en compte également.

Ces projets présentent actuellement (année 2024) respectivement 20, 8 et 5 ans de service, avec des performances conformes aux attentes. Quelles sont les caractéristiques pour lesquelles une solution d'étanchéité par géomembrane a été retenue ? La basse perméabilité de la géomembrane, essentielle, est cependant une caractéristique commune à tous type de masques utilisés dans ces projets. Au contraire, spécifique de la géomembrane est sa capacité d'allongement, par conséquent son aptitude à ponter des joints en mouvement ou des fissures qui s'ouvrent, ou à compenser les tassements et déplacements différentiels. Une géomembrane très flexible et déformable, avec un système de fixations périphériques permettant de s'adapter aux mouvements différentiels attendus, est le seul masque permettant d'atteindre ces objectifs. Evidemment, la géomembrane doit avoir une longue durée de vie et par conséquent une résistance certaine vis-à-vis de l'exposition cyclique aux UV et des sollicitations dues aux cycles chargement/déchargement. La durabilité des géomembranes ici présentées a été démontrée dans plusieurs projets avec géomembranes exposées dont la durée de service dépasse les 40 ans. Concernant la résistance aux phénomènes de fatigue, les 18 bassins du Canal de Panama permettent de tirer les premières conclusions : depuis la mise en service en 2016 jusqu'à ce jour, les systèmes d'étanchéité par géomembrane ont soutenu avec succès environ 15.000 cycles de remplissage/vidange, qui correspondent à plus de 40 ans de cycles de remplissage/vidange quotidiens d'une STEP traditionnelle.

Les atouts opérationnels d'un masque flexible sont une installation rapide, possible aussi sur pentes très raides, permettant de produire de l'énergie dans un délai plus court, une empreinte carbone réduite en comparaison avec d'autres solutions d'étanchéité, un coût global inférieur, aucun entretien de routine, réparabilité du système en cas de dommages accidentels réalisable à sec mais également sous l'eau. La quantité d'énergie stockée étant proportionnelle au volume d'eau, avoir des pentes plus raides peut contribuer à la rentabilité du projet.

L'utilisation d'un masque par géomembrane peut également permettre d'optimiser les travaux de gros œuvre sur des projets de STEP. En effet, l'épaisseur du remblai peut être optimisée en supprimant la couche de matériaux drainant et en la remplaçant par un géodrain synthétique, la qualité du matériau de support peut être optimisée en appliquant un géotextile anti-poinçonnant en sous couche de la géomembrane. De plus, l'utilisation d'une géomembrane permet de limiter les besoins de compactage et de s'accommoder de tassements structurels importants en intégrant à la conception une extra longueur de matériaux (type "soufflet") dimensionnée suivant les projets.

4.3. Conception et études de cas

4.3.1. *Eléments généraux de conception*

La majorité des réservoirs de STEPs est formée par excavation et par barrages en remblai. Pour les raisons déjà énoncées, paramètres cruciaux pour la sélection de la géomembrane sont ses propriétés mécaniques, en particulier sa résistance au poinçonnement/éclatement, sa flexibilité, et sa capacité d'allongement. Formulation, configuration et épaisseur de la géomembrane sont déterminées en fonction des couches adjacentes (couche/s de support/drainage couche de couverture le cas échéant), des agressions environnementales (essentiellement UV et gradients de température) et de la durée de vie requise.

Le système d'ancrage doit maintenir la géomembrane stable face au soulèvement par le vent, tendue et adhérente à la couche de support lors des variations quotidiennes des niveaux d'eau. En effet, les plis étant des zones de concentrations de contraintes, ils peuvent entraîner des phénomènes de fatigue et un vieillissement prématuré de la géomembrane. L'ancrage est généralement réalisé par lignes continues longitudinales (couronnement, bermes, radier) ou verticales (talus) avec un espacement calculé avec des méthodes bien connues [3] en fonction des effets de succion du vent et des variations du plan d'eau.

Le type de remblai, qui dépend des matériaux locaux disponibles et peut avoir trois configurations différentes, influence le choix du type et de l'épaisseur de la géomembrane et détermine d'autres éléments, tels que le choix de la couche de drainage. Si les remblais sont en terre, en pente douce (e.g., 3H/1V), avec matériaux homogènes ou zonage, la couche de support de la géomembrane est un matériau cohérent compacté et une couche de drainage doit être prévue entre la couche support et la géomembrane. Si les remblais sont en petits enrochements (graviers, pierres), avec une pente relativement forte (typiquement 2H/1V), et matériaux homogènes ou zonages, la couche de support de la géomembrane est constituée de graviers compactés et sélectionnés avec une capacité telle à assurer le drainage au-dessous de la géomembrane. Si les remblais sont en gros enrochements (pierres, galets, rochers), avec une pente raide (typiquement 1,6H/1V) et des sections zonées, la couche de support de la géomembrane est constituée de béton poreux, en couche relativement mince (200-300 mm) ou en forme de bordures extrudées, et le drainage est assuré par le béton poreux. Les options d'ancrage en fonction des types de remblais et du sol excavé sont présentées à travers les études de cas qui suivent.

Lorsque la géomembrane intercepte des ouvrages en béton, elle est ancrée par un joint périphérique étanche conçu pour résister à la pression de l'eau et aux déplacements différentiels entre remblais déformables et ouvrages rigides. Le joint, développé par Carpi pour les nouveaux barrages en remblai, et appliqué à de nombreux projets depuis 1996, a été largement discuté dans la littérature.

4.3.2. *Remblais en terre compactée : Kokhav Hayarden, Israël 2020/2021*

La STEP de Kokhav Hayarden, 344 MW, située dans la région nord d'Israël, comprend deux réservoirs d'une capacité d'environ 3 millions de mètres cubes chacun. Le réservoir supérieur est formé par des remblais en terre compactée et par excavation du sol, constitué de dépôts fluviaux d'argile et d'un mélange argile-gravier. L'inclinaison des talus est de 3,5H/1V, la fluctuation du plan d'eau est d'environ 22 m. Le réservoir inférieur est formé par un remblai continu en terre compactée, composé de dépôts fluviaux d'argile et d'un mélange d'argile limoneuse et de gravier. L'inclinaison des talus est de 3H/1V, la fluctuation du plan d'eau est d'environ 21 m. Les réservoirs ne sont jamais totalement vidangés.

La conception initiale du masque pour les deux réservoirs consistait en une géomembrane en polyéthylène haute densité (PEHD) placée sur une couche granulaire compactée, ancrée en couronnement dans une tranchée longitudinale et en radier par l'action de lestage de l'eau toujours présente au fond des réservoirs. Cette conception fut modifiée pour améliorer la résistance au soulèvement par le vent et pour éviter que le revêtement ne reste lâche et sensible à la formation de plis, d'autant plus que les géomembranes PEHD sont sensibles à la formation de plis importants en raison des variations de température. Ces problèmes sont amplifiés dans une STEP, car les cycles de remplissage/vidange causent une exposition plus longue de la géomembrane aux effets négatifs du vent et de la formation de plis. Le revêtement finalement retenu est SIBELON® CNT 3100, une géomembrane thermoplastique en chlorure de polyvinyle (PVC) de 2,0 mm d'épaisseur, thermo-associée lors de sa fabrication à un géotextile en polypropylène non tissé aiguilleté de 500 g/m^2. Cette géomembrane a une meilleure flexibilité, une capacité d'allongement permettant de résister à des tassements importants, et une moindre prédisposition à la formation de plis.

Le système d'ancrage a été rendu plus robuste en ajoutant des lignes d'ancrage verticales à intervalle régulier et espacement différent en parties hautes et basses des talus, en fonction de la géométrie et du soulèvement du vent. La vitesse de conception est d'environ 150 km/h (réservoir supérieur) et de 130 km/h (réservoir inférieur) ; l'espacement retenu pour les deux réservoirs est de 8 m pour le tiers supérieur des talus, et 16 m pour les 2/3 inférieurs des talus (Fig. 16).

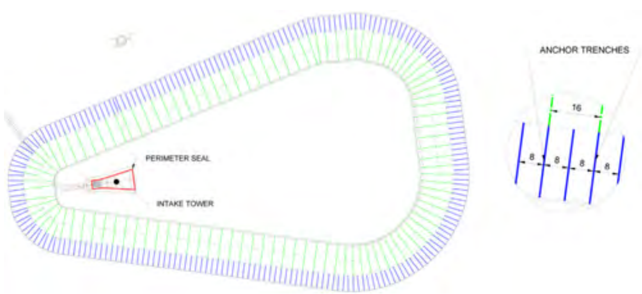

Fig. 16
Kokhav Hayarden, réservoir inférieur : schéma des tranchées d'ancrage
Kokhav Hayarden, lower reservoir: scheme of anchor trenches

Les lignes d'ancrage consistent en des tranchées creusées dans les talus et dans lesquelles une bande d'ancrage en géomembrane est insérée puis lestée avec un matériau granulaire compacté (Fig. 17), fournissant ainsi une ligne d'ancrage résistante à laquelle la géomembrane d'étanchéité est fixée par thermo-soudage.

Fig. 17
Kokhav Hayarden : préparation des tranchées d'ancrage
Kokhav Hayarden : preparation of anchor trenches

La couche de drainage conventionnelle en matériau granulaire prévue à l'origine pour éviter les sous-pressions a été remplacée par un géodrain synthétique composite assurant deux fonctions : le drainage via un élément de type géofilet et la filtration via un élément de type géotextile. Ce géodrain synthétique est plus performant, en termes d'efficacité, constructibilité, qualité et coûts, qu'une couche en matériau granulaire. Après installation du géodrain sur les remblais, les lés de géomembrane sont déroulés au-dessus et fixés par thermo-soudures aux lignes d'ancrage en géomembrane ; ils sont ensuite joints entre eux de façon étanche (Fig. 18 à gauche), créant un revêtement continu sur toute la surface des réservoirs.

Fig. 18
Kokhav Hayarden : géodrain et soudage de la géomembrane
Kokhav Hayarden: geodrain and seaming of geomembrane

L'installation du masque géomembrane dans le réservoir inférieur a débuté le 21 juillet 2021 et s'est achevée le 29 septembre 2022. Celle du réservoir supérieur a débuté le 20 juillet 2020 et s'est achevée le 17 décembre 2022. Au total, 433.000 m^2 ont été installés. Les essais de remplissage pour la mise en service sont en cours. Le suivi est fait via piézomètres (pression de l'eau sous la géomembrane, à l'intérieur du corps et des fondations du barrage, et aux niveaux des eaux souterraines), déversoirs à encoche en V (débits d'eau de fuite), extensomètres (tassements des barrages à différentes positions et élévations, tassements de surface du sommet des réservoirs), et inclinomètres (déplacement horizontal du corps du barrage dans 4 directions). Les données disponibles à présent (bassin inférieur) montrent pour tous les piézomètres des courbes de pression interstitielle avec valeurs négatives et inférieures aux valeurs d'alerte, à l'exception d'un joint de la prise d'eau, où une inspection subaquatique a constaté que l'augmentation de pression notée était due à une fuite provenant d'un défaut local (poinçonnement) de la géomembrane en correspondance d'un joint vertical de la prise d'eau. Le défaut, trouvé et réparé temporairement sous l'eau, sera réparé de façon définitive quand les essais de remplissage seront terminés. L'inspection subaquatique a aussi mis en évidence un déplacement différentiel de plus de 25 cm entre le sol de fondation et la prise d'eau, supporté sans dommage par la géomembrane. En ce qui concerne le débit des fuites, dans les 3 compartiments contigus à la prise d'eau le débit avant réparation du défaut local variait entre 0,852 et 1,496 L/s, des valeurs de 0 L/s ont été observées dans 3 compartiments, et entre 0,083 et 0,0183 L/s dans les 4 autres compartiments.

4.3.3. *Remblais en petits enrochements : abdelmoumen, maroc 2021/2024*

Abdelmoumen est une STEP de 350 MW située au Maroc sur la rivière d'Issen. Le projet comprend deux réservoirs stockant 1,3 millions de mètres cubes d'eau, constitués de remblais en matériau granulaire compacté, avec une inclinaison de 2H/1V et une fluctuation du niveau d'eau de 20 m. L'inclinaison des remblais nécessitait un très bon compactage et un procédé particulier a été développé pour fournir des talus stables intégrant en phase de construction des lanières d'ancrage rectangulaires en géomembrane, solidement noyées dans les talus. Une bande de géomembrane verticale, thermo-soudée aux lanières d'ancrage sur toute la hauteur des remblais formant une ligne d'ancrage continue (Fig. 19 à gauche) a permis de répartir les contraintes. L'avantage de ce système réside essentiellement dans le fait qu'il évite la construction et le remplissage des tranchées : une fois le remblai intégrant les lanières d'ancrage achevé, on procède de manière autonome à la pose du système d'ancrage.

La géomembrane sélectionnée est de type SIBELON® CNT 4400 L, constitué d'une géomembrane thermoplastique en PVC de 3,0 mm d'épaisseur, thermo-associée lors de la fabrication à un géotextile en polypropylène non tissé aiguilleté de 500 g/m^2. La géomembrane comprend un traitement de surface laqué (L), conçu pour améliorer la durée de vie du matériau sous le rayonnement UV intense. La géomembrane a été installée directement sur la couche en matériaux granulaires

(Fig. 19 à droite), qui constitue aussi l'élément de drainage, et ancrée par thermo-soudure aux bandes en géomembrane.

La vitesse de vent pris en compte dans le dimensionnement du système d'ancrage des deux réservoirs est de 88,6 km/h, déterminant un espacement régulier des lignes de fixation de 8 m sur les remblais et 16 m sur le radier (Fig. 20).

Fig. 19
Abdelmoumen : lanières, bandes d'ancrage, et pose de la géomembrane
Abdelmoumen: anchor strips and bands, and placement of the geomembrane

Sur le réservoir inférieur, l'installation des bandes d'ancrage a commencé en avril 2021 et le système géomembrane a été achevé en août 2022. Sur le réservoir supérieur, l'installation des bandes d'ancrage a commencé en mai 2022 et le système géomembrane a été achevé en en janvier 2023. Au total, environ 195 500 m^2 de géomembrane exposée. Les essais de remplissage sont en cours.

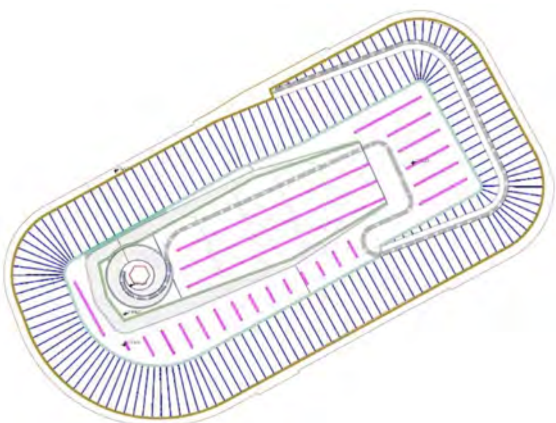

Fig. 20
Abdelmoumen : schéma du système d'ancrage du réservoir supérieur
Abdelmoumen: layout of the anchorage system at upper reservoir

4.3.4. *Remblais en grands enrochements : Pinnapuram, Inde, en cours*

Le projet de Pinnapuram Integrated Renewable Energy, 1.000 MW d'énergie solaire, 550 MW d'énergie éolienne et 1.680 MW de capacité de pompage-turbinage autonome, est la première STEP développée par Greenko, producteur d'électricité en Inde ; les travaux sur sa prochaine STEP, Gandhi Sagar, conçue avec un système de géomembrane exposée, vont démarrer en automne 2024.

Le réservoir supérieur de Pinnapuram est constitué d'un barrage en enrochement continu de 6,5 km de longueur et d'une hauteur maximale d'environ 40 m, formant un réservoir de forme quasi rectangulaire. Le réservoir inférieur se compose de trois barrages individuels en enrochement reliant les talus naturels existants, avec une longueur totale d'environ 3,3 km et une hauteur maximale d'environ 46 m. Les pentes sont assez raides : 1,6H/1V pour le réservoir inférieur et 1,8H/1V pour le réservoir supérieur. La conception du système d'étanchéité prévoyait initialement un masque en béton bitumineux ; une ultime évaluation technique et économique, du béton bitumineux l'a remplacé par un système géomembrane, SIBELON® CNT 4400 (matériau identique à celui adopté pour Abdelmoumen mais sans traitement de surface), installé sur une couche de support constituée d'une couche de béton poreux. À la suite de la demande de Greenko d'inclure un système de détection de fuites par câbles à fibres optiques, la nécessité d'une couche de béton conventionnel s'est imposée. Une couche béton a été placée sur la couche de transition, agissant comme support pour les câbles, et couverte par une couche en béton poreux. Le système d'ancrage de la géomembrane consiste à réaliser des tranchées dans les deux couches béton (traditionnel et poreux, Fig. 21), dans lesquelles des bandes d'ancrage en géomembrane ont été placées et lestées par un remplissage en béton poreux, de manière à construire une surface plane continue en béton poreux, agissant comme couche de support et couche de drainage. La vitesse du vent utilisée pour les calculs est de 196 km/h, ce qui ce qui a induit un espacement des tranchées de 8 m.

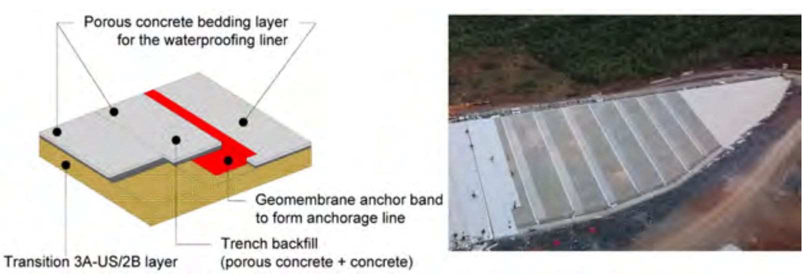

Fig. 21
Pinnapuram, réservoir inférieur : tranchées d'ancrage, bandes d'ancrage et mise en œuvre de la géomembrane sur la couche de béton poreux
Pinnapuram, lower reservoir: anchor trenches, anchor bands and placement of the geomembrane on the porous concrete layer

Sur le réservoir supérieur, pour optimiser la durée des travaux sur le barrage long de plus de 6 km, le béton poreux a été remplacée par un géodrain synthétique similaire à celui de Kokhav Hayarden (Fig. 22 à gauche). En août 2024, les travaux d'installation du système géomembrane seront repris sur le barrage formant le réservoir supérieur (Fig. 22 à droite). Le remplissage du réservoir inférieur est actuellement en cours et les travaux d'étanchéité commencent également au niveau du canal de fuite, où un masque en géomembrane exposée a remplacé le système avec béton bitumineux prévu à l'origine.

Fig. 22
Pinnapuram, réservoir supérieur : du premier plan à l'arrière-plan, géodrain synthétique, bandes d'ancrage, et mise en œuvre de la géomembrane sur le géodrain synthétique
Pinnapuram, upper reservoir: from foreground to background, synthetic geodrain, anchor bands and placement of the geomembrane on the synthetic geodrain

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CHANGEMENT CLIMATIQUE EN FRANCE: UNE ADAPTATION NÉCESSAIRE DES BARRAGES ET RÉSERVOIRS, VISION NATIONALE ET EXEMPLE LOCAL (*)

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FRANCE

SUMMARY

The impact of climate change on water resources is already noticeable in France. The year 2022, marked by exceptional temperatures and drought, highlighted that one of its main effects is the scarcity of water resources in summer.

For the future, the simulations carried out as part of the Explore2 exercise project a general decrease in summer flows across the entire territory and a more uncertain situation in winter with a probable increase in flows over a large part of France. Furthermore, for mountain basins, the increase in air temperatures results in earlier snowmelt.

This change in the hydrological cycle induces a change in EDF's hydroelectric production, both in annual volume with a slight downward trend but especially in

Climate change: a necessary adaptation for dams and reservoirs, national view and regional study case

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terms of seasonal distribution. The spring contribution due to snowmelt appears earlier, its volume gradually decreasing under the effect of the reduction in snow cover.

This new hydrological situation calls for adaptations. We present the concrete case of the adaption project of the Lauch dam in Alsace, wich purpose is to support low flows in summer. For this dam, an increase of 3m would result in a 75% increase in the exploitable volume, thus ensuring the current mission of this structure of supporting low flows.

RÉSUMÉ

L'impact du changement climatique sur les ressources en eau est déjà perceptible en France. Ainsi l'année 2022, marquée par des températures et une sécheresse exceptionnelle, a souligné que l'un de ses effets principaux est la raréfaction de la ressource en eau en période estivale.

Pour le futur, les simulations réalisées dans le cadre du projet Explore2 projettent une diminution généralisée sur le territoire des débits en été et une situation plus incertaine en hiver avec une augmentation probable des débits dans une grande partie de la France. Par ailleurs pour les bassins de montagne l'augmentation des températures d'air se traduit par une fonte des neiges plus précoce.

Cette évolution du cycle hydrologique se traduit par une évolution du productible hydro-électrique d'EDF, à la fois en volume annuel avec une légère tendance à la baisse mais surtout en termes de répartition saisonnière. L'onde d'apport printanière notamment est de plus en plus précoce, son volume diminuant progressivement sous l'effet de la baisse de l'enneigement.

Cette nouvelle donne hydrologique appelle des adaptations. Le rapport présente ainsi le cas concret du projet d'adaptation du barrage de la Lauch, en Alsace, dont la vocation est le soutien d'étiage. Pour ce barrage une réhausse de 3m conduirait à une augmentation de 75% du volume exploitable, permettant ainsi de sécuriser la mission actuelle de soutien d'étiage associée à cet ouvrage.

1. INTRODUCTION

L'année 2022 a été une année exceptionnellement chaude en France : l'été 2022 a ainsi été le deuxième été le plus chaud depuis 1900, avec 33 jours cumulés de vague de chaleur, la première vague de chaleur de juin étant la plus précoce jamais enregistrée. Cet été caniculaire s'est accompagné d'une sécheresse exceptionnelle rappelant à tous que le changement climatique est en marche, et que l'un de ses effets principaux est la raréfaction de la ressource en eau en période estivale. Ainsi l'intensité et la durée des sécheresses des sols ont été multipliées par deux depuis les années 1960 en France métropolitaine et par trois dans le sud du pays. Le constat est clair : les effets du réchauffement climatique sont déjà à l'œuvre et l'état français cherche à insuffler une dynamique globale d'adaptation pour toute la société [1].

Dans ce contexte le monde des barrages n'est pas inactif. Nous allons montrer dans cet article comment l'évolution de la ressource en eau est appréhendée globalement par la communauté des hydrologues français, et plus spécifiquement par EDF s'agissant de l'évolution du potentiel énergétique associé *(productible hydro-électrique)*. Dans une seconde partie nous montrerons au travers des résultats d'une étude menée par ARTELIA un exemple concret de projet de réhabilitation d'un barrage dédié au soutien d'étiage (barrage de la Lauch).

2. PROJECTIONS CLIMATIQUES ET HYDROLOGIQUES EN FRANCE POUR LE XX^{E} SIECLE

2.1. Le projet EXPLORE2 et le projet MOSARH21

Le projet EXPLORE2 (2021-2024) [2], financé par l'état français, a eu pour ambition de mettre à jour les connaissances de l'impact du changement climatique sur l'hydrologie en France métropolitaine et de faciliter l'appropriation des données produites notamment via la mise à disposition des résultats sur un serveur dédié (https://www.drias-eau.fr/). La chaine de modélisation mobilisée reprend la structure classique d'une modélisation de l'impact du changement climatique en hydrologie et voit l'enchainement de plusieurs modèles / hypothèses depuis les scénarios d'émission de gaz à effet de serre, les modèles climatiques, les méthodes de descente d'échelle, et enfin la modélisation hydrologique.

Le projet MOSARH21 (2015-2018) [3], antérieur, n'a concerné que le territoire du nord-est où se situe le barrage de la Lauch. Pour autant ces deux projets partagent un grand nombre de données en commun et – comme on le verra par la suite – présentent des résultats tout à fait cohérents.

Les scénarios ainsi que les modèles climatiques utilisés dans le cadre du projet EXPLORE2 sont issus de l'exercice CMIP5 associé au 5^{e} rapport du GIEC. Trois scénarios d'émission sont retenus par le projet (RCP2.6, RCP4.5 et RCP8.5) mais seuls les deux derniers scénarios (RCP4.5 et RCP8.5) seront considérés ici. Le scénario RCP8.5 est un scénario « extrême » décrivant un futur excluant toute politique de régulation du climat tandis que le scénario RCP4.5 est un scénario « intermédiaire » pour lequel les émissions continuent de croître pendant quelques décennies pour finir par se stabiliser et décroitre avant la fin du XXIe siècle.

Ces scénarios sont ensuite traduits en projections climatiques d'abord réalisées à l'échelle globale par des modèles de circulation générale (GCM) simulant le climat de la Terre entière à une résolution de 100 à 200 km. Les modèles climatiques régionaux, baptisés RCM, pilotés par les modèles globaux, simulent ensuite le climat à haute résolution sur des zones restreintes. Les couples GCM/RCM utilisés dans le cadre du projet EXPLORE2 sont issus de l'ensemble EURO-CORDEX. 17 de ces projections sont retenues pour le scénario RCP8.5 et 9 pour le scénario RCP4.5. Enfin, des ajustements statistiques sont appliqués de façon à corriger certains défauts des simulations climatiques en corrigeant leurs biais par rapport à un jeu de données de référence.

Les projections de débits ont ensuite été obtenues par application de plusieurs modèles hydrologiques (jusqu'à 9 selon le territoire), parmi lesquels le modèle GRSD de l'INRAE [4] et le modèle MORDOR d'EDF [5].

Le projet MOSARH21 de son côté a eu pour objectif de faire une évaluation de l'impact des changements climatiques sur les débits de la partie française des affluents du Rhin (Moselle-Sarre-Rhin), en utilisant également des simulations climatiques du 5e rapport du GIEC. Les mêmes scénarios d'émission sont considérés (RCP2.6, RCP4.5 et RCP8.5) et jusqu'à 6 trajectoires climatiques parmi lesquelles deux couples GCM/RCM de l'ensemble EURO-CORDEX décrits plus haut. Enfin deux modèles hydrologiques ont également été utilisés parmi lesquels le modèle GRSD de l'INRAE [4].

Comme on le verra plus bas les résultats des deux projets seront exprimés en écart par rapport à une période de référence. Le projet EXPLORE2 utilise la période 1976-2005 comme période de référence tandis que le projet MOSARH21 utilise la période 1971-2000. Ces deux périodes de 30 ans sont très proches l'une de l'autre et font que les résultats sont directement comparables.

2.2. Projections climatiques : températures d'air et précipitations

Les tendances climatiques moyennes projetées en France par le projet EXPLORE2 sont résumées sur les Figures 1 et 2. S'agissant des températures d'air la nette augmentation, déjà perceptible depuis les années 1980, se poursuit quel que soit le scénario de gaz à effet de serre envisagé. L'augmentation est plus forte pour le scénario RCP8.5 que pour le scénario RCP4.5.

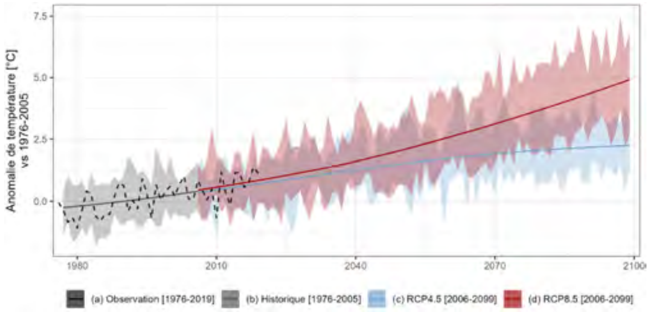


Fig. 1
Évolution de la température moyenne annuelle en France au cours du XXIe siècle pour les deux scénarios RCP4.5 et RCP8.5
Evolution of average annual temperature in France over the 21st century for both scenarios RCP4.5 and RCP8.5.

Concernant les précipitations annuelles, la moyenne d'ensemble des projections n'évolue que faiblement même en fin de siècle peu importe le scénario de gaz à effet de serre considéré. Cependant, cette faible évolution est marquée d'une forte incertitude [-30% à +30%] suivant les membres de l'ensemble considérés. De plus, ce faible changement des précipitations en moyenne annuelle masque en réalité des évolutions régionales et saisonnières importantes (Figure 3). Ainsi, un signal d'augmentation des précipitations est visible sur le nord en moyenne d'ensemble alors qu'une diminution apparait dans le sud. De plus, sur l'hiver une hausse généralisée des précipitations est visible sur la totalité du territoire français (avec des augmentations plus fortes au nord), alors que les précipitations estivales tendent à diminuer.

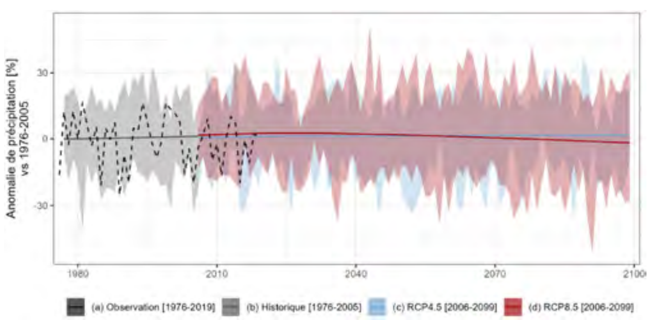


Fig. 2
Évolution des précipitations moyennes annuelles en France au cours du XXI^{e} siècle pour les deux scénarios RCP4.5 et RCP8.5
Evolution of average annual precipitation in France over the 21st century for both scenarios RCP4.5 and RCP8.5

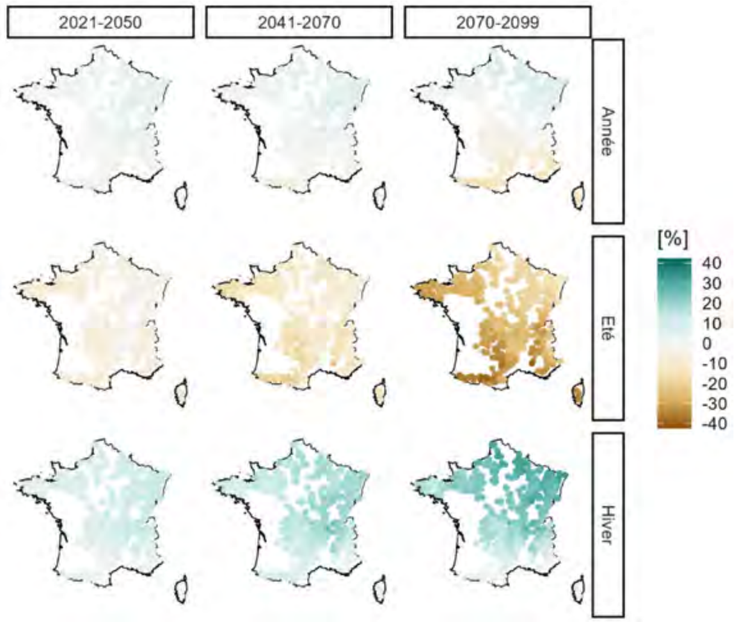


Fig. 3
Cartes des évolutions de précipitations pour différentes saisons et horizons de temps. Les valeurs représentent la moyenne de l'ensemble EXPLORE2, pour le scénario RCP8.5 (moyenne de 17 RCM)
Evolution of precipitation for different seasons and time horizons. Outcomes represent the average of the EXPLORE2 project, for the RCP8.5 scenario (average of 17 RCM).

2.3. Impacts sur le cycle hydrologique

L'évolution des débits simulés avec le modèle MORDOR [5] (Figure 4), moyennée à l'échelle de la France, présente comme pour les précipitations de fortes incertitudes [-50% à +50%] en fin de siècle. La moyenne d'ensemble des projections n'évolue que faiblement, même si une légère baisse semble visible dans le scénario RCP8.5 alors que celle-ci reste stable dans le scénario RCP4.5. Un contraste spatial existe entre le nord et le sud (Figure 5) avec respectivement une augmentation et une diminution. Le contraste saisonnier est également renforcé avec (1) des diminutions dans les débits estivaux, excepté sur le bassin parisien où le rôle des nappes reste important pour soutenir les étiages et (2) une possible augmentation des débits hivernaux sur la quasi-totalité du territoire.

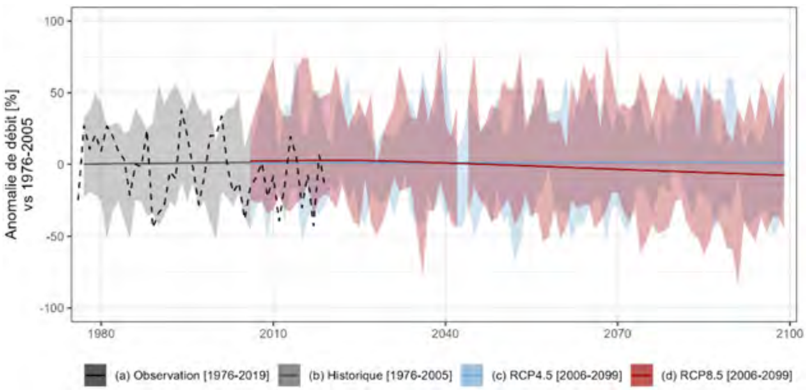


Fig. 4
Évolution des débits moyens annuels en France au cours du XXIe siècle pour les deux scénarios RCP4.5 et RCP8.5
Evolution of the average annual flows in France over the 21st century for both scenarios RCP4.5 and RCP8.5.

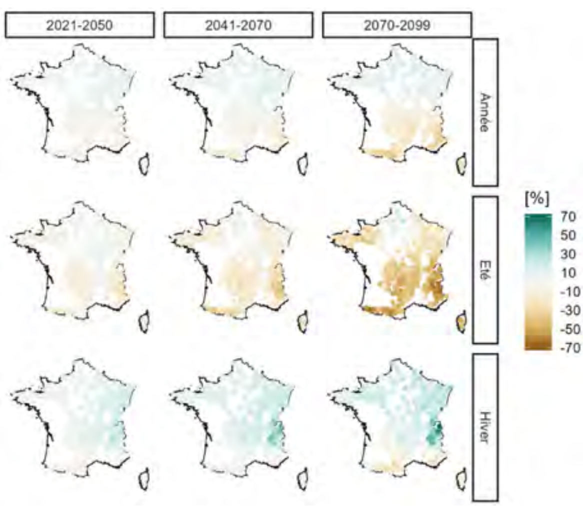


Fig. 5
Cartes des évolutions de débits pour différentes saisons et horizons de temps. Les valeurs représentent la moyenne de l'ensemble EXPLORE2, pour le scénario RCP8.5 (moyenne de 17 RCM)
Flow evolution for different seasons and time horizons. Outcomes represent the average of the EXPLORE2 project, for the RCP8.5 scenario (average of 17 RCM).

L'évolution de la saisonnalité des apports hydrologiques, consécutive à la modification des précipitations et températures, est illustrée sur la Figure 6 pour deux bassins contrastés qui alimentent tous deux un réservoir à vocation hydro-électrique : (1) l'Ain à Vouglans, bassin du Jura caractérisé par un régime pluvio-nival et (2) la Durance à Serre-Ponçon, bassin des Alpes du Sud caractérisé par un régime nival.

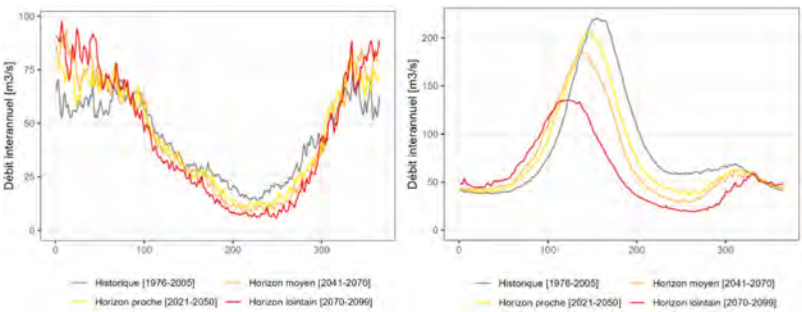


Fig. 6
Évolution du régime hydrologique de deux bassins versants en fonction de l'horizon de temps (l'Ain à Vouglans à gauche, la Durance à Serre-Ponçon à droite). Les valeurs représentent la moyenne de l'ensemble EXPLORE2, pour le scénario RCP8.5 (moyenne de 17 RCM)
Evolution of the hydrological regime of two watersheds for different time horizon (the Ain at Vouglans watershed on the left, the Durance at Serre-Ponçon watershed on the right). Outcomes represent the average of the EXPLORE2 project, for the RCP8.5 scenario (average of 17 RCM).

Sur le bassin de l'Ain, les projections montrent une accentuation des contrastes saisonniers tout au long du XXIe siècle, avec des débits hivernaux plus importants sous l'effet de l'augmentation des précipitations et de la hausse de la limite pluie-neige, et des étiages estivaux plus marqués (de l'ordre de -50% en fin de siècle) sous l'effet de la diminution des précipitations en été et de l'augmentation de l'évapotranspiration. Les débits de printemps et automne, sont également orientés à la baisse, sous le double effet des tendances sur les précipitations et l'évapotranspiration.

Sur le bassin de la Durance, les projections montrent un glissement progressif d'un régime nival vers un régime pluvio-nival. Les débits hivernaux ont tendance à augmenter, principalement sous l'effet des températures et de l'élévation de la limite pluie-neige en hiver. L'onde de fonte nivale printanière est de plus en précoce au printemps, et son volume diminue sensiblement sous l'effet de la baisse de l'enneigement. Les débits d'étiage estivaux subissent une baisse très marquée, à la fois due à la baisse des précipitations en été et au moindre soutien de la fonte en altitude.

3. IMPACT SUR LE PRODUCTIBLE HYDRO-ELECTRIQUE D'EDF

Pour une vallée donnée, le productible hydro-électrique est l'énergie maximum théorique que peut produire un ensemble d'aménagements compte tenu de la ressource en eau disponible. Cet indicateur, exprimé en GWh, est construit à l'échelle d'une vallée à partir de témoins de débits et de relations spécifiques qui tiennent compte des équipements, des règles d'exploitation et des autres usages de l'eau. Ces relations sont par ailleurs établies sans tenir compte du stockage dans les réservoirs comme si l'eau était tout de suite valorisée d'un point de vue énergétique. Cet indicateur peut ainsi être vu pour une journée donnée comme « l'énergie en train de couler dans la vallée » : on transforme les débits moyens journaliers exprimés en m3/s en une énergie potentielle journalière exprimée en GWh.

Cumulés à l'échelle de la France ces indicateurs régionaux permettent ensuite d'établir le « productible global France ». Il s'agit alors d'un indicateur de choix pour suivre pour une année donnée la ressource disponible d'un point de vue énergétique pour l'ensemble du parc Hydraulique. Par suite, ce même indicateur national, cumulé à l'échelle d'une année permet d'apprécier les éventuelles tendances climatiques sur une longue période.

Sur la base d'un tel indicateur les Figures 7 et 8 proposent une vision de l'évolution probable du productible hydro-électrique d'EDF au cours du XXIe siècle, à parc hydro-électrique et autres usages de l'eau inchangés.

On note tout d'abord une tendance globale à la baisse, peu marquée, mais avec une accentuation en fin de siècle dans le cas du scénario RCP8.5. Cette baisse en moyenne annuelle – plus perceptible que sur la Figure 4 qui représentait la moyenne spatiale des débits sur l'ensemble du territoire français s'explique par la répartition des ouvrages hydro-électriques en France, principalement dans les massifs montagneux des Alpes, des Pyrénées et du Massif-Central c'est-à-dire plutôt dans la moitié sud de la France. Comme illustré sur la Figure 6 au droit de deux ouvrages cette figure globale cache bien sûr des disparités régionales très fortes. Par ailleurs à l'échelle du productible agrégé c'est surtout la forte évolution de la saisonnalité qui émerge (Figure 8). Du fait des évolutions climatiques présentées plus haut le productible a tendance à augmenter progressivement en hiver. L'onde d'apport printanière est de plus en précoce, son volume diminuant progressivement

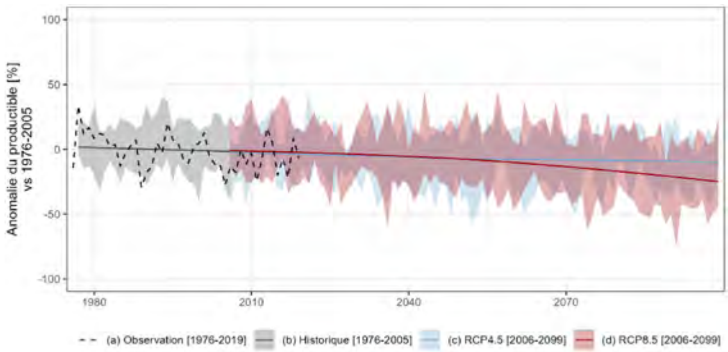


Fig. 7
Évolution du productible hydro-électrique (à parc hydro-électrique et autres usages inchangés) au cours du XXIe siècle pour les deux scénarios RCP4.5 et RCP8.5
Hydro generation (with hydroelectric assets and other uses unchanged) over the 21st century for the RCP4.5 and RCP8.5 scenarios

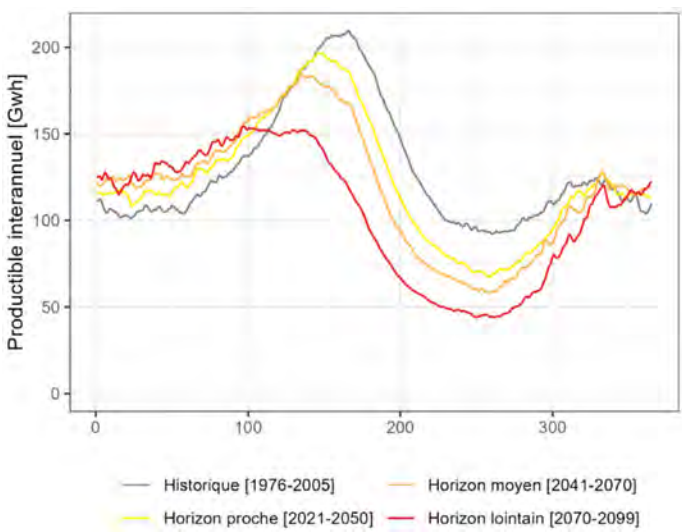


Fig. 8
Évolution du productible hydro-électrique (à parc hydro-électrique et autres usages inchangés) en fonction de l'horizon de temps. Les valeurs représentent la moyenne de l'ensemble EXPLORE2, pour le scénario RCP8.5 (moyenne de 17 RCM)
Variation of Hydro generation for different time horizons (with hydroelectric assets and other uses unchanged). Outcomes represent the average of the EXPLORE2 project, for the RCP8.5 scenario (average of 17 RCM).

sous l'effet de la baisse de l'enneigement. Les apports aux différents barrages qui constituent le productible d'EDF subissent ensuite une baisse très marquée en été qui se prolonge en automne.

En résumé les résultats du projet EXPLORE2 montrent que les changements climatiques que l'on a pu observer en France ces dernières décennies devraient continuer à imprimer leur impact sur le cycle de l'eau avec notamment des débits d'étiage à la baisse pour tous les scénarios et tous les horizons de temps (milieu et fin de siècle) avec des disparités régionales fortes. L'intérêt d'une gestion concertée et anticipée des retenues sera essentiel pour s'adapter. Outre la gestion des retenues existantes, la construction de nouveaux barrages où l'augmentation de la capacité d'ouvrages existants est également une option à considérer. C'est ce que nous allons voir maintenant au travers de l'exemple du barrage de la Lauch.

4. PROJET DE RÉHABILITATION DU BARRAGE DE LA LAUCH

Le barrage de la Lauch est le dernier barrage alsacien propriété de l'Etat qui a vocation à être rétrocédé par convention de transfert à la Collectivité européenne d'Alsace (CeA) à l'issue de travaux nécessaires de réhabilitation.

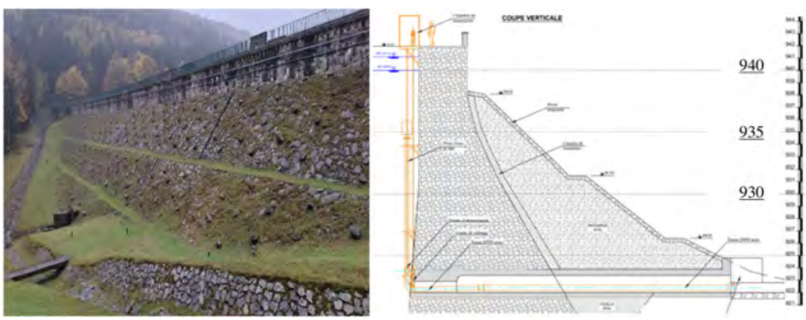


Fig. 9
Coupe du barrage et de sa recharge aval existante
Cross section of the Lauch Dam.

Situé à 942 m d'altitude (crête de digue) dans le département du Haut-Rhin, il s'agit d'un barrage de type poids en maçonnerie construit entre 1889 et 1894 et conforté par une recharge aval.

Il est un ouvrage indispensable (en duo avec le barrage du lac du Ballon) au bon équilibre de la ressource en eau sur le territoire de la Communauté de

Communes de la Région de Guebwiller (CCRG), à travers le soutien des étiages de la rivière Lauch pour assurer notamment les besoins en eau des milieux aquatiques et la satisfaction des usages (principalement l'alimentation en eau potable de la vallée de Guebwiller).

D'une hauteur initiale de retenue d'eau de 22 mètres, cet ouvrage disposait alors d'un volume de 690 000 m^3 à la cote 940,00 mNGF (retenue normale). Actuellement ce barrage ne peut être exploité que jusqu'à la cote 937 mNGF (420 000 m^3), afin d'assurer sa stabilité en cas de séisme. Le barrage de la Lauch est donc dans l'attente de travaux importants de réhabilitation et de sécurisation. La CeA est désignée par l'Etat en tant que maître d'ouvrage délégué de ces travaux.

4.1. Approche globale et durable de la ressource en eau

Dans une logique d'approche globale et durable du projet, et en conformité avec les orientations et dispositions du SDAGE Rhin-Meuse 2022-2027 et du Plan d'Adaptation et d'Atténuation au Changement Climatique du bassin Rhin-Meuse 2019-2024, et dans le respect de la mise en œuvre des enjeux et dispositions du Schéma d'Aménagement et de Gestion des Eaux (SAGE) de la Lauch, la CeA a souhaité intégrer dès le départ la nécessité de concevoir le projet au regard des scénarios connus à ce jour d'évolutions climatiques. La maîtrise d'œuvre globale des études et des travaux est confiée à ARTELIA et la méthodologie prévoit une étude hydroclimatique préliminaire, détaillée dans les paragraphes ci-après.

4.2. Les enjeux/contraintes de gestion du réservoir

Les règles de gestion du réservoir sont multiples et répondent à des enjeux différents.

4.2.1. *Enjeu de soutien des étiages de la rivière Lauch, en été et automne*

Grâce à leurs capacités de retenue, les barrages de la Lauch et du Ballon assurent le **soutien d'étiage de la Lauch amont jusqu'à Guebwiller,** en restituant en saison estivale voire automnale une partie importante des eaux stockées durant ou pendant la fin de la période hivernale.

Les **règlements d'eau des barrages** fixent notamment les conditions de ce soutien d'étiage en termes d'exploitation des deux retenues avec une assignation à respecter :

- les **débits réservés** à maintenir à l'aval immédiat des barrages Lauch et Ballon, respectivement 18 L/s et 4 L/s ;
- les **débits objectifs** (ou seuils d'alerte étiage) de la Lauch aux stations hydrométriques de Linthal et Guebwiller, respectivement 150 L/s et 230 L/s.

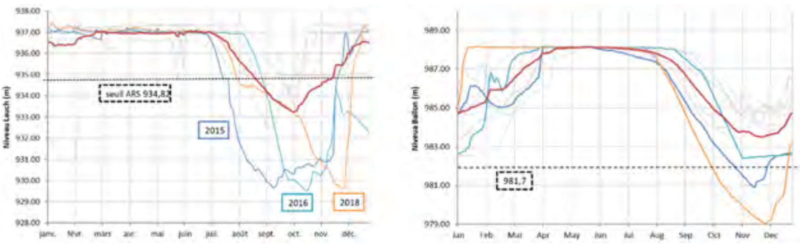


Fig. 10
Séries journalières observées (2012-2021) du niveau dans les retenues de la Lauch (gauche) et du Ballon (droite)
Water levels of Lauch Reservoir (left) and Ballon Reservoir (right) (2012-2021)

4.2.2. *Enjeu de préservation de la bonne qualité des eaux des lacs face aux cyanobactéries*

Les eaux du lac de la Lauch sont concernées depuis 2015 par la présence de cyanobactéries, qui prolifèrent désormais chaque année de manière saisonnière de l'été jusqu'à l'automne lorsque les eaux de surface se réchauffent suffisamment.

Par application des seuils réglementaires, et sur la base d'un retour d'expériences testé avec succès sur site durant les années 2016 et 2017, l'ARS Grand-Est a développé depuis 2018 un protocole sanitaire de décision pour la préservation de la bonne qualité de l'eau potable distribuée à partir de la prise d'eau potable sur la Lauch à Linthal en aval des deux barrages de la Lauch et du Ballon. Ce protocole intègre notamment une atténuation préventive de la pointe de prolifération des cyanobactéries, avec une cote limite basse du plan d'eau en été-automne du lac de la Lauch (13 m d'eau restant ou 934,82 mNGF), en dessous duquel le débit sortant du barrage de la Lauch doit être au débit réservé et les eaux de la Lauch soutenues majoritairement par les eaux du lac du Ballon (non contaminé).

4.2.3. *Enjeu de protection contre les crues dans la vallée de Guebwiller*

Le bassin versant de la Lauch est très concerné par **l'aléa inondation** et bénéficie à ce titre depuis 2006 d'un Plan de Prévention du Risque Inondation

(PPRI) couvrant le territoire de 15 communes. Les épisodes de crues de la Lauch ont lieu essentiellement en période hivernale et printanière suite à des pluies abondantes parfois associées à la fonte du manteau neigeux.

Ainsi, le barrage de la Lauch peut être également amené à jouer à cette période de l'année (hiver) un rôle important de **protection contre les crues des communes de la vallée de Guebwiller,** en particulier par la mise en œuvre d'une exploitation saisonnière ménageant un creux préventif de stockage des volumes de crues dans la retenue en hiver. Afin de ménager une tranche de laminage dans la retenue pour l'écrêtement des crues d'hiver, le niveau objectif dans la retenue est forcé 3 mètres en dessous de la cote RN après la campagne de soutien d'étiage et jusqu'au 14 février de l'année suivante. Puis, du 15 février au 14 mars, on vise un remplissage progressif linéaire pour atteindre la cote RN au plus tôt le 15 mars.

4.3. Résilience de la ressource en eau du système lacs de la Lauch et du Ballon et stratégies d'adaptation identifiées face au changement climatique

Le Plan d'adaptation et d'atténuation pour les ressources en eau du bassin Rhin-Meuse adopté par le Comité de bassin en 2018 dresse le bilan des changements climatiques déjà observés et à venir sur le territoire Rhin-Meuse et leurs impacts sur l'hydrologie : **augmentation de l'intensité des crues**, **accentuation de l'étiage**, augmentation des températures, **sécheresses plus fréquentes et plus marquées**, réchauffement de l'eau.

Le SAGE de la Lauch fixe actuellement à ce titre un cadre (de préservation de la disponibilité des ressources en eau) pour l'évolution des activités socio-économiques consommatrices en eau (industries agro-alimentaires, agriculture et irrigation, alimentation en eau potable, etc.) à travers le statut quo (plafonnement) **des prélèvements** (de toute nature) dans la Lauch et sa nappe d'accompagnement à hauteur de la moyenne globale des prélèvements durant les années 2006-2015.

Dans ce contexte, **la résilience** de la retenue du barrage de la Lauch **face au changement climatique a été évaluée**, c'est-à-dire sa **capacité à conserver ses fonctions** de **soutien d'étiage** et de **protection contre les inondations** à **l'horizon 2100.** Cette vérification implique de dresser l'état initial et l'état futur du **bilan ressources-besoins** du bassin versant de la Lauch à l'amont de la prise d'eau de Linthal.

4.4. Modèle d'allocation (ou de gestion)

4.4.1. *Données*

Le modèle d'allocation des ressources en eau est développé à l'aide du logiciel Mike Hydro Basin du *Danish Hydraulics Institute*. A titre illustratif de l'environnement logiciel, une capture d'écran du modèle d'allocation est présentée à la figure ci-dessous. Les composants principaux du modèle sont comme suit :

- Les retenues de la Lauch et du Ballon ;
- Les stations hydrométriques de Linthal et Guebwiller (points de contrôle) ;
- La prise d'eau de Linthal ;
- Les bassins versants d'intérêt.

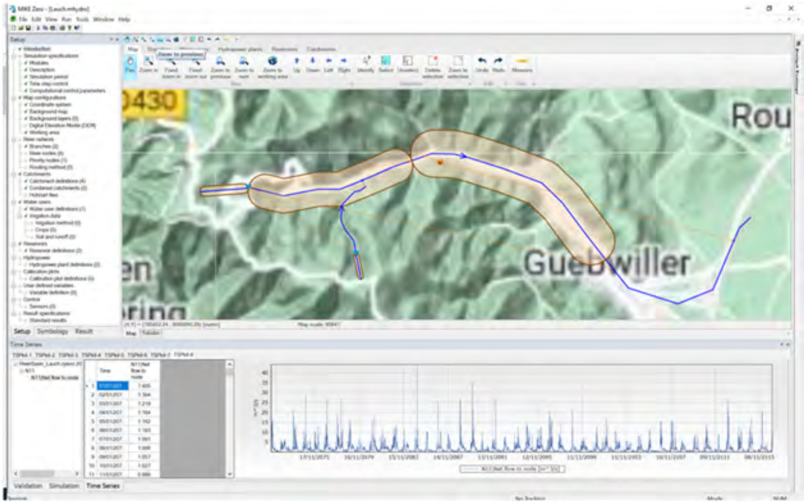


Fig. 11
Capture d'écran du modèle d'allocation de la Lauch
Screen shot of the hydraulic numerical modelling (Mike Zero, DHI)

Les règles de gestion retenues dans le paramétrage visent à reproduire le plus fidèlement possible la gestion réelle observée au cours des 10 dernières années. Parmi ces règles de gestion, on trouve par exemple les objectifs de gestion, les niveaux RN, les niveaux limites à ne pas dépasser, les débits réservés. Les principales règles de gestion retenues à ce stade sont détaillées ci-dessous.

Tableau 1
Règles de gestion du barrage de la Lauch

	Lauch	**Ballon**
Niveau RN (m) (m^3)	937,00 (425 000)	988,00 (1 070 000)
Niveau minimum (m) (m^3)	930,00 (64 000)	981,70 (620 000)
Niveau seuil cyano-bactéries (m) (m^3)	934,82 (270 000)	-
Débit réservé (L/s)	18	4
Débit seuil d'alerte étiage (L/s)	150 L/s à Linthal 230 L/s à Guebwiller	

Dans la suite, ce niveau seuil sera adopté comme niveau limite en dessous duquel les lâchures de la Lauch sont limitées au débit réservé.

Le niveau minimum au Ballon (981,70 m,) est pris assez supérieur au niveau minimum précisé dans le document règlementaire (972,50 m) pour correspondre à la gestion réelle des retenues (réserve ultime en cas d'hiver très sec ne permettant pas de remplir les retenues + faible taux de renouvellement (ou remplissage) annuel). Ainsi, le volume réellement disponible au Ballon (sans toucher à sa réserve ultime interannuelle) vaut 1 070 000 – 620 000 = 450 000 m^3.

Le principe de gestion retenu est la satisfaction, à tout instant, du débit objectif à Linthal et Guebwiller sous contraintes des règles de gestion.

Le débit de prélèvement à la prise d'eau de Linthal est pris constant égal à 60 L/s sur toute la période de simulation. Cette valeur de débit est extraite dans le modèle de la Lauch entre les stations de Linthal et de Guebwiller.

La comparaison de l'évolution des débits observés et simulés à Linthal 2012-2021 est illustrée aux figures ci-dessous (moyenne mensuelle). On observe globalement une assez bonne cohérence entre les séries simulées et observées. En moyenne, les débits simulés à Linthal sont inférieurs de 6% par rapport aux débits observés. Les débits simulés en période d'étiage sont très similaires. Pour la Lauch à Guebwiller, les différences entre simulé et observé sont aussi assez faibles, de l'ordre de 1% sur le débit moyen annuel.

4.4.2. *Projections temps futur*

A l'échelle régionale, les travaux récents du projet MOSARH21 (https://webgr.inrae.fr/projets/projets-acheves/mosarh21/) ont eu pour objectif d'évaluer les impacts futurs des changements climatiques sur les débits en utilisant les dernières

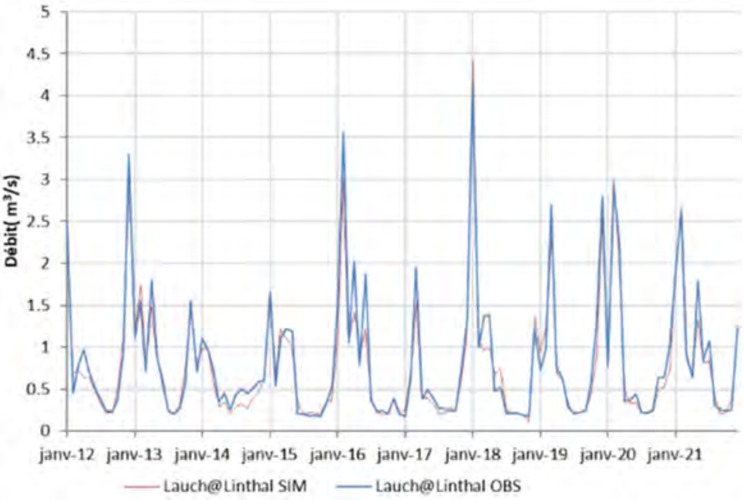


Fig. 12
Comparaison des débits observés et simulés à Linthal
Comparison of observed and simulated flows at Linthal

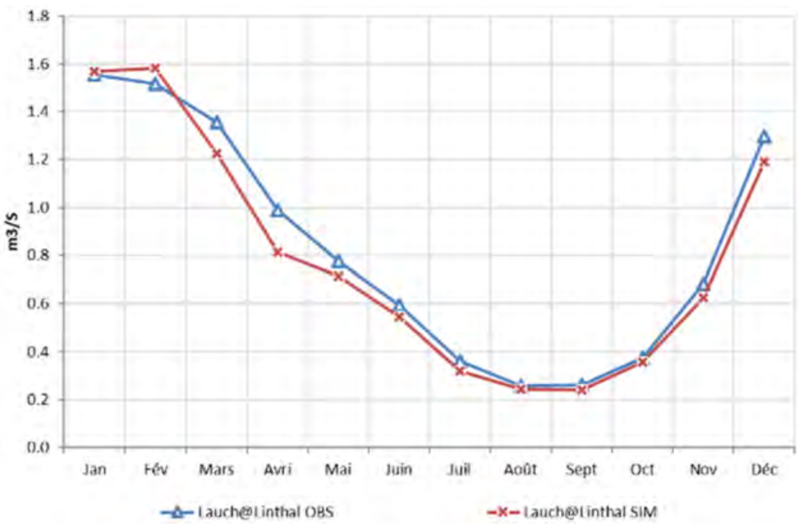
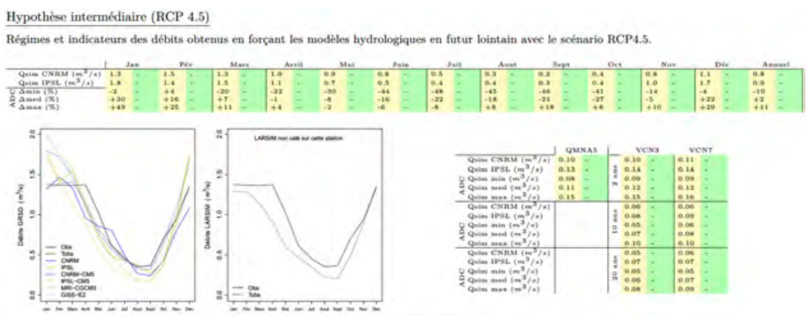


Fig. 13
Comparaison des débits observés et simulés à Linthal (moyenne mensuelle)
Comparison of observed and simulated flows at Linthal (monthly average)

simulations climatiques disponibles produites dans le cadre du cinquième rapport du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC).

Les fiches de synthèse par bassin versant produites par le projet MOSARH21 fournissent les ordres de grandeur des débits futurs possibles des cours d'eau résultant des modèles climatiques et des différents scénarios RCP du cinquième rapport du GIEC. Ces fiches sont utilisées comme référence pour l'évolution des débits dans le bassin versant de la Lauch en temps futur.

La figure ci-dessous donne un extrait de la fiche de synthèse du bassin versant de la Lauch à Linthal pour un futur lointain (2071-2100) pour le scénario RCP 4.5.



	Jan		Fév		Mars		Avril		Mai		Juin		Juil		Aout		Sept		Oct		Nov		Déc		Annuel	
Qsim CNRM (m^3/s)	1.3	-	1.5	-	1.3	-	1.0	-	0.9	-	0.8	-	0.5	-	0.3	-	0.2	-	0.4	-	0.8	-	1.1	-	0.8	-
Qsim IPSL (m^3/s)	1.8	-	1.4	-	1.5	-	1.1	-	0.7	-	0.5	-	0.4	-	0.4	-	0.3	-	0.4	-	1.0	-	1.7	-	0.9	-
ADC Δmin (%)	-2	-	+4	-	-20	-	-22	-	-30	-	-44	-	-48	-	-45	-	-46	-	-41	-	-14	-	-4	-	-10	-
ADC Δmed (%)	+30	-	+16	-	+7	-	-1	-	-8	-	-16	-	-22	-	-18	-	-21	-	-27	-	-5	-	+22	-	+2	-
ADC Δmax (%)	+49	-	+25	-	+11	-	+4	-	-2	-	-6	-	-8	-	+8	-	+18	-	+8	-	+10	-	+29	-	+11	-

		QMNA5			VCN3		VCN7	
ADC	Qsim CNRM (m^3/s)	0.10	-	2 ans	0.10	-	0.11	-
	Qsim IPSL (m^3/s)	0.13	-		0.14	-	0.14	-
	Qsim min (m^3/s)	0.08	-		0.09	-	0.09	-
	Qsim med (m^3/s)	0.11	-		0.12	-	0.12	-
	Qsim max (m^3/s)	0.15	-		0.15	-	0.16	-
ADC	Qsim CNRM (m^3/s)			10 ans	0.06	-	0.06	-
	Qsim IPSL (m^3/s)				0.08	-	0.09	-
	Qsim min (m^3/s)				0.05	-	0.06	-
	Qsim med (m^3/s)				0.07	-	0.08	-
	Qsim max (m^3/s)				0.10	-	0.10	-
ADC	Qsim CNRM (m^3/s)			20 ans	0.05	-	0.06	-
	Qsim IPSL (m^3/s)				0.07	-	0.07	-
	Qsim min (m^3/s)				0.05	-	0.05	-
	Qsim med (m^3/s)				0.06	-	0.07	-
	Qsim max (m^3/s)				0.08	-	0.09	-

Fig. 14
Évolution possible des débits de la Lauch à Linthal (RCP4.5 horizon 2071-2100)
Possible evolution of flows at Linthal (RCP4.5 horizon 2071-2100) – source : MOSARH21

L'horizon retenu est l'horizon « 2071-2100 » ou « futur lointain » comme identifié dans le rapport MOSARH21, car il correspond à l'horizon de temps ciblé dans le cadre de la présente étude, et le scénario d'émission de gaz à effets de serre retenu est le RCP4.5. L'évolution des débits de la Lauch telle qu'établie par le projet MOSARH21 est celle d'une augmentation en moyenne des débits d'hiver et d'une diminution en moyenne des débits d'été et d'automne.

L'évolution des régimes hydrologiques telle que documentée par les résultats du projet MOSARH21 est appliquée de manière homogène, pour chaque série d'apports, à la chronique des débits reconstitués sur la période historique de référence.

Les débits moyens mensuels des apports hydrologiques à la Lauch en temps présent et en temps futur sont illustrés à la Figure 15 ci-dessous. La zone hachurée en bleu correspond à une évolution à la hausse des précipitations moyennes saisonnières et des débits (période hivernale), tandis que la zone hachurée en rouge correspond au contraire à une évolution à la baisse des précipitations et des débits (période été-automne).

En moyenne, les débits d'hiver (décembre à février) sont en augmentation de 18%. Les débits de printemps sont relativement inchangés et les débits d'été et d'automne (juin à novembre) sont diminués de -23%. En moyenne sur l'année, le débit moyen augmente de 5%.

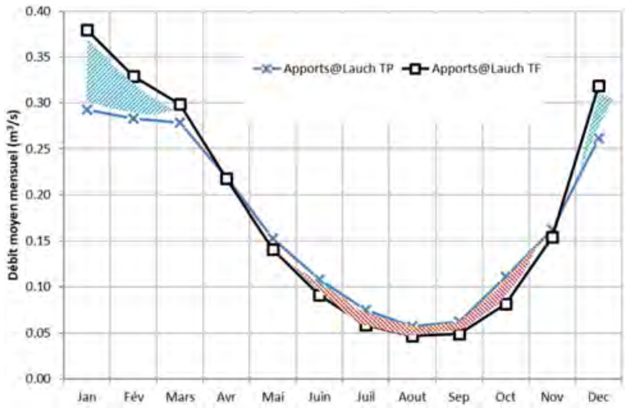


Fig. 15
Débits moyens mensuels des apports à la Lauch temps présent (TP) et temps futur (TF)
Average monthly inflows, present time (TP) and future time (TF)

4.5. Résultats de la projection Temps futur sur le barrage existant

Les séries de niveau des lacs de la Lauch et du Ballon sont illustrées aux figures ci-dessous. Sans exception, le niveau RN 940 à la Lauch est atteint chaque année de la période de simulation. De ce fait, l'introduction de la **fonction de protection contre les crues** (creux préventif) est sans effets sur les performances de **soutien d'étiage** et **ces fonctions s'avèrent donc conciliables du point de vue de la gestion de la ressource en eau**.

L'introduction de la fonction de protection contre les crues entraîne en moyenne une augmentation sensible des débits relâchés (+30%) et donc des débits à

Linthal (+6%) pendant le mois de décembre, et à l'inverse une diminution des débits pendant la période février-mars (respectivement -20% et -4%).

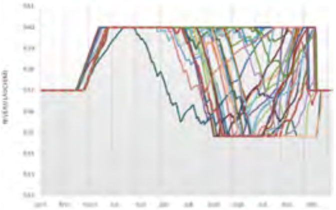


Fig. 16
Série du niveau simulé du barrage de la Lauch - temps future
Simulated Lauch reservoir water level series - future time

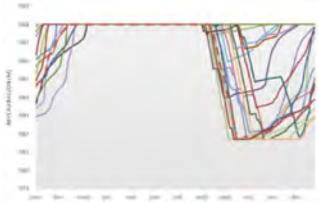


Fig. 17
Série du niveau simulé du barrage du Ballon - temps future
Simulated Ballon reservoir water level series - future time

En résumé les résultats des projections climatiques à l'horizon 2100 sont synthétisés dans le tableau ci-dessous. On rappelle que, comme pour tout exercice d'étude prospective des impacts du changement climatique, les résultats sont associés à des incertitudes.

Tableau 2
Résultats des projections climatiques à 2100

Nom de la ressource en eau	**Simulation du temps présent (TP)**	**Simulation du temps futur (TF)**
Rivière Lauch et bassin versant modélisé (en amont de Guebwiller)	Débit seuil d'alerte à Linthal (150L/s) : satisfait 99% du temps mais **épisodes d'étiages inférieurs 1 année sur 15** et de durée entre 10 et 40 jours consécutifs Débit moyen simulé à Linthal : 520L/s de mai à novembre, 340 L/s de juillet à septembre	Débit seuil d'alerte à Linthal (150L/s) : satisfait 98,5% du temps mais **épisodes d'étiages inférieurs 1 année sur 6** (+250%) et de durée jusqu'à 60 jours consécutifs (+50%) Débit moyen simulé à Linthal : 450 L/s de mai à novembre (-13%), 285 L/s de juillet à septembre (-15%)
Lac de la Lauch	**Seuil cyanobactéries** (934,82m) atteint ou dépassé (par le bas) environ **1 année sur 3**	**Seuil cyanobactéries** (934,82m) atteint ou dépassé (par le bas) environ **1 année sur 2** (+50%)
Lac du Ballon	Niveau seuil de réserve ultime (981,70m) atteint ou dépassé (par le bas) environ **1 année sur 15**	Niveau seuil de réserve ultime (981,70m) atteint ou dépassé (par le bas) environ **1 année sur 6** (+250%)

Les résultats des simulations au temps futur montrent un accroissement de la tension sur la ressource en eau. Le non-respect des règles de gestion du réservoir s’accentue et les épisodes d’étiage (non-respect du débit minimum à Linthal) sont plus fréquents et plus marqués.

4.6. Stratégie d’adaptation – rehausse du barrage de la Lauch

Fig. 18
Topographie existante aux abords du réservoir de la Lauch
Topographic layout of the surrounding of the reservoir

Face à cette tension sur la ressource en eau, des scénarios d’adaptation des aménagements présents sur le bassin versant ont été étudiés.

En particulier, l’impact sur la gestion de la ressource en eau d’une éventuelle réhausse du barrage de la Lauch entre +1 m et +5 m a été évalué grâce à la modélisation. La fonction de protection contre les crues est maintenue en assurant en hiver (comme précédemment dans l’étude) un creux théorique de 3 m sous le niveau RN simulé.

La série du niveau à la Lauch pour le cas de la réhausse +1 m (respectivement +3 m et +5 m) est illustrée aux figures ci-dessous. Le niveau dépassé en moyenne 9 années sur 10 est également représenté (trait rouge épais).

Pour les réhausses +1 m et +3 m on constate que le remplissage de la retenue est atteint chaque année de simulation sans exception. Pour la réhausse +3 m, le remplissage est néanmoins un peu plus difficile que pour la réhausse +1 m car, à apports hydrologiques constants, le volume à reconstituer est plus important.

Fig. 19
Série du niveau simulé du barrage de la Lauch - temps futur – réhausse +1 m
Simulated Lauch reservoir water level series - future time – Dam raising + 1m

Fig. 20
Série du niveau simulé du barrage de la Lauch - temps futur – réhausse +3 m
Simulated Lauch reservoir water level series - future time – Dam raising + 3m

A l'inverse, pour la réhausse +5 m on constate un risque de non remplissage complet de la retenue pour au moins 1 année de simulation. Plus généralement, le remplissage total est atteint en moyenne plus tardivement au printemps que dans les cas précédents.

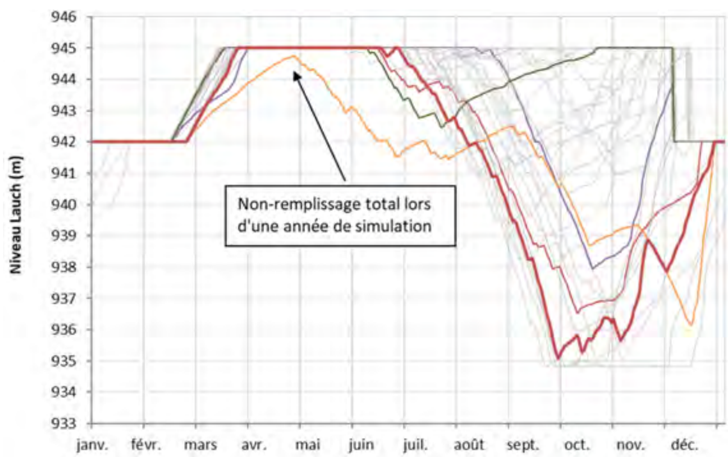


Fig. 21
Série du niveau simulé du barrage de la Lauch - temps futur – réhausse +5 m
Simulated Lauch reservoir water level series - future time – Dam raising + 5m

Les résultats des simulations sont détaillés dans le tableau ci-dessous, en particulier les volumes totaux sous RN, les volumes exploitables aux retenues de la Lauch et du Ballon (450 000 m^3, inchangé), le volume total de soutien d'étiage fourni par la Lauch et le Ballon sur une année moyenne, sur l'année maximale et le quantile 9 années sur 10, la fréquence de non-atteinte du débit objectif à Linthal et la durée maximale de persistance de non-atteinte.

Tableau 3
Résultats des simlations

	Volumes Retenues				Soutien d'étiage (m^3)					
	Lauch			Ballon	Lauch			Ballon		
	RN (m)	Volume sous RN (m^3)	Volume exploitable (m^3)	Volume exploitable (m^3)	Année moyenne	Quantile 9/10	Année maximale	Année moyenne	Non-atteinte du débit objectif à Linthal (1 année sur X)	Durée de persistance (jours)
Réf temps présent	*940*	*698 350*	*426 500*	*450 000*	*333 630*	*671 200*	*1 139 600*	*110 850*	*1/15*	*40*
Temps futur +0m	940	698 550	426 500	450 000	352 150	664 700	1 013 500	157 200	1/6	60
+1m	941	800 500	528 300		391 600	739 600	1 120 500	136 750	1/6	50
+2m	942	907 530	635 300		424 400	846 300	1 231 800	115 500	1/9	40-45
+3m	**943**	**1 020 000**	**747 850**		**456 800**	**962 850**	**1 346 320**	**91 700**	**1/15**	**40**
+4m*	944	1 137 000	885 700		485 800	1 085 000	1 458 000	68 600	1/15	30
+5m*	945	1 280 432	988 280		509 300	1 166 000	1 483 900	52 275	1/20	15

**Risque identifié lors de la simulation de non remplissage complet entre 2 campagnes de soutien d'étiage (hors effets cumulatifs d'années successives)*

Les principales observations sont comme suit :

- Le volume exploitable à la Lauch augmente avec la réhausse, de +25% pour une réhausse de 1 m, **+75% pour une réhausse de 3 m**, et +130% pour une réhausse de 5 m.
- **Le niveau RN à la Lauch est atteint sans exception chaque année de la période de simulation pour une réhausse jusque +3 m**. Au-delà, on voit apparaître le risque de ne pas remplir complètement la retenue entre 2 campagnes de soutien d'étiage (présence de séries n'atteignant pas la RN).
- Une non-atteinte du débit objectif à Linthal est observée en moyenne 1 année sur 6 pour une durée de quelques jours jusqu'à un maximum de 50 jours consécutifs pour une réhausse de +1 m, en moyenne 1 année sur 15 pour une durée jusqu'à un maximum de 40 jours consécutifs pour une réhausse de +3 m (conservation de la situation actuelle), et en moyenne 1 année sur 20 pour une durée maximale 15 jours consécutifs pour une réhausse de +5 m.
- Avec la réhausse et l'augmentation associée du volume exploitable à la Lauch, et compte-tenu du principe de gestion qui accorde la priorité du soutien d'étiage à la Lauch avant le Ballon, on observe que la période pendant laquelle la retenue de la Lauch assure seule la fonction de soutien d'étiage augmente, et par suite aussi le volume annuel de soutien d'étiage (respectivement +10%, **+35%** et +45% **pour une réhausse** de 1 m**, 3 m** et 5 m).
- Par suite, le volume moyen annuel de soutien d'étiage associé au Ballon diminue avec la réhausse du barrage de la Lauch, par exemple **-17% pour une réhausse de 3 m**.

En conclusion, avec une réhausse de 3 m, les performances de soutien d'étiage sont trouvées équivalentes à celles de la référence temps présent. Ceci est permis par une augmentation du volume exploitable à la Lauch de +75%, qui permet une augmentation moyenne des volumes annuels de soutien d'étiage de 35% (et **même 45%** pour les années les plus déficitaires). Cette augmentation permet de compenser la diminution des débits naturels d'été et d'automne en temps futur.

Moins impactante sur l'environnement qu'une rehausse de +5m, cette hauteur de réhausse de + 3m n'est cependant pas sans conséquences. En effet, le Conservatoire Botanique d'Alsace (C.B.A.) signale à minima la présence de 4 espèces floristiques patrimoniales dans l'emprise ou à proximité immédiate de l'aménagement envisagé. En complément, le site du barrage de la Lauch se situe dans et à proximité de plusieurs zonages de protection réglementaires d'espaces naturels. Des études environnementales spécifiques sont actuellement menées préalablement à l'autorisation et la mise en œuvre du projet.

Pour les raisons évoquées ci-dessus, une rehausse de 3 mètres du barrage de la Lauch se distingue parmi les valeurs de la plage étudiée.

5. CONCLUSION

Les projections climatiques et hydrologiques en France dépeignent un futur où les températures d'air continuent d'augmenter tandis que les précipitations connaissent d'importantes modifications saisonnières, avec des étés plus secs et des hivers plus humides. Les débits des rivières devraient ainsi continuer de diminuer en été, allongeant les périodes d'étiage, tandis que les risques de crues hivernales pourraient croître. Les impacts varieront selon les régions, rendant certaines zones, comme le sud-est, particulièrement vulnérables.

Cette évolution du cycle hydrologique se traduit par une évolution du productible hydro-électrique, à la fois en volume annuel avec une légère tendance à la baisse mais surtout en termes de répartition saisonnière avec des apports plus faibles en période estivale, tout ceci dans un contexte où les usages de l'eau évoluent par ailleurs (agriculture, tourisme). Les projections hydrologiques constituent ainsi une aide précieuse pour imaginer des futurs de l'eau et continuer à adapter la gestion de la ressource en eau aux effets du changement climatique.

Tout un éventail de solutions devra être déployé pour adapter le stockage de l'eau à cette nouvelle donne hydrologique : construction de nouveaux barrages, recharge artificielle de nappe phréatique, solutions fondées sur la nature ... L'augmentation de la capacité d'ouvrages existants est également une option à considérer. C'est ce que nous avons pu voir au travers de l'exemple du barrage de la Lauch situé dans le nord-est de la France. Pour ce barrage une réhausse de 3m conduirait à une augmentation de 75% du volume exploitable, permettant ainsi de sécuriser la mission actuelle de soutien d'étiage associée à cet ouvrage.

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INNOVATIVE DESIGN AND FEEDBACK OF WATERWAYS FROM A MAJOR PUMPED STORAGE PROJECT IN ARID REGION (*)

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ARTELIA

FRANCE

SUMMARY

The report reviews the experience gained from a PSHPP project located in an arid region, with an installed capacity of 2x150 MW and a 150 m head. This technical report presents a focus on the design of two keys aspects of the PSHPP: the design of the waterways and the vibratory analysis of the powerhouse.

Intakes are critical to the efficiency of the development, whether in terms of head losses, flow stability, limitation of water losses through the massif, operating flexibility or risk of air entrainment.

For this project, the successive implementation of analytical and then numerical and/or physical models enabled us to significantly evolve the design of the water intake and identify the “critical” points to which the engineer’s attention must be focused. The alternating operation of these intakes in turbining or pumping mode, and the problems associated with sediment management of high tidal ranges in a closed or semi-open circuit, results in additional modeling and design efforts, in comparison with the intake structures of more common hydroelectric installations.

**Innovations et retour d’expérience sur les chemins d’eau au travers d’un projet de STEP en milieu aride*

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In addition, an innovative concrete lining alternative was developed for the waterways to meet the extremely demanding seepage criterion, while avoiding to a maximum the use of steel lining. The solution consists of a reinforced concrete lining, combined with prestressing and a waterproof membrane. These solutions required the development of advanced numerical models to take account of specific criteria linked to high transient regimes, the specific geometry of the lining and construction conditions. This approach has enabled us to highlight significant differences with analytical lining models assumed to be perfectly circular, and to adapt the lining design accordingly.

RÉSUMÉ

Le rapport dresse un bilan du retour d'expérience engrangé à travers un projet de STEP située dans en région aride de puissance installée 2x150 MW pour une hauteur de chute de 150 m de chute. Il s'articule autour de la conception des circuits hydrauliques.

Les prises d'eau sont des ouvrages critiques vis-à-vis de l'efficacité de l'aménagement, que ce soit en termes de pertes de charge, de stabilité des écoulements, de limitations des pertes d'eau à travers le massif, de flexibilité d'exploitation ou de risque d'entraînement d'air.

Pour ce projet, la mise en œuvre successive de modèles analytiques puis numériques et/ou physiques a permis de faire évoluer significativement la conception de la prise d'eau et d'identifier les points « critiques » sur lesquels l'attention de l'ingénieur doit être portée. L'alternance du fonctionnement de ces prises en turbinage ou pompage, et les problématiques liées à la gestion sédimentaire de forts marnages en circuit fermé ou semi-ouvert nécessitent en effet des efforts complémentaires de modélisation et de conception, en comparaison avec des ouvrages de prise d'installations hydroélectriques plus courantes.

Par ailleurs, une alternative innovante de revêtement béton a été développée pour les chemins d'eau pour répondre à des critères extrêmement exigeants de débit de fuite, tout en limitant le recours à une solution de blindage de facto plus coûteuse. La solution retenue consiste en la mise en œuvre d'un revêtement béton armé, combiné avec l'utilisation de précontrainte et la mise en œuvre d'une membrane étanche. Ces solutions ont nécessité le développement de modèles numériques avancés permettant de prendre en compte des critères spécifiques liés aux régimes transitoires forts, à la géométrie spécifique du revêtement et aux conditions de construction. Cette approche a permis de mettre en exergue des différences significatives avec les modèles analytiques de

revêtement supposés parfaitement circulaires et d'adapter en conséquence la conception du revêtement.

1. INTRODUCTION

The water intakes and waterways of Pumped Storage Hydropower Plan Projects (PSHPP) are critical to the efficiency of the power plant, whether in terms of head losses, flow stability, limitation of water losses, operating flexibility or risk of air entrainment.

In comparison with more conventional hydroelectric installation, minimization of the water losses requires additional design effort for PSHPP since it drives the overall efficiency of the scheme, both in turbining and pumping mode. Furthermore, water leakages management is challenging for project located in arid regions where natural inflows can be very limited or nil for closed loop PSHPP, thus resulting in severe design criterion with regard to this aspect.

This article describes the feedback earned through a major pumped storage project in the Middle East. ARTELIA has been involved in the project has principal Design Engineer of the Civil Work Joint Venture Contractor.

This project comprises an installed capacity of 2x125MW and includes a main RCC dam and a RCC saddle dam, a power intake tower, a pressure tunnel, a powerhouse as well as a significant length of access roads involving two access tunnels. The two pump-turbine units are equipped with variable speed motor-generators enabling the powerplant to have high charge-discharge cycle efficiency over an extended waterhead range.

For this project, the successive implementation of analytical, then numerical and physical models have enabled us to make significant progress in the design of the intakes, and to identify the “critical” points on which the engineer's attention must be focused.

In addition, an innovative concrete lining alternative was developed for the waterways to meet the extremely demanding seepage criterion, while avoiding to a maximum the use of steel lining. The solution consists of a reinforced concrete lining, combined with prestressing and a waterproof membrane. These solutions required the development of advanced numerical models to take account of specific criteria linked to high transient regimes, the specific geometry of the lining and construction conditions. This approach has enabled us to highlight significant differences with analytical lining models assumed to be perfectly circular, and to adapt the lining design accordingly.

Dedicated concrete mix and constructional aspect have also been considered for the RCC dams to ensure their watertightness. Those are detailed in the article "*Watertightness of dams and reservoirs of PSP: specific features, design, and feedbacks*" (Q. 108).

2. HYDRAULIC DESIGN OF THE INTAKES

2.1. Intakes description

The upper and lower water intakes feature long and profiled structures, suggesting favorable hydraulic operating conditions. Both have been studied through CFD modelling and physical modelling, for various flow rates (minimum, maximum and 1.5 x maximum for vortex risk identification) and various reservoir levels (Full Supply Level (FSL), Minimum Operating Level (MOL) and Extreme Minimum Operating Level (EMOL).

The lower structure consists of two parallel low-pressure culverts with a rectangular cross-section ending to a long and streamlined intake, divided by a central wall. The numerical and physical models both covered the intake from the bend approaching the final part of the intake structure to the outlet into the reservoir, and part of the reservoir itself.

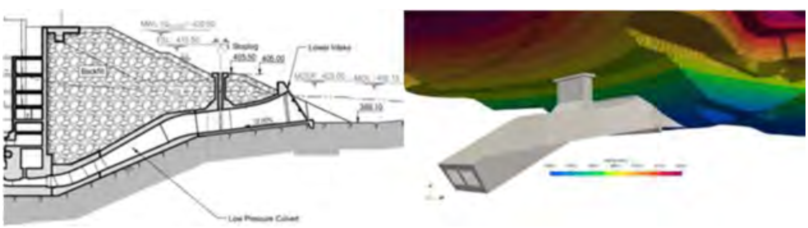

Fig. 1
Lower intake – Initial layout – Longitudinal profile and 3D view

The upper intake has a classical configuration, consisting in a streamlined transition structure between a large rectangular trashrack plane and a circular tunnel section, with a central supporting guiding wall. Both the numerical and physical models represented the intake and a part of the tunnel, as well as the reservoir (completely for the numerical model, partly for the physical model).

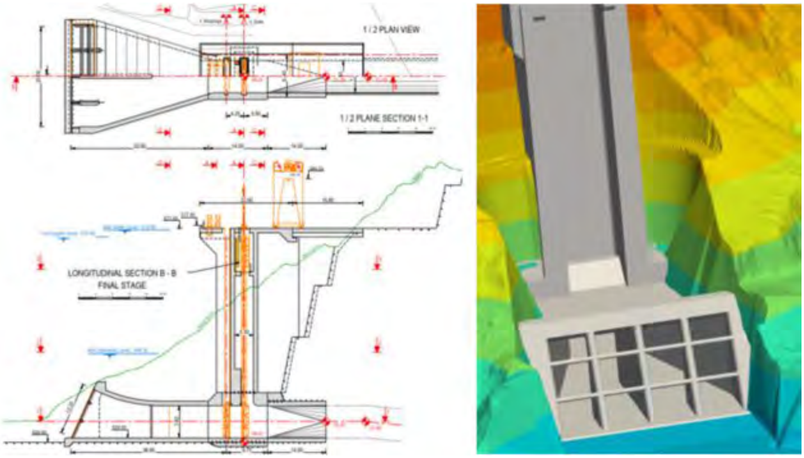

Fig. 2
Upper intake – Initial layout – Plan view and plane section, longitudinal profile and 3D view

2.2. 3D Numerical modelling

Firstly, 3D numerical modelling of upper and lower intakes has been carried out with the aim of identifying the flow conditions around and through the structures, of characterizing the flow distribution between the zones within the reservoirs, and of assessing the risk of vortex formation. To this end, the Computational Fluid Dynamics software OpenFOAM has been used.

2.2.1 *Diffusion numerical scheme influence*

In addition to the iterative simulations of geometry modifications, complementary simulations were carried out in pumping operating mode in order to identify the effect of the numerical diffusion scheme on the results obtained (flow configuration, head losses), for both the upper and lower intakes. Upon analyzing the results and comparing them with the physical model tests, it was concluded that the phenomena were most accurately represented by the less diffusive numerical scheme. This is reflected in the following observations:

- for the lower intake: for the simulations with the less diffusive numerical scheme, the head losses obtained are slightly greater (+10 cm) than those obtained with the first more diffusive scheme, i.e. around 10% of the total head loss in the structure.

- for the upper intake: at MOL, the outflow is mainly oriented to the East side of the intake structure and covers about 75% of the trashrack plane, while the remaining 25% of the intake section encounter an inflow direction. This result (based on a less diffusive numerical scheme) is consistent with the physical model tests, while the first more diffusive scheme initially tested did not identify instabilities in the outflow mode.

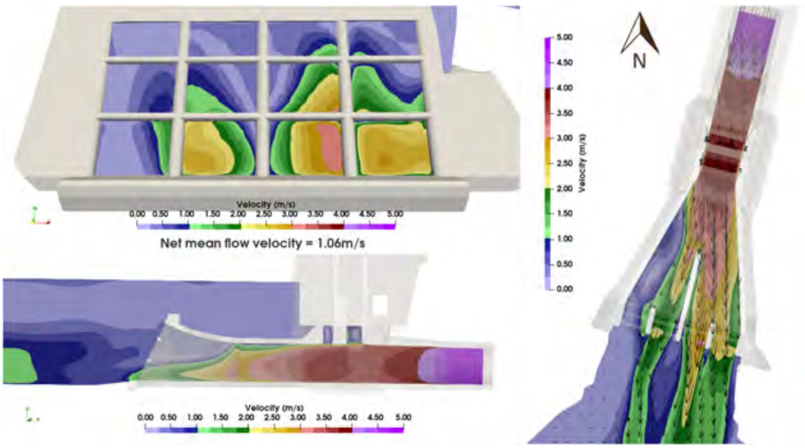

Fig. 3
Upper intake – Screen repartition, vertical and plan view – Less diffusive numerical scheme

2.2.2. *Sensitivity analysis over the upper intake shape*

With a view to optimizing the hydraulic operation of the structures (and therefore securing their energy production), a sensitivity analysis has been conducted on the shape of the upstream intake structure, in order to identify possible adaptations that would make it possible to obtain more satisfactory flow conditions.

The successive modifications consisted in changing the shape of the ceiling of the water intake without changing the total length of the structure, starting from the initial design with an arched shape: first by testing a plane shape, then a first elliptical shape, and finally a second elliptical shape by also changing the shape of the side walls (elliptical shape instead of plane shape). In some cases, the results obtained made it possible to improve vertical dissipation, but to the detriment of horizontal dissipation. Without the possibility of increasing the length of the structure, the initial design ultimately proved to be the best compromise between the size of the structure and the flow conditions within it (dissipation, velocity field, head losses, recirculation currents). The only way to improve the overall performance of the structure would have been to lengthen it, but as its operation still met the required specifications, a total reconfiguration was not studied further.

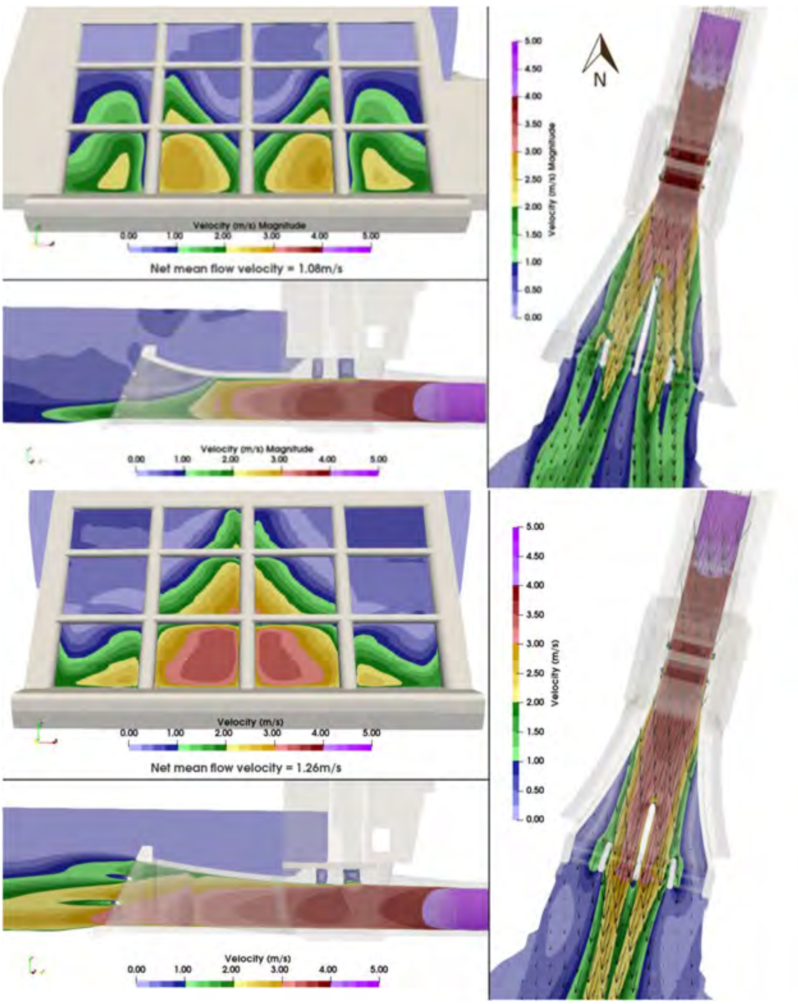

Fig. 4
Upper intake – Outflow conditions at MOL for the initial layout (top) and modified layout (change in the shape of the ceiling and side walls) (bottom)

2.2.3. *Outflow mode*

For the upper intake in outflow mode, as highlighted in the previous paragraphs, recirculation currents developed within the structure, generating head losses greater than those estimated through theoretical calculation approach. In addition, high velocities have been identified in the lower part of the structure, far exceeding the design criteria. The local maximum flow velocity reaches 1.5 m/s at MOL, and 2.8 m/s at FSL.

For the lower intake structure in outflow mode, at MOL the average velocity in the trashrack plane is around 1.2 m/s but reaches locally 2.5 m/s in the lower part of the structure, while a return current is identified in the upper part. At FSL, the flow is better distributed over the trashrack plane, with a maximum velocity of 1.5 m/s and negligible return current.

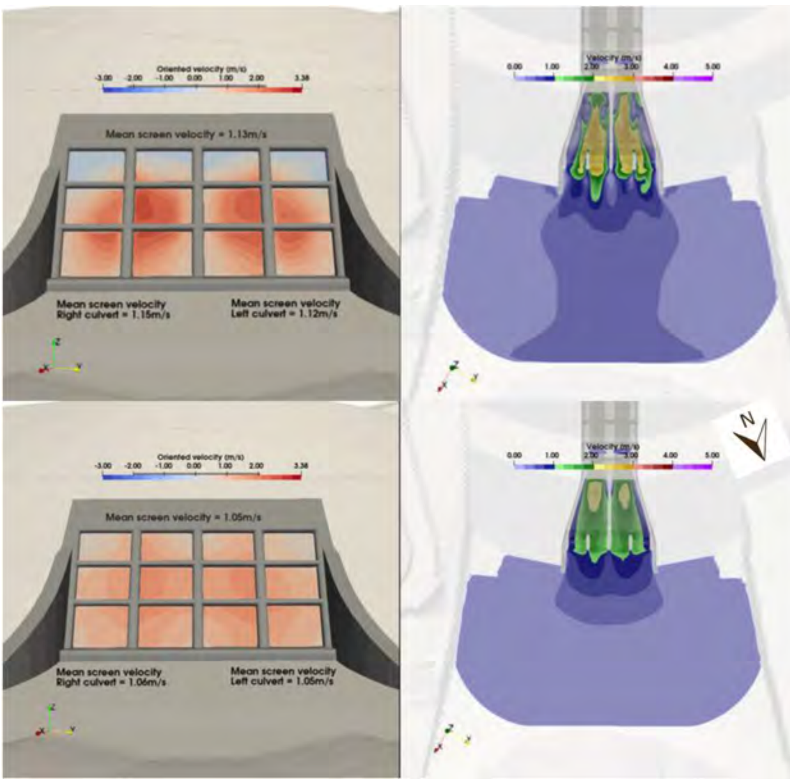

Fig. 5
Lower intake – Outflow conditions at MOL (top) and FSL (bottom)

2.2.4. *Inflow mode*

For the upper intake structure in inflow mode, flow velocities are fairly well distributed in the intake section, with a local maximum velocity around 1.3 m/s at MOL, and between 1.5 and 1.75 m/s at FSL.

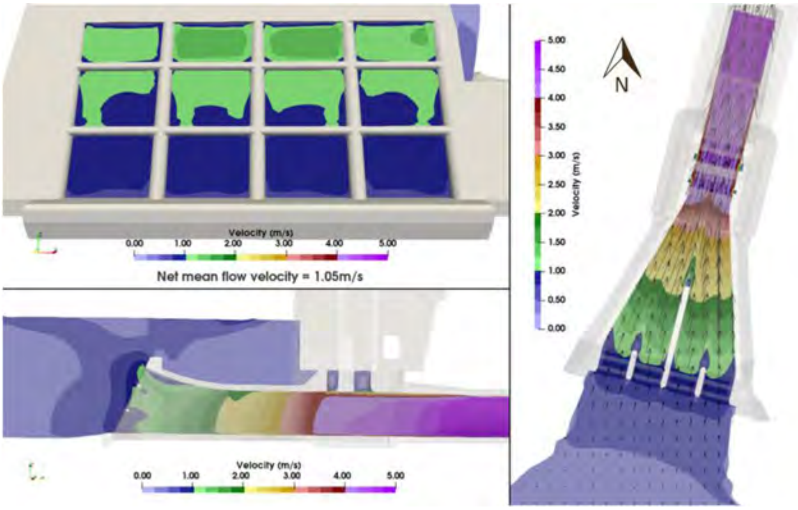

Fig. 6
Upper intake - Inflow conditions at MOL

For the lower intake structure in inflow mode, flow velocities are also rather well distributed over the trashrack plane, with only limited velocity reduction on the sides of the intake.

2.2.5. *Head losses*

The 3D numerical model allows to assess the total head losses through the upper and lower intakes, for both operating conditions. At the maximum flow rates, and considering an absolute surface roughness of 0.6 mm, the total head losses are in the range of 11 to 23% of kinetic energy in the waterway for the inflow mode and 44 to 46% for the outflow mode, respectively for upper and lower intakes.

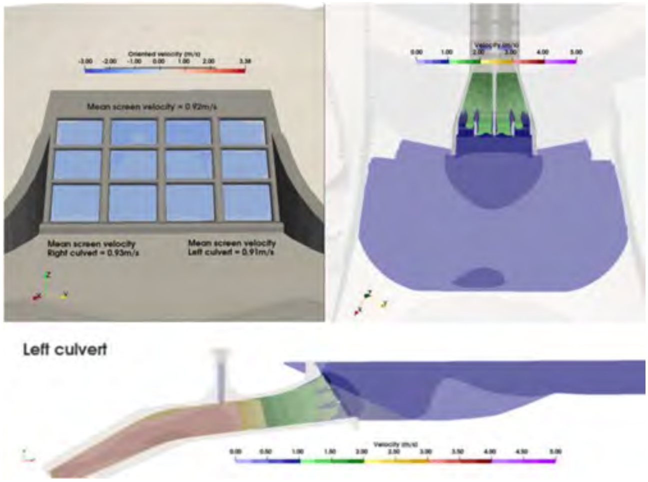

Fig. 7
Lower intake - Inflow conditions at Minimum Operating Level

2.3. Physical modelling

Following on from the 3D numerical modelling studies, scale model tests have been carried out to supplement the information provided by the CFD models, focusing in particular on the flow conditions in the vicinity of and through the structure, in order to identify the risks of vortex formation or features that could reduce the overall effectiveness of the scheme.

The physical models of the upstream (1:35 scale model) and downstream (1:38 scale model) intakes represented the whole structures and part of the reservoirs, and made it possible to simulate the whole range of operating conditions (variable levels and flows, generating mode and pumping mode).

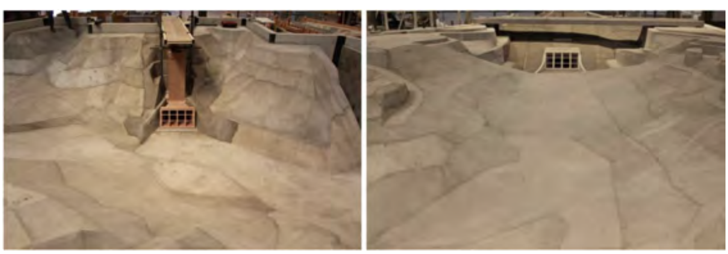

Fig. 8
General views of the physical models: Upper intake (left) and Lower intake (right)

For the upper intake structure, the tests carried out identified the following points:

- In generating (inflow) mode, the formation of vortices at certain levels and flows, even though this does not hinder the operation of the structure (weak and intermittent vortices), and the absence of vortices at the lowest levels: the flow is then directed head-on towards the structure, which prevents any recirculation of the flow at the surface, which could lead to the formation of vortices. This observation contradicts the empirical formulas established to date and used as “state of the art” recommendations during the preliminary design phases. Such formulas lead indeed to the assumption that the lower the water level in front of the intake structure, the greater the risk of vortex formation (for a given geometry and given flow rate). However, tests have shown that in this case, lowering the reservoir level below the intake ceiling eliminates the rotational axes of the flow, thereby reducing the risk of vortex formation.
- In pumping (outflow) mode, the great instability of the flow leaving the intake: the flow is dissymmetrical, concentrated either on the left side or the right side of the structure, depending on the very weak return currents observed in the reservoir, which changed direction depending on the level in the reservoir due to the a-symmetrical topography. Measurements and observations identified irregularly distributed velocity values with some values reversed on the intake side, with a maximum velocity reaching 2.8 m/s for any level considered in the reservoir.

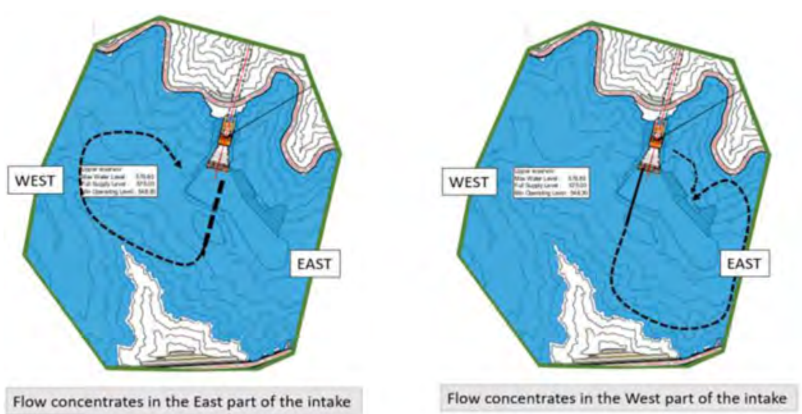

Fig. 9
Upper intake physical model – Unsteady flow pattern at Minimum Operating Level and Full Supply Level

For the lower intake structure, the tests carried out identified the following points:

Fig. 10
Lower intake physical model – Vortex type 3 with the initial design (left) and anti-vortex device (right)

- In generating (outflow) mode, the relative heterogeneity of the flow leaving the structure (already identified during numerical modelling) generates lateral return currents, which lead to unsteady operation (jerky flow), alternately entering and leaving the structure. These lateral recirculating currents go hand in hand with a central flow characterized by high velocities (up to 3 m/s).
- In pumping (inflow) mode, the formation of strong, regular vortices in front of the structure (type 3 according to ARL classification [1]). As this vortex intensity and frequency did not completely meet the design requirements, an anti-vortex device was implemented on the intake in order to reduce the vortex risk and ensure a more satisfying hydraulic functioning during pumping operation. The anti-vortex device simply consists of a horizontal plate positioned on the roof of the intake structure, overhanging in the reservoir direction. Preliminary tests enabled to find the optimum overhanging length (identified as 3.5 m) necessary to have a significant effect on the vortex formation, before verifying its effectiveness for the whole range of operating conditions.

2.4. Conclusion on hydraulic design of intakes

Numerical (CFD) and physical modelling of the upper and lower intakes that have been carried out during design studies highlighted the following points:

- In numerical modelling, the choice of an appropriate diffusion numerical scheme is of primary importance in order to correctly assess the flow pattern, and therefore the influence it may have on head losses characterization.

- Expressed as a proportion of the kinetic energy in the tunnel or low pressure culverts, the head losses through the water intakes have globally been estimated at between 10% and 25% during inflow mode, and around 45% during outflow mode;
- Identification (by both numerical and physical modelling) of irregular and non-homogeneous velocity fields through the trashrack plane is essential to identify any possible countermeasures required (through trashrack design, maintenance procedures ...) to ensure a safe and reliable operation of the scheme.
- Physical model remains an essential research tool for identifying in a first step unpredictable, irregular phenomenon (such as unsteady flow pattern) and for characterizing the formation of vortices in front of structures. In a second step, it also helps in the definition and testing of solutions to remedy such situation, or in the identification of design criteria, operation and maintenance rules adapted to the conditions identified.
- Finally, physical and numerical analysis allow to optimize the water intake design to achieve minimum operating head losses but also minimum submergence for different operating conditions which has a significant impact on the cost of water intake construction works and reservoir dead storage volumes.

3. STRUCTURAL DESIGN OF THE CONCRETE LINING

3.1. Geological and geomechanical context

The bedrock of the project is exclusively composed by Harzburgites and dunites, the latter having been rarely observed in the borehole cores.

Following several site visits before the commencement of the works and taking into account the geological and geotechnical tendering baseline, the general condition of the Harzburgite rock mass has been judged to be associated to favourable excavation conditions (surface cuts and underground excavations).

The main geological feature suspected to be associated with unfavourable tunnelling conditions is the fault-controlled-valley crossing the central section of the high pressure tunnel alignment (presenting a width of 15 m across the bottom of the valley surface) but as a result of the difficult access conditions it has not been possible to plan the execution of any borehole reaching the tunnel elevation. Thus, it has not been possible to assess the tunnelling conditions within the fault stretch at the tunnel depth beforehand.

As a consequence, and due to the lack of reliable deep investigations, the support and final lining design has accounted for a number of hypothetical fault situations of increasing difficulty by considering a wide range of low to very low Q-values (Q value$<$0.7).

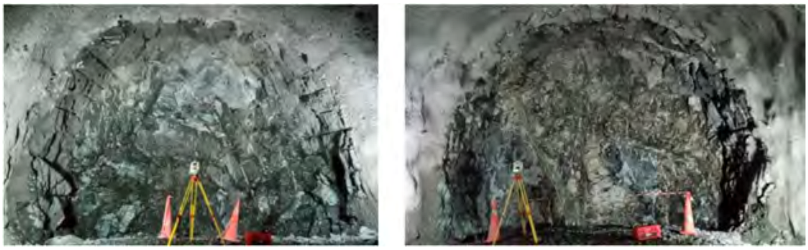

Fig. 11
High pressure tunnel face. Regular Harzburgite with Q-value range 15 to 24 (left) & central fault with Q-value range 0.5 to 6 (right)

3.2. Waterways overview

The underground waterways are approximately 1200 m long with a 9.5% slope. The maximal overburden reaches almost 250 m and the tunnel is concrete lined along 935 m, followed by a 265 m long steel liner in the downstream section in order to manage the hydrojacking risk. The high-pressure tunnel is excavated by drill & blast method.

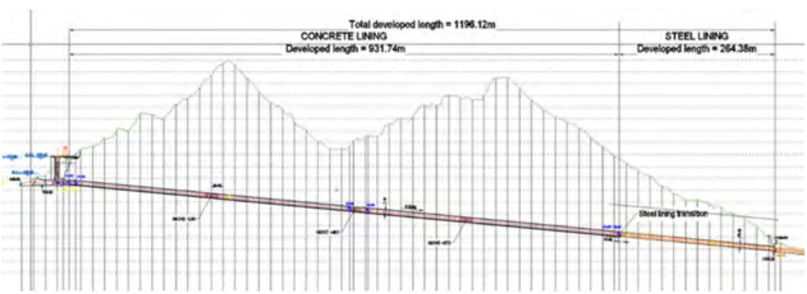

Fig. 12
High pressure tunnel longitudinal view

The typical cross-section of the concrete lining is near circular with an internal hydraulic diameter of 7.45 m and a concrete thickness of 35 cm on the upper half, slightly increasing on the lower half. The cross-section presents two particularities inducing significant modifications in terms of design:

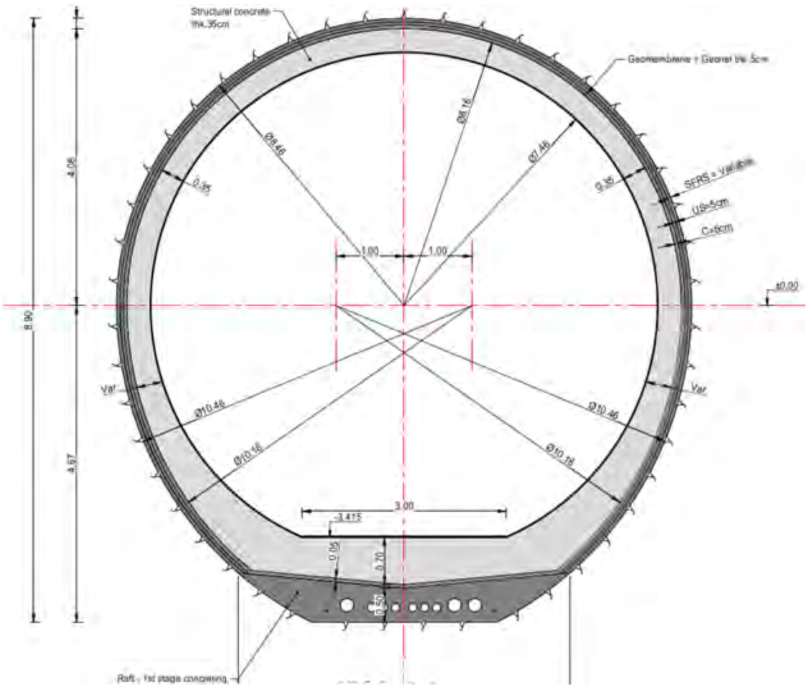

Fig. 13
HP tunnel concrete lining typical cross-section

- A primary near flat raft is implemented below the lining. Its purpose is to ease excavation works and to allow installation of power cables feeding the upper reservoir equipment,
- The lower part of the hydraulic section is flat on a 3 m width, as requested by the Contractor for constructional purposes.

3.3. Design philosophy

One of the main project specifications driving the design was that the concrete liner must include a waterproofing membrane allowing to warranty the seepage performance of less than 150 l/min for the entire tunnel length. Thus, in order to achieve watertightness performance, a VLDP geomembrane and a geogrid are placed between the shotcrete and the final lining.

Fig. 14
VLDP geomembrane lining installation at concrete/steel lining transition

This design concept offers several benefits for the hydraulic tunnel projects located in arid regions with limited natural water resources and high sediment yields.

- The geomembrane layer provides high watertightness performance;
- The concrete lining provides abrasion protection to the geomembrane, long term durability and structural stability for transient pressure hydraulic conditions.

At long term under nominal steady pressure, due to concrete joints, permeability and potential cracks, the same pressure will be applied at both faces (intrados and extrados) of the concrete lining which will thus be at mechanical equilibrium. This load case is not critical, providing the rock mass can withstand the pressure without excessive deformation.

On the contrary immediately after watering-up or during transient pressure phase, the counter-pressure on the extrados of the lining is not yet established and is either null or lower than the internal pressure. Consequently, the concrete lining will be submitted to tensile stresses and could crack.

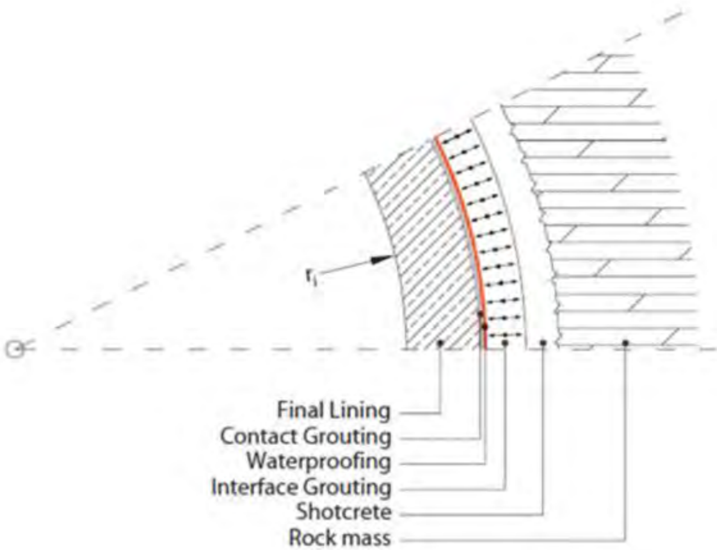

Fig. 15
Detail of final lining with interface grouting (extract from [2])

It shall also be taken into account that the waterways will be submitted to frequent and high transient pressure conditions, regarding to “conventional” waterways without fast generation/pumping mode switches. The maximum transient internal pressure can be up to 37% of the static internal pressure and this load case could be designing depending on the section studied.

Two risks are then identified with regards to the tensile force induced in the lining:

- A brittle failure of the lining leading to convey pieces of concrete through the waterways to the turbines / pumps causing damages. This risk can be managed by either providing minimal reinforcement to the lining or/and pre-stressing the concrete so that it will remains in compression under every loads combinations;
- Damaging the watertight membrane during transient phases due to pressure changes causing the membrane to be locally trapped in the cracks and ripped by differential displacements. A rule-of-thumb from return of experience is that the membrane is able to bridge a crack without damage if this crack is less than one-half the membrane thickness.

Both reinforcement only or pre-stressing only do not appear to be economically viable due to the high transient pressure, the particular non-circular shape of the lining and the local poor rock condition (as expected during design stage).

Therefore, it has been decided to combine both:

- Pre-stressing by grouting to withstand most of the static load combination;
- Reinforcement of the concrete lining to manage the transient load combination as well as providing additional safety with regards to the non-circular shape of the lining.

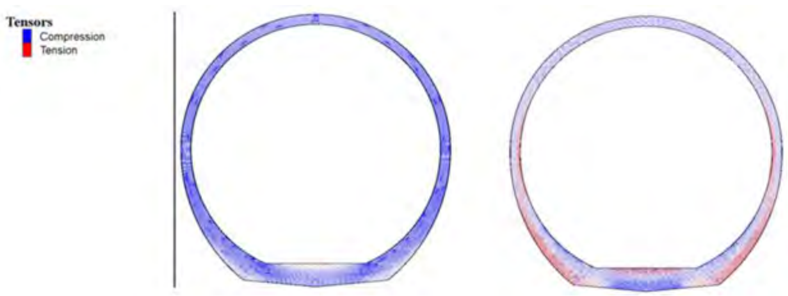

Fig. 16
Stress tensor distribution after pre-stressing by grouting (left) and for max internal pressure (right)

3.5. Analytical and numerical design

Comprehensive design studies have been necessary from Basic Design to Detailed Design and construction works, in order to adapt and optimize continuously the concrete lining design to the actual geological conditions, the construction materials and methods. Analytical and numerical methods and process used at Detailed Design stage are summarized as follow:

- In a first stage, the part of the internal pressure under operation that the concrete lining can withstand without cracking is defined using analytical methods. This analysis is carried out according to the mathematical theory developed by Seeber [1]. The design of the concrete thickness and the prestressing pressure includes provisions for losses of prestressing due to shrinkage, creeping and temperature change. Conservatively, a loss 40% of prestressing pressure is considered for shrinkage and creep.
- For economical purpose, the lining reinforcement is then designed to withstand the part of the internal pressure due to transient phases. This analysis is carried out according to a method derived from the ASCE waterways guide [3];

- The concrete lining is also checked with various analytic formula regarding grouting, end of construction and rapid dewatering conditions.
- In a second stage, numerical models are used to provide detailed analysis of the most critical sections and load conditions taking into account, the tunnel egg-shape and first stage raft, the concrete self-weight (slenderness effects) and the effect of both disturbed rock mass and undisturbed rock mass surrounding the lining.

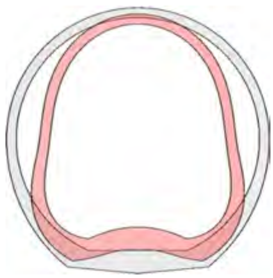

Fig. 17
Magnified displacement of the concrete lining (100 times) after 15 bars grouting

As expected, analytic and numerical methods show significant results differences on the lower part of the lining due to its non-circular shape and presence of embedded pipes in the invert. The main results are:

- The non-circular shape leads to bending moments on the lower half of the lining during prestressing. Thanks to the orthoradial compression, reinforcement is not required to withstand these bending moments;
- The shape of the lining tends to decrease the efficiency of the prestressing, with overall compressive stresses reduced from -7% on the top to -25% on the bottom of the lining, in comparison with a perfectly circular shape;
- Local compressive peak value are observed. As a consequence, the concrete compressive strength criterion is reached for a prestressing grouting pressure 12% lower than for a perfectly circular shape. This can be managed by increasing the compressive strength of the concrete and thus the amount of cement in the concrete mix. In such case, attention shall be paid to potential issues due to heat generation during concrete curing.

The three-dimensional modelling has allowed analysis of particular load cases such as non-homogeneous contact grouting, etc.

A dedicated model has also been carried out to analyze the influence of the concreting process. It has indeed been decided by the Contractor to cast the full section in one step, leading to high loads (4 x 32.5 tons) applied by the pads of the formworks to the crown of the previously casted concrete lining section.

The geogrid placed at the extrados of the watertight membrane aims to create a sufficient space to allow the grout to flow easily during the prestressing works. Consequently, when the formworks pads transmit load to the lining prior to any grouting operations, these loads cannot be transferred to the surrounding rock, and additional reinforcement of the lining has been consequently provided locally.

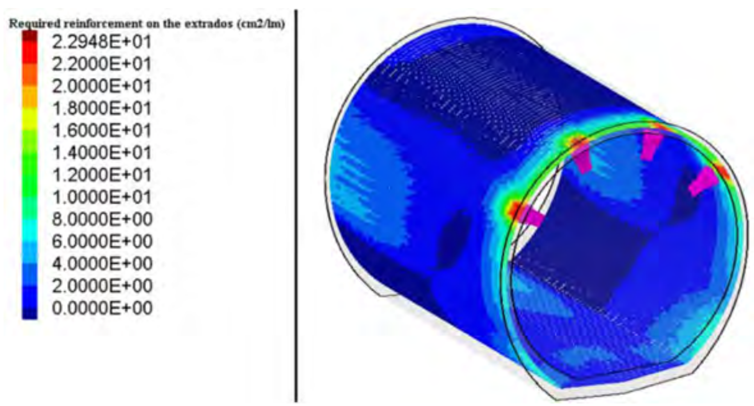

Fig. 18
Illustration of required additional circular reinforcement due to formworks load (pads area in pink arrays)

Finally, with consideration to better-than-expected rock quality observed during excavation and in order to ease the lining construction, design modification have been made to provide the same reinforcement all along the concrete lined waterways and only adjust the prestressing grouting pressure with the chainage.

The final chosen reinforcement is close to the minimum one, and prestressing pressure ranges from 3 to 15 bars.

3.6. Conclusion on structural design of the lining

With regards to very high transient loads, the specific geometry of the lining including a flat raft as required by the Contractor and the geotechnical condition as expected during design stage, the usual technical solution for the concrete lining considering reinforcement only or pre-stressing only do not appear to be economically viable to meet the severe leakage criterion of the project ($<$ 150 l/min for the entire tunnel length).

The solution of combining both prestressing for the static load cases and reinforcement to improve the structural strength during transient load case made it possible to avoid the need for steel lining (except where a hydrojacking risk has been identified).

The numerical model has highlighted the influence of non-circular shape, leading to bending moments on the lower half of the lining during prestressing and significant decrease of the efficiency of the prestressing: overall compressive stresses reduced from -7% on the top to -25% on the bottom of the lining, in comparison with a perfectly circular shape. This model also allows several modifications during the works to consider the actual rock condition, excavation size, grouting process, etc.

Furthermore, the numerical models have allowed to locally adapt the reinforcement of the lining to take into account the actual concreting process leading to high loads applied by the pads of the formworks to the crown of the previously casted concrete lining section.

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ADAPTATIONS TO THE DESIGN OF ABDELMOUMEN PUMPED-STORAGE SCHEME DURING THE CONSTRUCTION PHASE (*)

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SUMMARY

Located at 70 km from Agadir the Abdelmoumen Pumped Storage Power Plant (PSP) with an installed capacity of 350 MW is part of the infrastructure program of the “Office National de l’Electricité et de l’Eau potable” (ONEE) of Morocco. This project is in line with Morocco’s decarbonization strategy by providing green energy at very competitive costs to domestic and industrial customers. It will meet peak demand for electricity through energy storage, optimize operation of generation assets, provide flexibility in the operation of the national electricity system, increase renewable energy integration capacity, and improve the stability of the national transmission electricity grid. The commissioning of this project in 2024 will increase by 20% the installed hydropower capacity of the Country reinforcing that of the 460 MW Afourer PSP in operation since 2004.

The scheme is equipped with: an upper and a lower water storage basins with an active storage volume of 1 300 000 m^3 each; a water way of about 3 km long connecting the two basins and supplying the plant (2200 m aerial high-pressure penstock and 800 m underground galleries); a plant housing two reversible Francis units of 175 MW each; a 225 kV substation including 2-group arrivals and 4-line

**Adaptations de la conception de la STEP d’Abdelmoumen pendant la phase de construction.*

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departures and a pumping station supplying water from the existing reservoir of the nearby Abdelmoumen dam for first filling and compensation for evaporation. The average net head is 560 mWC in pumping mode and 540 mWC in turbine mode. The plant has been designed to be able to switch rapidly from pump mode to turbine mode, and to perform up to 20 start/stop cycles per day to meet the needs of the national grid. Closed-circuit operation reduces the impact of the plant on the environment and on water resources.

The main adaptations to the project during the construction phase were aimed at improving the reliability of the scheme and its flexibility of use:

- Implementation of individual servomotors for the turbine guide vanes, allowing for asynchronous guide vanes, which is useful for start-up in turbine mode and during load rejections;
- Supplying the pumping station for first filling and topping up by a floating station in the Abdelmoumen dam reservoir, particularly well suited to the wide drawdown range;
- Reinforcement of the anti-lift system of the upper basin geomembrane with concrete ballast weights and air extraction system behind the geomembrane, following an episode of strong wind;
- Reinforcement of the watertightness of the intake gate shaft, following the appearance of resurgence during the first filling of the upper basin.

RÉSUMÉ

Située à 70 km d'Agadir dans le sud du Maroc, la Station de Transfert d'Energie par Pompage (STEP) d'Abdelmoumen, avec une capacité installée de 350 MW, fait partie du programme de développement d'infrastructures de stockage d'énergie de l'Office National de l'Electricité et de l'Eau potable. L'aménagement s'intègre dans la stratégie de décarbonation de l'énergie mise en œuvre pour fournir de l'énergie verte à des prix très compétitifs. Il permet de satisfaire la demande en électricité en période de pointe, d'optimiser l'exploitation des unités de production, de fournir de la flexibilité au gestionnaire du système électrique national, d'augmenter la capacité d'énergie renouvelable et d'améliorer la stabilité du réseau électrique. La mise en service de la STEP d'Abdelmoumen en 2024 augmentera de 20% la capacité installée de production hydroélectrique au Maroc, renforçant celle de la STEP d'Afourer en exploitation depuis 2004.

La STEP est équipée de deux bassins, inférieur et supérieur, étanchés par géomembrane, d'une capacité de 1 300 000 m^3 chacun. Le chemin d'eau, de près de 3 km, comprend près de 2 200 m de conduite forcée aérienne et 800 m de galeries souterraines. L'usine est équipée de 2 groupes Francis réversibles de 175 MW. La hauteur de chute nette moyenne est de 560 mCE en mode pompage et de 540 mCE en mode turbine. La sous-station de 225 kV comprend l'arrivée des deux

groupes et quatre lignes de départ. Une station de pompage amène l'eau pour le premier remplissage et la compensation de l'évaporation à partir du réservoir existant du barrage d'Abdelmoumen. L'aménagement a été dimensionné de manière à pouvoir basculer rapidement d'un mode pompage à un mode turbinage, et à réaliser jusqu'à 20 cycles de démarrage/arrêt par jour pour satisfaire les besoins du réseau électrique national. Le fonctionnement en circuit fermé réduit l'impact de l'aménagement sur l'environnement et sur les ressources en eau.

Les principales adaptations du projet pendant la phase de construction visent à améliorer la fiabilité de l'aménagement et sa souplesse d'utilisation :

- Mise en œuvre de servomoteurs individuels pour les directrices des turbines autorisant une désynchronisation utile au fonctionnement en mode turbine au démarrage et lors des rejets de charge,
- Alimentation de la station de pompage pour le premier remplissage et l'appoint par une station flottante dans la retenue du barrage d'Abdelmoumen particulièrement adaptée aux marnages importants,
- Renforcement du dispositif anti-soulèvement de la géomembrane d'étanchéité du bassin supérieur par des lests en béton et un dispositif d'extraction d'air derrière la géomembrane, suite à un épisode de vent violent,
- Renforcement de l'étanchéité du puits de la chambre de la vanne de tête, suite à l'apparition de résurgences lors du premier remplissage du bassin supérieur.

1. INTRODUCTION

The Abdelmoumen Pumped Storage Power Plant is an ambitious energy project located around 70 km north-east of Agadir, in Taroudant Province, Morocco. With an installed capacity of 350 MW, it is part of the infrastructure program of the Office National de l'Électricité et de l'Eau Potable (ONEE). Its main objective is to strengthen smart electricity storage solutions to support the development of renewable energies. In particular, it will contribute to the decarbonization of the Moroccan energy sector. Its closed-circuit operation makes it independent of other uses of water resources and rainfall, currently largely insufficient in Morocco. At a total cost of around €285 million, the Abdelmoumen PSP will increase Morocco's installed hydropower capacity by 20% and supply green energy at competitive prices to domestic and industrial customers.

This article presents the main adaptations to the initial design during the construction phase that were instructed by TRACTEBEL Engineering as part of its technical assistance to the Owner ONEE for the supervision of the works.

2. PRESENTATION OF THE ABDELMOUMEN PSP

The Abdelmoumen PSP comprises an upper and a lower water storage basin with an active storage volume of 1 300 000 m^3 each, a waterway approximately 3 km long including a penstock connecting the two basins and supplying the plant which houses two reversible units of 175 MW each, a 225 kV substation comprising 2-group arrivals and 4-line departures, as well as a pumping station supplying water from the existing Abdelmoumen reservoir for first filling and compensation for evaporation (see Fig. 1). The works have been carried out by a joint venture led by VINCI Construction Grands Projets (France) involving ANDRITZ Hydro GmbH (Germany) and ANDRITZ Hydro GmbH (Austria).

Fig. 1
Schematic view of the Scheme (1: Access roads; 2: Upper Basin;3: Lower Basin; 4: Penstock; 5: Plant and Switchyard; 6: Valve Chamber Shaft; 7: Upper Tunnel, 8: Lower Tunnel; 9: Pumping Station 5km to the south-west)
Vue de l'aménagement

The average net head is 560 mWC in pumping mode and 540 mWC in turbine mode. During transient the maximum overpressure at spiral entrance remains below 900 mWC. The units are operated at a synchronous speed of 600 rpm and are designed for a maximum transient overspeed of 915 rpm.

As the PSP is designed to compensate for the variability and intermittence of wind farm production, the number of start and stop cycles either in pumping mode or in turbine mode over the course of a day can be as many as twenty according to the grid needs. What is more, the need to react quickly to a rapid decrease or increase in wind speed requires the ability to switch quickly from one mode to the other. To this end, the reversible pump turbines have been designed to operate in synchronous compensator mode[†] with a dewatered runner. Due to the high number of load cycles all mechanical components that are subjected to load variations have been verified by fatigue calculation in order to ensure a margin of safety over the expected lifetime of the installation. These include all the waterway components (penstock, main inlet valves, draft tube gate, spiral case, guide vanes, turbine covers...) as well as the components of the rotor.

The upper and lower storage basins are partially excavated and partially surrounded by a rockfill embankment, taking advantage of the topography of the site. The height of the embankments is 21 m, with a maximum height of embankment from lowest foundation of 33 m for the lower basin and 27 m for the upper basin. Watertightness is provided by a geomembrane installed on a support layer into which a system collecting and draining water has been incorporated. A monitoring system (flowmeters, piezometers in the rockfill and foundation, pore pressure cells at the bottom of the basin, etc.) alerts the operator in the event of a leak.

The high-pressure penstock is 2 575 m long, from the water intake in the upper basin to the spiral case. It comprises several sections from upstream to downstream:

- A 5 m diameter concreted tunnel approximately 295 m long housing the intake gate;
- An overhead steel section (steel grades S460, S500 and S690), manufactured on site in a dedicated workshop, approximately 2035 m long, 4.80 m to 3.60 m in diameter and 14 mm to 44 mm thick. The pipe is fixed to concrete blocks at the bends, which take up the pipe's thermal loads in the absence of expansion joints, and to sliding supports for the straight sections;
- A 3.6 m diameter concreted vertical shaft, approximately 60 m high, extended by a 3.6 m diameter concrete horizontal section ending in a 2.6 m diameter concrete bifurcation fitted with 1.6 m diameter converging pipe before the main inlet valves and the spiral cases.

The low-pressure penstock has a length of 440 m from the draft tubes of the turbines to the intake structure of the lower basin. From upstream to downstream, it comprises several sections:

- Two 3.6 m diameter concreted sections, ending in a bifurcation, immediately downstream of the draft tube gates;
- A 5 m diameter concreted tunnel, about 390 m long.

The intake gate installed in the intake gate shaft is a wheel gate with downstream sealing (height 4.3 m, width 3.4 m, 65 mWC) operated by a hydraulic servomotor installed above the upper basin level and fifteen suspension stems

[†] *The group operates as a motor (absorbing active power from the grid and supplying/ absorbing reactive power to the grid) and not as a generator (supplying active power to the grid).*

connecting the gate to the servomotor. The main function of this gate is to cut the flow in all conditions in the event of an incident on the penstock. A mechanical overspeed mechanical sensor installed on the penstock triggers the closure of the intake gate without recourse to the control system.

The main inlet valves located at the entrance to the spiral case, immediately upstream of the turbines, are spherical valves (diameter 1.6 m, 632 mWC); they are used to cut the flow in the event of an emergency in pump mode and in turbine mode (high-pressure valves) and to isolate the units for maintenance.

The draft tube gates (height 3.6 m, width 3.6 m, 85 mWC) are wheel gates with downstream sealing operated by a hydraulic servomotor (low-pressure gates) at the top of a hermetic cover. The main function of these gates is to protect the powerhouse from flooding from the lower basin and to dewater the turbines for maintenance operations. A flap gate in the gate chamber isolates these gates for maintenance.

3. MAIN ADAPTATIONS TO DESIGN DURING CONSTRUCTION PHASE

3.1. Asynchronous guide vanes for the turbines

The power station is equipped with two reversible synchronous Francis generators, each with a capacity of 175 MW. The supplier of the machines and the main electromechanical equipment is Andritz Hydro. The plant is designed to produce an average annual energy output of 632 GWh in turbine mode and to consume 796 GWh in pump mode at an average head of 550 m. The machines are designed to operate for 20 years without major refurbishment, with an average of 20 mode changes per unit per day, depending on the demands of the Moroccan electrical grid.

Because of the head and the power of the units, the chosen synchronising speed is 600 rpm. This results in machines of relatively modest dimensions in relation to the power of the machines, with a stator bore diameter of 3 950 mm. The shaft line layout is a 3-bearing machine with a combined thrust bearing located on the upper spider.

Given the high level of availability required for the equipment, dismantling the runner through the rotor was ruled out. The chosen arrangement is to have the runner dismantled from the middle by means of a removable turbine-generator transition shaft and handling equipment enabling the runner to be brought to an area served by the plant’s overhead crane. The Contractor did not see fit to propose a different organisation with dismantling of the runner from below, even though this was a little more common.

At the suggestion of the supplier, the turbine distributor was designed with a servomotor for each of the 24 guide vanes. The more conventional solution, with an operating ring and two control servomotors described in the specifications, was not chosen despite its advantages:

- Less control equipment, so less risk of failure, and therefore more robust;
- A much smaller number of oil pipes, with fewer connections;
- Faster commissioning, as only two servomotors need to be installed and calibrated.

The solution implemented with individual servomotors offers greater flexibility to adapt to the operating conditions of the scheme, which was also beneficial during commissioning. There is no decisive advantage in terms of cost between a solution with an operating ring and a solution with a servomotor for each of the 24 guide vanes.

The efficiency hill chart in transient condition has the usual characteristics of a high-head pump-turbine, with instability of the runaway[‡] curve. Sometimes it is necessary to use devices such as desynchronised guide vanes to enable stable operation of the unit at synchronous speed, before it is connected to the grid.

The desynchronization was not considered necessary at the beginning of the project, particularly after acceptance of the model tests. Commissioning tests have indeed shown that the machine can operate with synchronized guide vanes as it would be with an operating ring. However, various tests were carried out with two or four unsynchronized guide vanes and different opening values, four of the control blocks being specific and allowing individual control of the asynchronous guide vanes evenly distributed around the distributor. The desynchronization tests were motivated by the need to be able to bring the units back to speed-no-load operating conditions after a load rejection[§] (in turbine mode with flow control devices closed) without having to shut down the units. This is quite usual for conventional Francis turbines but rarer on high-head reversible Francis turbines, especially since the transient regimes with long aerial penstock (2035 m) are demanding for the resistance of this penstock.

The results of the desynchronization tests were conclusive. An overspeed threshold set slightly above the nominal speed is directly related to the asynchronous guide vanes. During a load rejection, the detection of this threshold causes the asynchronous guide vanes to open more than the synchronous guides so as to reduce the important radial forces and modify the instability zone where the turbine-pump is located, the behaviour is thus closer to that of a conventional Francis turbine (see Fig. 2).

[‡] *Zero torque curve of the hill chart.*
[§] *Sudden removal of resisting torque (removal of the resisting torque induced by the generator following a power outage or failure of the electrical grid).*

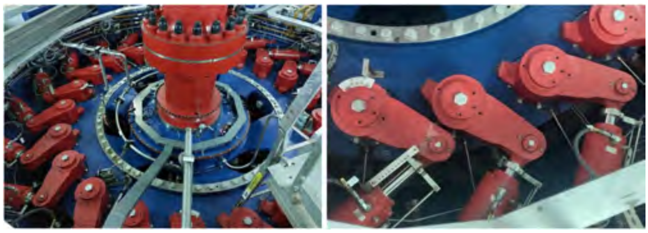

Fig. 2
Distributor and independent actuators (left) – Asynchronous opening of a guide vane after a load rejection (right)
Distributeur et servomoteurs indépendants (gauche) – Ouverture d'une directrice asynchrone après un rejet de charge (droite)

The desynchronization of the guide vanes is also important at the time of turbine mode start-up. Without having the resistive electric torque, the turbine-pump enters its runaway speed instability zone just before the connection to the grid («S» zone in Fig. 3).

For a fixed opening of the guide vanes, the speed will tend to vary, and the desynchronization of the guide vanes allows to modify the instability zone thus allowing for the precise adjustment of the nominal speed and the safe coupling to the network. The tests also allowed to optimize the stability and vibration level for the start in turbine mode which is beneficial for the long-term operation of the units.

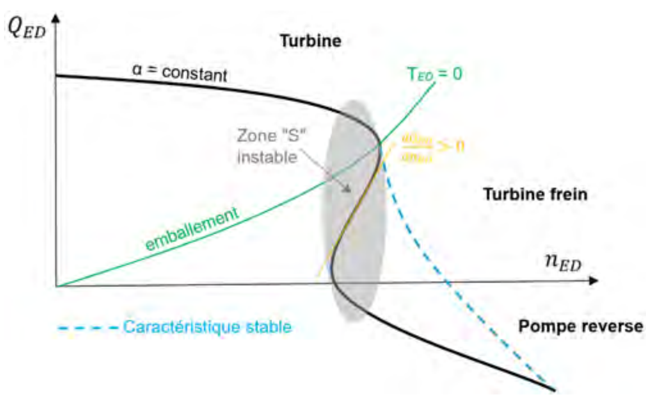

Fig. 3
Turbine-quadrant of a turbine-pump four-quadrant zones of operation diagram – Characteristics of S-zone
Quadrant turbine du diagramme des modes de fonctionnement d'une turbine-pompe – Caractéristique de la zone « S »

3.2. Control system

The responsibility for engineering, procurement, installation, testing and commissioning of the control system was assigned to Andritz Hydro, which supplied its 250 SCALA SCADA product and SICAM for automation cells. The system performs data acquisition, monitoring and control of the excitation system, the turbine speed governor and the electrical and mechanical auxiliaries of each of the two reversible units and all installed electrical and mechanical equipment, including the high-voltage substation and the upper and lower reservoirs; it is also used for data exchange with the remote supervision and control center(s) (dispatching).

Without being an adaptation during the construction phase in the strict sense, research into availability and optimization of response time was strongly present in the various development phases of the Abdelmoumen PSPP control system in terms of equipment, operation and programming in order to provide ONEE teams with a high-performance working tool.

The equipment used to build the control system architecture proved to be particularly interesting in terms of standardization. From the Programmable Logic Controllers (PLC) through the speed regulator and up to the communication gateway, ONEE's operations and maintenance teams have a small number of automation products, all from the same product range (SICAM). This is also true for the excitation system and the electrical protection relays where the HIPASE range from Andritz Hydro is deployed.

During the first operating tests of the reversible units, the human-machine interface made available on the supervision system proved to be particularly user-friendly, with in particular a resolution capacity for the display of analog quantities rarely encountered before. Without completely eliminating the interest of an oscilloscope**, the installed system demonstrated its effectiveness in the assistance it can provide in the event that a first rapid analysis of faults is necessary.

The programming of the PLCs for the start and stop sequences of the reversible units of the PSPP was carried out in such a way that the sequence times were minimized. An early start of each auxiliary of the unit and an optimized paralleling of the actions during the sequences are the two main factors which made it possible to best respond to this need for maximum reactivity for the power plant.

** *A device recording disturbances on an electrical connection for a posteriori analysis (trouble recorder oscillograph).*

3.3. Floating pumping station for first filling and evaporation compensation

The contract for the construction of the Abdelmoumen PSP included a pumping station for the initial filling of the lower basin of the PSP and for the compensation of the evaporation losses. This pumping station, located close to the existing Abdelmoumen reservoir below, consisted of an underground pumping station (see Figure 4).

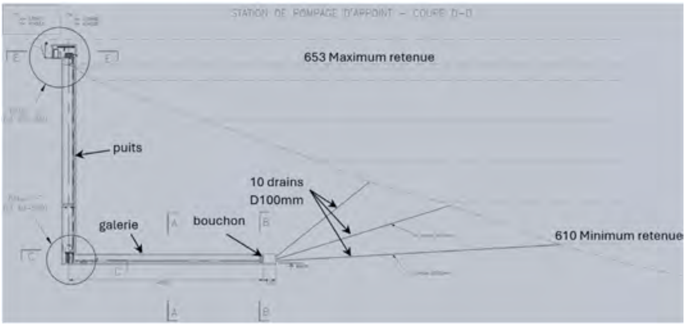

Fig. 4
Original layout of pumping station (vertical cross-section)
Conception d’origine de la station de pompage (vue en coupe)

Evaporation losses from the surface of the two basins (upper and lower) were estimated at 31 000 m^3 per month for the hottest months taking into account a cumulative average surface area of both basins (whose surface areas vary due to water level fluctuations) of around 90 000 m^2. These losses need to be compensated as regularly as possible, not only to maintain the active storage volume of the basins, but also to avoid any increase in salt concentration in the turbined water. This compensation can be achieved using a single 30 l/s pump. However, in order to fill the lower basin (1,300,000 m^3) for the first time without impacting on the overall schedule, it was necessary to increase the number of pumps so that the first filling operation could be carried out in masked time outside the critical path. As the construction schedules showed a margin of around 125 days for this first filling activity, four 30 l/s pumps delivering a total flow rate of 120 l/s were therefore provided.

The original design was an underground structure pumping station fed by water filtered through the surrounding rock in order to avoid heavy siltation concentration in the water after heavy rainfalls. The pumping station initially provided for in the Contract consisted of:

- A 48 m deep vertical shaft;
- A 48 m long horizontal gallery to get closer to the water table fed by the Abdelmoumen reservoir;

- A chamber collecting the drainage water at the end of the gallery, separated from it by a watertight plug;
- Three series of drains radiating into the water table;
- A 500 mm diameter pipe between the chamber and the wellhead (thus passing through the watertight plug), extended by a 400 mm diameter underground carbon steel pipe to the lower basin, around 5 km away.

Borehole pumping tests carried out by the Contractor at the beginning of the construction showed that it was not possible to supply the flow rate needed for the first filling of the lower basin by pumping groundwater. From the tests a flow rate of around 75 l/s (60% of the specified flow rate) could be expected, which would have significantly delayed the first filling schedule by at least two months. The number of drains could have been increased, but a second chamber at a distance from the first would have been needed, at a cost deemed too high. All parties then agreed to modify the concept of the pumping station. Alternative studies led to select a floating pumping station on the reservoir of the existing Abdelmoumen dam. An instruction to modify the installations was issued by the Owner.

The new pumping station consists of a floating intake (fitted with low-pressure pumps) moored and connected to the shore by a flexible link into which the discharge pipe and the electrical and control cables are incorporated (see Fig. 5). A second pumping station with booster pumps and flow-control valves is installed on the bank to lift the water approximately 100 meters upper into the lower basin.

Designing the mooring of the platform is very tricky, as it should withstand current speeds of around 1.5 m/s when the spillway of Abdelmoumen dam is in operation as well as reservoir level fluctuations of 60 meters.

Fig. 5
Views of the Pumping Station after completion
Vues de la station de pompage réalisée

The discharge pipe linking the pumping station described above and the lower basin, with a length of around 4 300 ml, was initially specified in the Contract documents as being made of carbon steel. In accordance with the Contractual Clauses, the Company applied for a deviation in the material used for the discharge pipe, proposing High Density Polyethylene (HDPE) instead of carbon steel. It was demonstrated that this change would have no impact on contractual Completion Date, the final quality of the Installations, system performance guarantees or the durability of the Installations. The Company justified the feasibility of its proposal, which was judged to be fully technically acceptable, as HDPE pipes have been successfully used in water supply systems for several decades. HDPE offers many advantages over steel. The flexibility of HDPE pipes enables them to absorb long bends in the pipe route, thus limiting the number of bends (see Fig. 6).

Fig. 6
PEHD Discharge Pipe during installation
Pose de la conduite de refoulement en PEHD

Moreover, unlike steel pipes, cathodic corrosion protection is not required. In addition to these technical advantages, which were of prime importance in the decision-making process, the proposal also offered savings of around 0.3% on the contract price, as well as positive spin-offs for the Moroccan economy, as HDPE pipe production units are based in Morocco, as opposed to carbon steel pipes. The difference in cost between the supply and laying of a steel pipe and an HDPE pipe is due to the lower cost of the raw material, and the greater ease with which HDPE pipes can be laid.

3.4. Ant-lift system for the upper basin geomembrane

The basins are made watertight with a 3mm-thick PVC-P (plasticized polyvinyl chloride) membrane protected by a 500 g/m^2 anti-perforation polypropylene geotextile. The membrane is anchored in a trench at the top and bottom of the slope. A special system for anchoring the geomembrane in the embankments has been designed using strips of geomembrane (210 cm x 21 cm) anchored at each meter of height to a depth of 1.50 m in the support layer as the works progress, called straps. These straps are welded to anchoring lines (vertical geomembrane strips 42 cm wide) which run the full length of the slope and are placed around the basin every 8 meters. The geomembrane panel covering the slope is welded to the anchoring line, and over its whole length, so as to be anchored in the embankment, and then welded to the adjacent panel to ensure continuity of the watertight liner (see Fig. 7).

Fig. 7
Geomembrane anchoring straps and anchored panels on slope (left) Anchoring line welded to the straps (right)
Lanières d'ancrage en talus et lés de géomembrane ancrés (gauche) Ligne d'ancrage soudée sur les lanières (droite)

The support layer also provides drainage under the watertight membrane. Leaks are collected by a drainage system consisting of trenches at the foot of the slope and a network of trenches and collection pipes at the bottom of the basin. The flows collected in this way are conveyed to the basin intake to be evacuated by pipe to their outlet. The leakage outlets are located at the point where the underground waterway passes overhead (upper basin) or crosses a wadi (lower basin), 250 to 300 m downstream of the intakes and 40 to 50 m below, and are equipped with a weir and a flowmeter for monitoring leakage flow rate. Two additional outlets have been built at the (downstream) toe of the upper basin embankments.

During a high-speed wind event on the upper basin in February 2023, before commissioning and when the basin was empty, the membrane lifted at the top of the west embankment and then fell back into place. Following this event, deformations of the geomembrane were observed near the anchoring lines. Close examination after the membrane had been cut in two places showed that the highest straps had slipped and that some of these straps had been torn in the upper part of the embankment in the area where the membrane had been lifted. The welds between the straps and the anchoring lines, between the anchoring lines and the panels and between the panels were otherwise intact. As a protective measure, the membrane was weighted down with sandbags attached to ropes anchored to the top of the embankment.

The wind speed measured on a platform halfway between the upper and lower basins during the event reached a value of 14 m/s. A calculation of the speed required to tear the anchoring straps resulted in a value of around twice that for the upper basin, which is higher than the value taken into account for the design of the straps, of around 16 m/s, on the basis of satellite readings and a multiplying factor for wind gusts. An anti-lift system for the upper basin membrane using prefabricated concrete blocks linked together by steel cables anchored at the top of the slope was therefore designed taking into account a revised wind speed value, higher than the estimated value for the February 2023 episode and based on the Moroccan standard NV65. The system was designed to withstand uplift and tilting, and the resistance to tearing (geomembrane) and to traction (welds) was checked. Given the lower wind speeds in the lower basin, implementing such system in this basin was not deemed necessary.

Lines of concrete blocks (1.40 m x 1.40 m x 0.30 m) spaced 15 cm apart and connected by cables were installed where the geomembrane had been lifted, between anchoring lines every 8 meters (see Fig. 8). The geomembrane on the slope was protected at the ballast lines by strips of geomembrane, with the anti-puncture geotextile bonded to the PVC-P geomembrane placed on the side of the blocks to improve friction between the blocks and the geomembrane. The cables are anchored at the top of the slope in a concrete beam bonded to the trench at the crest.

Fig. 8
Temporary ballast on the geomembrane (sandbags), permanent ballast made of concrete blocks anchored on top of slope
Lestage provisoire de la membrane d’étanchéité par sacs de sable, installation du lestage définitif par blocs de béton ancré en tête de talus

In addition to the anti-lift system described above, cylindrical tubes are distributed around the crest of the embankments to provide a connection through the geomembrane between the outside air and the air trapped in the drainage layer on which the geomembrane is installed (see Fig. 9).

Fig. 9
Pipe of an air vent (left) Test of the air vents (right)
Tube cylindrique d'un évent (gauche) Test des évents (droite)

Judiciously placed at the top of the slopes of the basins where the winds are at their strongest, the low pressures generated by these winds allow some of the air to be extracted from beneath the watertight geomembrane through these cylindrical tubes. A negative pressure is then created, partially balancing the uplift forces due to the low pressure generated by these same winds on the directly exposed face of the geomembrane. This air extraction system needs to be carefully designed to ensure that it will generate sufficient suction force without damaging the geomembrane, in addition to the anchorages provided. To this end, prior to the installation of these vents, a survey was carried out on a few typical vents (measurement of wind speed and associated pressures at various points above and below the geomembrane) in order to prove their effectiveness. This principle of stabilizing geomembranes has been widely developed since the early 1980s.

3.5. Reinforcement of the watertightness of the intake gate shaft

Filling of the upper basin started in February 2023. A few weeks later, an unusual resurgence of a few liters per second appeared in the mountain massif more than 1.5 km from the upper basin. The filling operation was immediately stopped, and the water level readings confirmed an abnormal lowering of the reservoir by around 42 mm per day, leading to a loss of water well in excess of the 7 mm/day estimated evaporation. The leakage rate was estimated at around 17.5 l/s.

Water conductivity measurements from both the basin and the resurgence concluded that there was a single origin. The watertightness of the upper basin was therefore called into question, but the total absence of flow in the water collection system beneath the watertightness and the absence of any rise in pressure measurements beneath the geomembrane led the Company to look for an origin of the leak other than a defect in the geomembrane.

As the underground waterway between the upper basin intake and the overhead penstock is fully lined with steel, attention was focused on the intake gate chamber shaft, whose water level is the same as that of the upper basin (except for head losses). This shaft, accessible from the crest of the upper basin, is used to operate and maintain the intake gate (see Fig. 10).

Hydrophones were lowered into the well to detect the sound of any flowing water, which was the case in the lower part of the well. Fluorescein was injected into the well and has been found 5 days later in the resurgent water (see Fig. 11). A subsequent underwater video inspection revealed the presence of a vertical crack in the concrete of the shaft over a height of 3 meters, with an opening of several

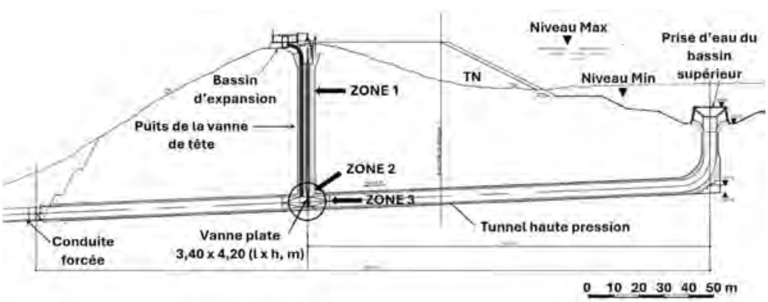

Fig. 10
Upper Basin, Intake Structure, Intake Gate Shaft and High-Pressure Tunnel
(Vertical Cross Section)
Bassin supérieur, prise d'eau, puits de la vanne de tête et tunnel haute pression
(vue en coupe)

millimeters at the exact location revealed by the hydrophones. A flow rate was estimated during the underwater inspection, confirming the origin of the leak and its location in the shaft (see Fig. 11). Several peripheral boreholes drilled into the rock surrounding the well did not reveal any surrounding pressure, as the rock is sufficiently permeable to instantly evacuate leakage flows via a network of cracks to the resurgence site.

Fig. 11
Fluoresceine injected in the Intake Gate Shaft (left) Leakage Flow Rate monitored during underwater survey (right)
Injection de fluorescéine dans le puits de la chambre de la vanne de tête (gauche) Débit de fuite mesuré lors de l'inspection subaquatique (droite)

The intake gate shaft is 66 m high. A layer of shotcrete was placed on the rock surface in the excavation, over which a product (MasterSeal 345 type) specially designed to seal concrete structures was sprayed. The shaft is divided into three zones, from top to bottom (see Fig. 10): **Zone 1** below the upper chamber (levels 1314 to 1260), made of rectangular precast elements providing an opening with internal dimensions of 5 m x 1.4 m, stacked, grouted and surrounded by concrete fill; **Zone 2** (levels 1260 to 1253), corresponding to the widening zone for the valve, made of internally-formed concrete fill; and **Zone 3** at the bottom, corresponding to the gate casing surrounded by concrete fill.

Following the complete drawdown of the upper basin (and therefore the intake gate shaft), an exhaustive survey of all cracks was carried out during a detailed visual inspection of the shaft's inner facings. These cracks are all located in zone 2 of the access shaft. Eight cracks were reported at the most fragile inertia sections (see Fig. 12).

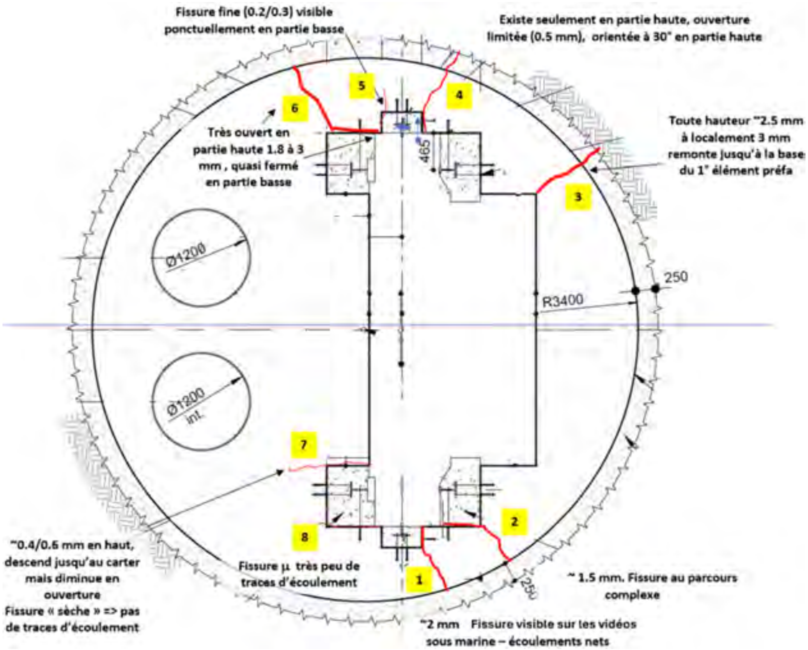

Fig. 12
Intake Gate Shaft - Cracks Survey on Bottom of Area 2 (horizontal cross section)
Puits de la vanne de tête - Relevé des fissures en partie basse de la zone 2 (coupe horizontale)

Unlike the upper part of the shaft (zone 1), zone 2 is only made of shotcrete. Numerical modeling confirmed the development of cracks with openings greater than the crack-bridging capacity of the watertight material applied to the shotcrete. A reinforcement mesh would have distributed the cracks more evenly, rather than concentrating them at weak points in the concrete. To repair the cracks, a PVC-P watertight geomembrane identical to that used for the upper basin was installed, fastened by stainless steel plates tightened by flat-head anchor bolts made of the same material (see Fig. 13). Calculations of the geomembrane's resistance to crack opening and to positive and negative pressures validated this type of repair.

Filling operations in the upper basin have resumed without reactivating the resurgence that had dried up following the drawdown. Water level monitoring in the upper basin shows no leak more than a year after the repairs were carried out.

Fig. 13
Repair of cracked areas
Réparation des zones fissurées

4. CONCLUSION AND PERSPECTIVES

The Abdelmoumen Pumped Storage Power Plant in Morocco will enable to generate electricity during peaks in consumption, store electricity produced by variable and intermittent renewable sources and improve the stability of the electricity grid, while preserving water resources, which are becoming increasingly scarce in Morocco as a result of climate change, due to its closed-circuit operation.

The main adaptations to the Abdelmoumen PSP during the construction phase, aimed at improving the reliability of the scheme and its flexibility of use, concerned the following points:

- Replacing the two servomotors controlling the turbine guide vanes provided for in the project with individual servomotors to desynchronize the guide vanes and optimize operation in turbine mode at start-up and during load rejection;
- Feeding the pumping station for the first filling and topping up by a floating station in the Abdelmoumen dam reservoir rather than by a well and a gallery with drains as planned in the project;

- Reinforcement of the anti-lift system of the upper basin geomembrane, made necessary by an episode of strong wind that lifted the geomembrane, with concrete ballast weights and additional air intakes at the crest to evacuate the air pressures likely to develop behind the membrane;
- Reinforcement of the watertightness of the intake gate shaft, following the occurrence of a resurgence during the initial filling of the upper basin.

The commissioning of the scheme in 2024 will increase Morocco's installed hydropower production capacity by 20%, thus bolstering that of the Afourer PSP, which has been in operation since 2004.

COMMISSION INTERNATIONALE DES
GRANDS BARRAGES

VINGT-HUITIEME CONGRES DES
GRANDS BARRAGES
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LE CANAL SEINE-NORD EUROPE, PROJET HYDRAULIQUE MAJEUR EN FRANCE (*)

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SUMMARY

The Seine-Nord-Europe Canal is a major waterway project in France, on which work began in 2023. The canal will link the Seine basin with the canals of Northern Europe and will be accessible to wide-gauge vessels.

The project, which is over 100 km long, comprises a series of reaches, which are filled by pumping water from the River Oise. It is essential to save water in order to limit withdrawals. This involves recycling lock volumes, waterproofing to limit percolation, and monitoring to detect leaks.

In addition, the canal reaches are surrounded by a series of dams, several of which are large enough to be classified in category A, the highest category under French

**The Canal Seine-Nord Europe, a major hydraulic project in France*

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regulations. These dams are subject to specific threats, such as potential navigation accidents, or accidental situations that could be provoked by the locks' operation.

The purpose of the presentation is to outline the project, present the water-saving issues associated with pumped filling and the measures adopted to achieve the desired performance, and present the hydraulic safety issues specific to this project.

RÉSUMÉ

Le Canal Seine Nord Europe est un grand projet de voie navigable en France, dont les travaux ont commencé en 2023. Ce canal reliera le bassin de la Seine et le bassin des canaux du Nord de l'Europe, et pourra être emprunté par des bateaux à grand gabarit.

Ce projet, dont la longueur dépasse 100 km, comporte une série de biefs, qui sont remplis par pompage depuis la rivière Oise. Il est nécessaire d'économiser l'eau de sorte à limiter les prélèvements. Cela passe par des dispositifs de recyclage des volumes d'eau éclusés, par des dispositions d'étanchéité destinées à limiter les percolations, et par des moyens de surveillance pour détecter les fuites.

Par ailleurs, les biefs sont ceinturés par une série de barrages, dont plusieurs sont suffisamment importants pour être classés en catégorie A, la plus élevée dans la réglementation française. Ces barrages subissent des sollicitations particulières, par exemple les sollicitations de navigation ou les éventuelles situations accidentelles que les écluses pourraient provoquer.

La présentation a pour objets la présentation du projet, la présentation des enjeux d'économie d'eau en lien avec le remplissage par pompage et les dispositions retenues pour atteindre les performances recherchées, et la présentation des enjeux de sécurité hydraulique spécifiques à ce type d'ouvrage.

1. LE CANAL SEINE-NORD EUROPE

Le canal Seine Nord Europe est le maillon central de la liaison fluviale Seine-Escaut, soit un réseau de 1100 kilomètres de voies fluviales à grand gabarit (pouvant accueillir des convois de 180 m de long sur 11.40 de large et de capacité de cale pouvant atteindre 4400 tonnes), desservant les grands ports du Nord-Ouest de l'Europe. La liaison Seine-Escaut est développée dans le cadre d'un partenariat entre les Voies Navigables de France (VNF), de Vlaamse Waterweg, le service public de Wallonie et la Société du Canal Seine Nord Europe (SCSNE).

Le coût du projet au stade des études d'avant-projet sommaire est évalué à 4,5 milliards d'Euros (base 2016) hors taxes. La mise en service est prévue en 2030 environ (source : Dossier d'Autorisation Environnementale, [3]).

Fig. 1

Le Canal Seine-Nord Europe, maillon central de la liaison Seine-Escaut

The Canal Seine-Nord Europe, central portion of the Seine-Escaut link

Les objectifs sont :

- de relier le réseau fluvial français au réseau nord européen à grand gabarit,
- de développer le transport fluvial, mode de transport écologique bas carbone,
- de renforcer la compétitivité des entreprises du territoire,
- d'améliorer l'attractivité des régions desservies pour de nouvelles implantations industrielles et logistiques,
- d'augmenter le potentiel des ports maritimes par de nouveaux débouchés de navigation.

La convention de financement du canal Seine-Nord Europe a été signée le 22 novembre 2019. Les partenaires financiers sont l'Union Européenne, l'Etat Français, les Régions des Hauts de France et de l'Ile de France, les Départements du Nord, du Pas de Calais, de la Somme et de l'Oise.

Le maitre d'ouvrage est la Société du Canal Seine Nord Europe créée en 2017 et transformée en Etablissement public local le 1 avril 2020.

Le projet du Canal Seine Nord Europe (CSNE), le plus grand projet européen actuel de transport fluvial, consiste en la création d'un canal de 107 km de long entre Compiègne et Aubencheul-au-Bac au nord de Cambrai (France). Quatre ports intérieurs seront développés le long de ce canal de manière à assurer la desserte des territoires.

Le canal franchira les 107 km séparant Compiègne du canal Dunkerque-Escaut par une série de 7 biefs, séparés par 6 écluses. Hormis le bief de raccordement sur la Sensée (long de 1 km), le bief le plus court est de 6,7 km (entre Marquion et Oisy-le-Verger), et le plus long de 40 km environ (entre Catigny et Allaines) – voir Figure 2. La plus haute écluse est de 25 m, la moins élevée de 6,4 m. Le canal Seine-Nord Europe joint directement l'Oise et la Sensée en franchissant la Somme par un pont-canal d'environ 1 300 m de longueur. Deux autres ponts-canaux franchissent les autoroutes A 26 et A 29.

Fig. 2
Tracé du canal Seine-Nord Europe entre Compiègne et Aubencheul-au-Bac et ses principaux ouvrages
Canal Seine-Nord Europe route between Compiègne and Aubencheul-au-Bac and its main components

Le «rectangle» de navigation à assurer pour permettre une circulation des plus grands bateaux est une section de 38 m de largeur sur 4 m de profondeur. La section du canal est donc généralement un trapèze d'une largeur au miroir de 54 m avec une profondeur de 4,50 m et des pentes à 2/1. Afin de limiter les pertes par infiltration, le canal est rendu étanche sur toute sa longueur. Le dispositif d'étanchéité doit permettre de limiter les pertes par infiltration à 0,62 m3/s sur l'ensemble du canal, qui est un critère particulièrement exigeant.

L'alimentation en eau du canal est assurée par un prélèvement dans l'Oise. Ce prélèvement est interrompu en période de basses eaux. L'alimentation est alors effectuée par l'intermédiaire d'un réservoir de 14 millions de mètres cubes connecté au bief de partage, le barrage-réservoir de Louette.

Les sas des écluses ont une longueur utile de 195 m, une largeur de 12.5 m et une profondeur de 5 m. Ces écluses comportent des portes levantes, à l'exception de l'écluse de petite chute dont les portes sont busquées. Les écluses de grande chute comportent des bassins d'épargne, structures étagées connectées au sas et qui récupèrent une grande partie de l'eau du sas lors de sa vidange. Le temps de remplissage ou de vidange des écluses est un objectif de performance fondamental pour assurer la capacité de la liaison. Il a été fixé à moins de 15 minutes. Le canal permet d'écouler un trafic jusque 18 à 19 millions de tonnes avec un temps de parcours moyen de 17 heures (la capacité de la liaison actuelle assurée par le canal du Nord est de 5 millions de tonnes avec un temps de parcours de 30 heures environ, soit près de deux jours en tenant compte de l'arrêt de nuit).

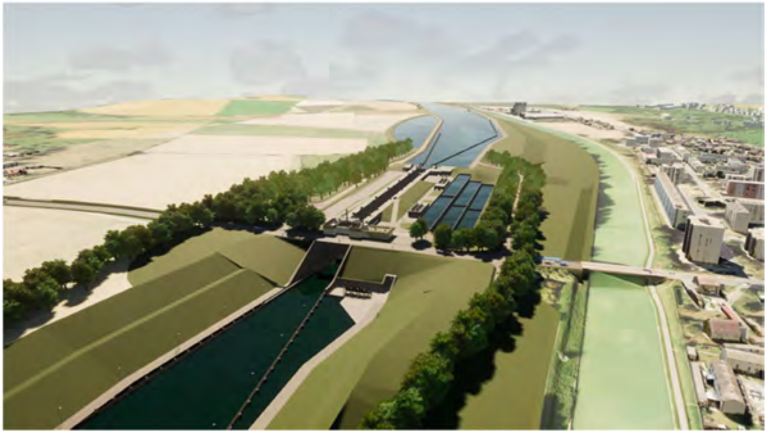

Fig. 3
L'écluse de Noyon avec les bassins d'épargne © ONE 5
the Noyon lock, with its saving basins © ONE 5

Le Canal Seine-Nord Europe a été conçu pour limiter les impacts sur la biodiversité dans le cadre d'une démarche désormais classique « Eviter, Réduire, Compenser» - principe E.R.C. Le canal donne de plus l'opportunité de réaliser des berges lagunées et des annexes hydrauliques permettant le développement de différentes espèces faunistiques et floristiques.

Au regard de la réglementation française sur les barrages et les ouvrages hydrauliques, les biefs du canal sont assimilés à des barrages (latéraux) ou à des ensembles de barrages. Le canal rassemble ainsi 14 barrages dont 5 barrages de classe A (la classe la plus élevée dans la réglementation française). La conception du canal doit suivre la réglementation issue de l'arrêté technique barrage de 2018 ([6]) et s'appuyer sur les recommandations du CFBR ([4], [5]).

Dans le cadre de la valorisation des terres excavées constituées en grande partie de limon et de craie, des programmes de recherche ont été conduits notamment pour utiliser les limons derrière les bajoyers de l'écluse de Marquion-Bourlon avec un traitement chaux et liants. En outre un modèle réduit a été réalisé de manière à pouvoir vérifier les conditions de mise en œuvre des matériaux derrière les bajoyers.

2. LES ENJEUX D'ÉCONOMIE D'EAU ET LA GESTION HYDRAULIQUE

2.1. Présentation generale

Un des enjeux majeurs du projet est la gestion de l'eau. Pour des raisons environnementales, le CSNE a été conçu pour limiter au strict nécessaire les besoins d'alimentation en eau.

Le Canal Seine-Nord Europe (CSNE) est constitué d'une série de biefs, assimilables à des retenues de barrage, dont le volume cumulé atteint 21,5 hm^3. La navigation «consomme» une partie de l'eau stockée dans les biefs, à chaque éclusée, et cette consommation est entièrement compensée par un pompage à chaque écluse, de la manière suivante:

- Des bassins d'épargne accolés à chacune des écluses permettent de limiter cette consommation. Le nombre de bassins varie de 2 (pour les écluses de chute 13 m) à 4 (pour les écluses de chute 25 m), ce qui permet un taux de recyclage de l'eau de 50% à 67%.
- Il subsiste un besoin de compensation des volumes non épargnés, qui est satisfait par une station de pompage accolée à chacune des écluses. Les débits d'équipement de ces stations de pompage sont échelonnés de 8,1 à 13,3 m^3/s selon les écluses.

L'épargne et le recyclage compensent intégralement les besoins générés par la navigation. Ils ne permettent pas de compenser les pertes par infiltration et évaporation. Les besoins en eau du canal pour compenser ces pertes ont été estimés à 1,2 m^3/s: 0,62 m^3/s par infiltration, dans l'hypothèse d'un étanchement systématique équivalent à une perméabilité 10^{-8} m/s sur une épaisseur de 40 cm ; 0,34 m^3/s par évaporation en période estivale ; et environ 20% de marge de sécurité (0,24 m^3/s)..

L'alimentation en eau pour satisfaire à cette demande est réalisée par pompage depuis la rivière Oise en extrémité sud du CSNE. Ce prélèvement ne peut être effectué qu'en période de hautes eaux de la rivière Oise. Pour cette raison, le projet prévoit la construction d'une retenue de stockage saisonnier, de volume 14 hm^3.

Fig. 4
Synoptique de l'alimentation en eau du CSNE
CSNE water supply diagram

Enfin, la première mise en eau du CSNE et du réservoir de Louette est également conçue de sorte à minimiser les incidences sur les milieux aquatiques, en respectant les critères de prélèvement dans l'Oise.

2.2. Dimensionnement hydrologique

Les études menées ont montré les limites de la ressource en eau sur la partie Nord du tracé (vallées de la Somme et de la Sensée) et mis en évidence des contraintes en périodes d'étiage dans la vallée de l'Oise. Le système d'alimentation du futur canal est conçu de manière à ne pas perturber le fonctionnement de cette rivière durant les périodes de rareté de la ressource de façon à préserver son fonctionnement avec une marge de sécurité sur les autres usages de l'eau et les besoins des milieux naturels. Les modalités de prélèvement intègrent les prescriptions de l'arrêté cadre sécheresse du 29 juillet 2022 au droit des stations hydrométriques de Creil et de Sempigny, situées de part et d'autre du lieu de prélèvement.

Le scénario retenu prévoit une modulation des débits prélevés en fonction des conditions hydrologiques de l'Oise :

Tableau 1
Critères pour les prélèvements dans l'Oise
Criteria for water abstraction from the River Oise

Seuils	**Alimentation en eau du CSNE : 1,2 m^3/s**
$<$ 32,9 m^3/s à Creil OU $<$ 4,6 m^3/s à Sempigny	Prélèvement dans l'Oise : 0 m^3/s Retenue de Louette : 1,20 m^3/s
$<$ 5,6 m^3/s à Sempigny	Prélèvement dans l'Oise : 0,60 m^3/s Retenue de Louette : 0,60 m^3/s
$<$ 6,7 m^3/s à Sempigny	Prélèvement dans l'Oise : 0,84 m^3/s Retenue de Louette : 0,36 m^3/s
Au dessus de ces seuils	Prélèvement dans l'Oise : 1,2 m^3/s

Ces critères ont été utilisés pour reproduire par simulation sur la période 1960-2022 les volumes d'eau à stocker pour pallier les périodes d'étiage de l'Oise – cf. Figure 5 :

Sur cette période 1960-2022, le volume nécessaire pour pallier les défaillances de l'Oise varie considérablement : 2,8 hm^3 en moyenne interannuelle, 5,4 hm^3 en année quinquennale sèche. Le volume de stockage de 14 hm^3 permet de faire face à une année sèche de période de retour environ 60 ans.

Le remplissage de la retenue est assuré par un pompage dans l'Oise de 1,35 m^3/s en moyenne sur 24 h. Ce prélèvement est réalisé en dehors des périodes d'étiage de l'Oise et vient s'ajouter au débit moyen de 1,2 m^3/s pour la compensation des pertes du canal.

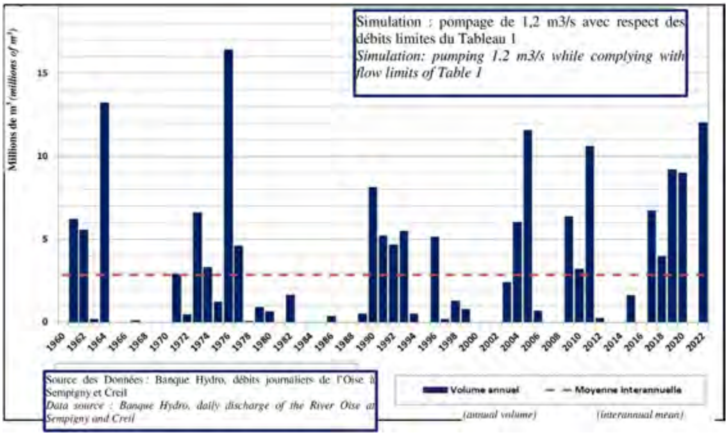

Fig. 5
Simulation des besoins de stockage d'eau
Simulation of water storage needs

2.3. Prise en compte du changement climatique

Les modèles climatiques issus de la production scientifique (internationale : GIEC, française : RExHySS, Explore 70 ou Climaware) convergent pour prévoir, à l'horizon 2065.

- une baisse des précipitations entre mai et octobre, la baisse moyenne étant estimée à 17 %,
- pour les mois de janvier et février, une tendance de précipitations à la hausse, les écarts restant toutefois très importants entre les différents modèles climatiques,
- une hausse de l'évapotranspiration potentielle (ETP).

Cet horizon temporel (2065) a été retenu pour l'analyse en raison de la disponibilité des données, et des incertitudes attachées au futur plus lointain.

Tous les scénarios étudiés ont en commun de proposer une sévérité accrue des étiages associée à un allongement de cette période. En parallèle, aucun modèle ne présente de tendance significative sur les crues (dynamique ou intensité) laissant supposer une relative stabilité de la situation actuellement observée.

L'évolution des précipitations est l'élément le plus incertain des projections de changement climatique, dans la zone de transition dans laquelle figure le bassin de la

Seine, entre l'Europe du Nord où les précipitations annuelles devraient augmenter, et l'Europe du Sud où elles auraient tendance à diminuer. Toutefois, la tendance de baisse des débits d'étiage résulte du réchauffement et de l'augmentation de l'évaporation associée, qui atténue l'incertitude liée aux seules précipitations.

Le schéma d'alimentation tel qu'il est conçu a la capacité d'absorber au moins en partie les effets de l'évolution climatique en raison :

- des marges de sécurité retenues : prise en compte d'une hypothèse d'évaporation supérieure d'environ 20 % à la valeur moyenne de l'ETP du mois le plus chaud de l'année ; prise en compte d'une marge de sécurité de 25 % sur les besoins en eau du canal ; non prise en compte des apports pluviométriques dans le schéma d'alimentation en eau du canal,
- du schéma d'alimentation du canal s'affranchissant des périodes d'étiages sévères de l'Oise grâce à la création d'une retenue de stockage alimentée en période de hautes eaux.

L'évaluation quantitative des effets du changement climatique a été conduite en considérant deux scénarios issus de RExHYSS [1] : le scénario GM et le scénario RC1, tous deux basés sur le scénario A1B du GIEC, avec un traitement statistique différent. Il apparaît que :

- selon le scénario GM, la demande annuelle moyenne milieu de siècle pourrait être typiquement représentée par ce qui a été observé dans les années passées 1993 ou 2005 ; ce qui représente une demande moyenne annuelle autour de 8 hm^3 (à comparer à 2,6 hm^3 en moyenne annuelle pour la période 1961-2013)
- selon le scénario RC1, la demande annuelle moyenne milieu de siècle pourrait être typiquement représentée par ce qui a été observé dans les années passées 1964 ou 1976 ; ce qui représente une demande moyenne autour de 15 hm^3.

Cela met en évidence la part importante d'incertitudes attachées à l'impact du changement climatique sur CSNE : sur la base des besoins estimés à 1,2 m3/s (estimation qui contient des marges des sécurité conséquentes),

- selon le modèle GM, la navigation peut être assurée avec les dispositions de prélèvement actuellement prévues ;
- selon le modèle RC1, le dimensionnement de la retenue serait limite, et des restrictions de navigations s'avèreraient alors nécessaires.

2.4. Premiere mise en eau des ouvrages

L'opération de première mise en eau des ouvrages se caractérise par son importance : il s'agit de remplir un volume de 36 hm^3, hors pertes par infiltration et évaporation.

Les simulations montrent qu'il est utile d'anticiper la mise en eau du CSNE et de la retenue de Louette sans attendre la construction de l'ensemble des ouvrages. La première mise en eau s'effectue alors en utilisant deux saisons « hivernales ». La condition nécessaire est que la retenue de Louette puisse être (au moins partiellement) remplie dès la première saison, de sorte qu'elle puisse être utilisée pour la mise en eau des biefs en période de basses eaux de l'Oise. Ce remplissage anticipé de la retenue de Louette est physiquement possible, en utilisant en particulier la possibilité de remonter l'eau de l'Oise via le Canal du Nord existant.

2.5. Etancheite de performance

Un point-clé du dimensionnement hydrologique réside dans les performances d'étanchéité du futur CSNE. L'objectif est fixé par le critère suivant : perméabilité de 10^{-8} m/s sur une épaisseur de 40 cm.

Les maîtres d'œuvre du projet ont proposé la mise en œuvre systématique d'un dispositif d'étanchéité rapporté, capable de remplir l'objectif de performance, validé par le maître d'ouvrage. En pratique, les maîtres d'œuvre ont retenu plusieurs solutions technologiques : béton bitumineux, géomembrane PVC, géomembrane bitumineuse.

Il s'agit donc systématiquement de dispositifs d'étanchéité minces, pour lesquels il n'est pas possible d'exclure que des défauts se produisent : défauts par l'effet d'imperfections de construction, défauts par suite de tassements différentiels, perte de performance par altération physico-chimique, défauts provoqués par des accidents de navigation.

La présence de la navigation est un facteur d'agressions variés : jets d'hélices, chutes d'ancres, pertes de cargaison, échouages, collisions. Cela a piloté certains points clé de la conception :

- la solution classique d'un drainage sous dispositif d'étanchéité n'a pas été retenue : en exploitation, la gestion des perforations accidentelles de l'étanchéité aurait été trop difficile,
- toutes les étanchéités minces sont placées sous une protection, en béton, béton bitumineux perméable ou remblai ; elles ne sont donc pas directement accessibles pour l'inspection et la réparation ; il importe alors de disposer de moyens de détections des fuites éventuelles,
- la détection des fuites utilise les fibres optiques ; des fibres sont systématiquement placées sous l'étanchéité aux raccordement entre talus et plafond et sous les raccordements entre étanchéité et ouvrages de génie-civil; en complément, un réseau classique de collecte et drainage des fuites est mis en œuvre dans les remblais.

Ces différentes précautions ne permettent pas d'exclure l'occurrence de défauts significatifs de l'étanchéité de performance. La conception en tient compte : l'étanchéité de performance n'est pas un organe indispensable pour assurer la sécurité hydraulique des remblais qui ferment les biefs, qui sont donc considérés comme des barrages (cf. §4).

3. CONTEXTE GÉOTECHNIQUE

3.1. Geologie et hydrogeologie

Situé dans la partie Nord du bassin sédimentaire de Paris, le projet recoupe les craies du Crétacé et, dans ses extrémités Nord et Sud, les terrains de l'Eocène (sables, grès, argiles). Ces formations anciennes ont été entaillées par de nombreux cours d'eau dans lesquels des formations alluviales, parfois compressibles, se sont déposées. Enfin, lors du dernier épisode glaciaire, des dépôts éoliens lœssiques, appelés limons des plateaux, se sont déposés : leur épaisseur peu atteindre jusqu'à 10m en bordure de plateau.

D'un point de vue hydrogéologique, la nappe principale se situe dans les craies. Les limons des plateaux sont généralement hors nappe. Dans les terrains de l'Eocène, des venues d'eau ponctuelles peuvent exister en fonction des contrastes de perméabilité et à la faveur d'épisodes pluvieux.

3.2. La reutilisation des craies et limons en remblais

Pour la construction des remblais, les principaux matériaux disponibles sont les craies et les limons des plateaux. Bien connus régionalement pour la construction des infrastructures ferroviaires, routières et autoroutières, ces matériaux ont peu ou pas été utilisés pour la construction d'ouvrages hydrauliques.

Les craies ont un comportement relativement différent selon la porosité du matériau lors du dépôt, le degré d'altération en partie supérieure de la formation et enfin le degré de saturation. Afin de garantir l'absence d'effondrement à long terme des craies compactées, la densification doit être suffisante pour assurer une granulométrie continue et un degré de saturation élevé. Pour limiter le risque de montée de pressions interstitielles pour les grands remblais (H$>$15m), la teneur en eau ne doit pas être trop élevée pour autoriser une densification suffisante. Selon le guide GTR [2] les craies rencontrées dans les déblais sont majoritairement R12 $(1,5 < \rho_d \leq 1,7)$ mais des craies R11 $(\rho_d > 1,7)$ et R13 $(\rho_d \leq 1,5)$ seront aussi recoupées. Pour les craies les moins denses et les plus humides, un traitement à la chaux sera nécessaire pour assurer la traficabilité à la mise en œuvre et/ou atteindre une densification suffisante après compactage. Pour les craies les plus denses, une fragmentation et une énergie de compactage importante sont nécessaires pour assurer une granulométrie continue, un enrobage correct des blocs et un degré de saturation élevé. Afin d'éviter de rigidifier le remblai, et limiter le risque de fissuration, le recours au traitement par liant hydraulique est interdit pour les remblais supportant le canal, contrairement aux usages routiers ou autoroutiers.

Les limons ont un indice de plasticité souvent faible (sensiblement inférieur à 8) et parfois plus fort (jusqu'à environ 20). Les limons les plus plastiques se traitent bien à la chaux et/ou aux liants hydrauliques pour un usage noble. Ainsi, l'écluse de Marquion-Bourlon, de plus de 40m de hauteur (Figure 6), est conçue avec des bajoyers minces grâce aux limons traités chaux et liants réduisant la poussée des terres.

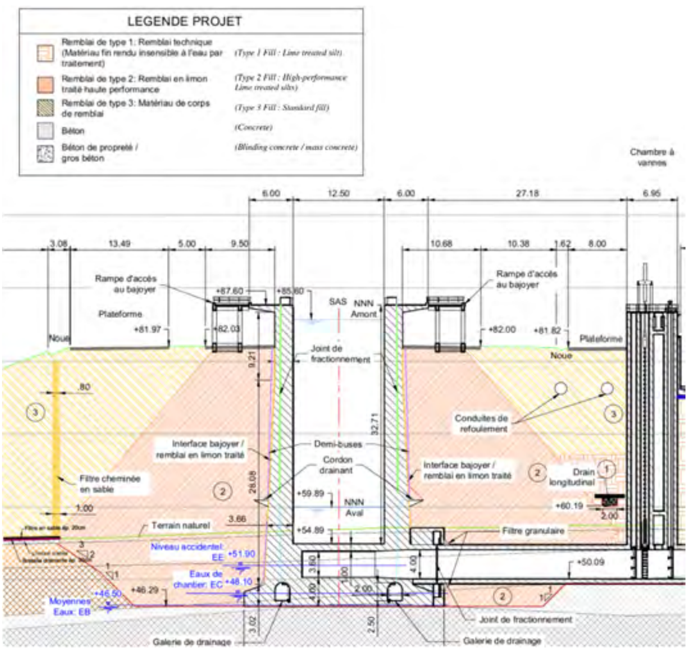

Fig. 6

Extraits coupe de l'écluse de Marquion-Bourlon. Les remblais techniques en limons traités ont permis la conception de bajoyers minces.

Extracts from the cross-section of the Marquion-Bourlon lock. Engineered embankments in treated silt were used to design slender lock walls.

1 Remblai en limons additionnés de chaux / *Lime treated silts*

2 Remblai en limons traités haute performance / *High-performance Lime treated silts*

3 Remblais classiques / *Standard fills*.

3.3. La conception « barrage » des remblais

Du point de vue de la règlementation française, le canal est une succession de barrages dont plusieurs sont classés en catégorie A, la plus élevée. La conception des remblais respecte donc les grands principes des différentes barrières de sureté successives : a) étanchéité, b) filtration, c) drainage. L'étanchéité de performance est obtenue au niveau du berceau du canal alors que le drainage des remblais est assuré par un drain cheminée vertical sur chacun des deux remblais latéraux fermant le canal (Figure 7).

3.4. Sensibilite des assises de remblai

La conception du projet doit considérer l'aléa cavité d'une part et celui d'effondrement des limons des plateaux d'autre part.

L'aléa effondrement des limons, lorsqu'il est avéré, conduit à une purge des matériaux, et leur remise en œuvre avec un compactage adéquat.

L'aléa cavité présente deux composantes : la première liée aux cavités anthropiques au-dessus de la nappe (tranchées de la guerre 14-18 ou marnière dans les craies), la deuxième liée au risque de soutirage des limons dans les craies (les cavités naturelles dans les craies sont a priori de taille modeste). Des reconnaissances systématiques (géophysique avec sondages de contrôle) sont prévues en phase travaux dans les zones à risque et les cavités seront comblées, au regard des enjeux de sûreté hydraulique et de performance d'étanchéité. De plus, ces zones font aussi l'objet de dispositions préventives : étanchéité de l'assainissement, réduction des infiltrations dans les limons (cf. couche 4 de la Figure 7), mise en place de géogrilles équipés d'instrumentation par fibre optique dans les zones de profil rasant ou remblai de faible hauteur.

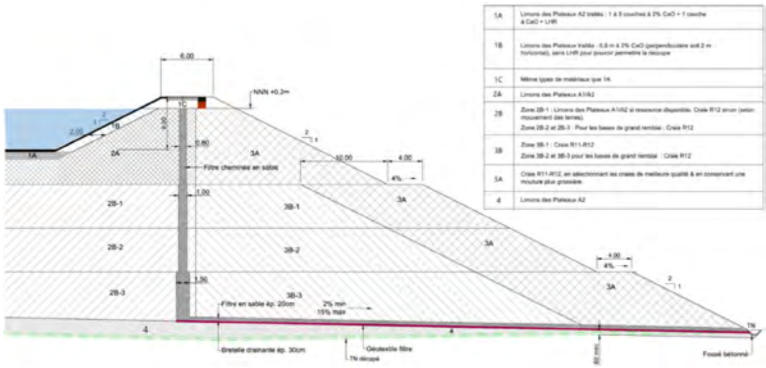

Fig. 7
Canal en remblai : exemple de coupe type de la conception barrage associant étanchéité, filtration et drainage.
Embankment canal: typical cross-section of the dam design combining watertightness, filtration and drainage
(1A and 1C: lime-treated IP>9 silts + one layer of cemented-treated silts; 1B: lime treated silts; 2A: silts; 2B – 3B: silts or chalk depending on available materials ; 3A: chalk ; 4: IP>9 silts)

4. LA SECURITE HYDRAULIQUE

4.1. LES PRINCIPAUX MODES DE DÉFAILLANCE

La règlementation française prévoit que des Etudes de Dangers (EDD) soient réalisées pour les barrages de Classe A et B. Ces EDD ont notamment permis de mettre en évidence les principaux scénarios d’accidents graves.

Conditions de fondation : Les ouvrages du CSNE sont fondés sur des formations géologiques à certains égards peu favorables (cf. §3) : effondrabilité des limons des plateaux, cavités dans les craies, alluvions compressibles sous nappe. Cela peut conduire à des accidents, en particulier à la première mise en eau, par des mécanismes de type érosion interne, des remblais ou de la fondation.

Talus de déblais : le long du CSNE, des déblais de hauteur importante sont par endroits requis. En cas d’instabilité, l’onde d’intumescence qu’ils provoqueraient peuvent menacer la stabilité des sections en remblais.

Soulèvement hydraulique : le Canal est conçu pour être exploité dans une gamme de hauteur d’eau réduite autour du Niveau Normal de Navigation (NNN) : entre NNN-1 m (cote minimale d’exploitation), et NNN+0,70 m (cote des PHE en crue exceptionnelle). Cependant, un abaissement plus important pourrait se produire, par exemple en cas d'amorce d'un scénario de brèche ; dans ce cas, le soulèvement de l'étanchéité par les sous-pressions doit être envisagé.

Ouvrages traversants : le CSNE est traversé en plusieurs dizaines d'endroits par des ouvrages de rétablissements : rétablissements hydrauliques des thalwegs et cours d'eau, rétablissements routiers, rétablissement de réseaux d'eau, gaz, électricité et télécom. Les tassements différentiels peuvent être à l'origine d'accidents par érosion interne. Il y a également de nombreux raccords d'étanchéité entre la section courante du canal et des ouvrages de génie-civil : écluses, ponts-canaux, quais, ducs d'Albe, qui sont autant de points faibles possibles pour l'étanchéité.

Agressions extérieures : la navigation est une source possible d'agression extérieure, par des collisions (chutes d'ancre, perte de colis, échouage, dérive de trajectoire) ou par incendies ou explosions. D'éventuels accidents routiers dans les passages inférieurs, avec incendie, doivent également être considérés.

Crues exceptionnelles et extrêmes On distingue les crues des thalwegs traversés par le Canal (agresseurs externes) et les crues se propageant dans le Canal (aléas internes). Selon la règlementation française, la sécurité doit être vérifiée d'une part pour les crues exceptionnelles (de période de retour 1 000 ans à 10 000 ans selon la classe des barrages) et d'autre part pour les crues extrêmes (de probabilité 10^{-4} à 10^{-5} par an selon la classe des barrages). En crue exceptionnelle, le barrage doit conserver la disponibilité de tous ses organes de sécurité ; en crue extrême, il faut vérifier qu'il n'y a pas rupture du barrage.

De plus, les barrages du CSNE sont exposés à l'occurrence de crues pendant les travaux, alors que les ouvrages d'évacuation ne sont pas nécessairement disponibles.

Tempêtes : les tempêtes peuvent occasionner des vagues, qui peuvent amener à des déferlements lorsque la configuration du canal comporte une longue section droite (dans laquelle les vagues se forment) suivie d'une courbe (dans l'extrados de laquelle il peut y avoir franchissement de la crête).

Séisme : le risque sismique est faible à très faible sur l'essentiel de l'itinéraire, et modéré à son extrémité Nord. Le potentiel de liquéfaction des sols de fondation est examiné, en particulier dans cette partie Nord.

Conduite des écluses : la conduite des écluses occasionne des risques particuliers, provoqués par les éventuelles ouvertures intempestives ou défauts de fermeture, des chocs de navires, ...

Parmi l'ensemble de ces risques, quatre sujets-clés sont développés cidessous : la maîtrise de l'aléa cavités, la maîtrise des niveaux en crue, la résistance aux accidents de navigation, la conduite des écluses.

4.2. Maitrise de l'alea cavites

Les *cavités naturelles* se manifestent sous la forme de fontis, qui sont formés par soutirage des sols de couverture (limons des plateaux essentiellement) vers les vides de la craie sous-jacente. Le zonage de l'aléa dépend des conditions de site : il est plus fort dans les situations où le battement de la nappe se fait autour de l'interface limons / craies ; il est plus fort quand la couche de limons est suffisamment épaisse pour développer des fontis de taille significative.

Les *cavités anthropiques* sont d'anciennes caves, d'anciennes carrières souterraines, d'anciens ouvrages militaires. Des exemples typiques de cavités sont illustrés ci-après (Figure 8).

L'aléa d'effondrement de cavités est augmenté par la mise en eau du canal, car la mise en eau s'accompagne, au moins en théorie, d'une augmentation des infiltrations. L'aléa sera surtout augmenté en cas de défaut d'étanchéité ou de conception qui conduit à des infiltrations localisées significatives.

Des dispositions sont prises pour limiter la probabilité d'un effondrement, et pour limiter ses conséquences :

- Enquête de terrains et valorisation des archives pour caractériser l'aléa, qui est variable le long du linéaire du canal ;
- Détection et traitement des cavités existantes ; la détection utilise les méthodes géophysiques (électromagnétique, et localement micro-gravimétrie) et une inspection systématique à pied après réalisation des fouilles ; le traitement consiste soit à excaver et remblayer les zones de cavités, soit à les combler ;
- Conception des ouvrages faite pour minimiser les infiltrations vers le substratum, et renvoyer les infiltrations vers les thalwegs : la coupe-type illustrée au §3 permet de capter l'essentiel des infiltrations dans le réseau de drainage ;
- Surveillance spécifique par fibres optiques : sont utilisées de manière systématique :
    - Une fibre optique « active » à méthode de chauffe, au pied du talus sous l'étanchéité, pour localiser les zones d'infiltration.
    - Des fibres optiques « passives » dans les secteurs d'aléa fort, pour mesurer les déformations.
- Conception des ouvrages faite pour éviter la rupture complète en cas de remontée de fontis :
    - Une géogrille de renforcement permet de retarder le percement du fontis, améliorant ainsi les chances d'une détection préalable.
    - Une bèche d'étanchéité est mise en œuvre sous le remblai pour couper les circulations d'eau directes qui seraient provoquées par un fontis ouvert, et qui pourraient causer une rupture par érosion interne de la fondation.

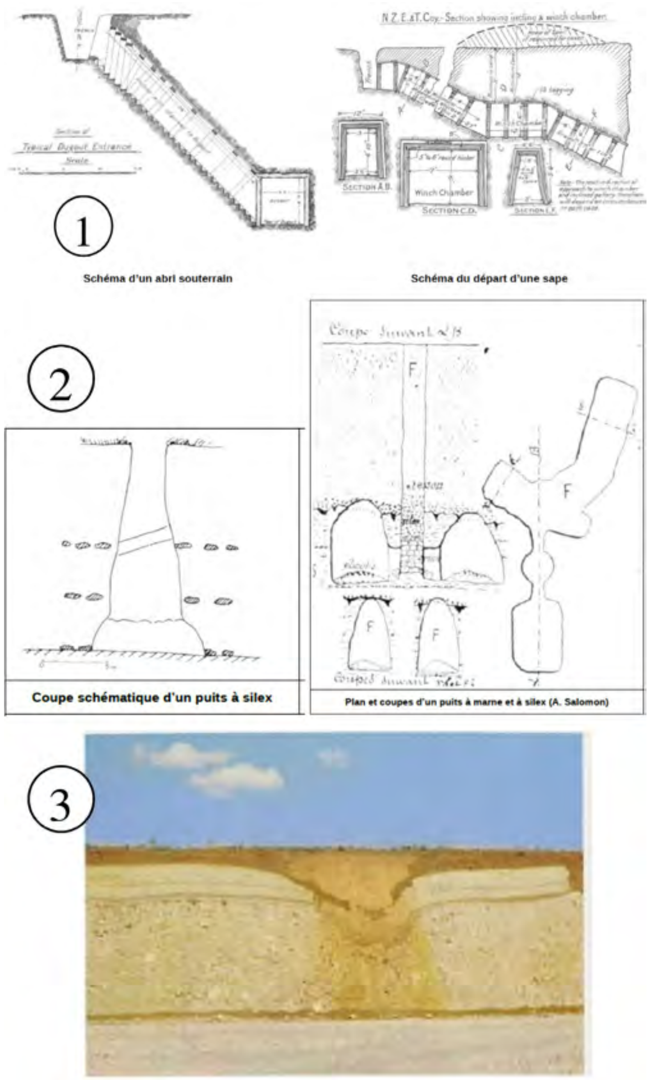

Fig. 8

Cavités anthropiques et naturelles susceptibles d'être rencontrées sous le canal. 1 : ouvrages militaires 2 : anciennes mines 3 : fontis par soutirage des limons dans les craies

Anthropogenic and natural cavities likely to be encountered beneath the canal. 1 : military structures from WWI 2 : old mines 3 : subsidence of silt into chalk joints

- Accessoirement, les zones 1 des remblais (cf. Figure 7), en matériaux traités, disposent d'une certaine cohésion, qui limite la possibilité de l'élargissement de la brèche dans le cas où un fontis aurait réussi à percer.

4.3. Maitrise des niveaux en crue

Les crues des vallons et thalwegs (agresseurs externes) sont pour l'essentiel évacuées sous le CSNE via les ouvrages traversants. Les ouvrages de rétablissement hydraulique sous le CSNE sont dimensionnés de sorte que : la crue centennale est évacuée en transparence hydraulique ; la crue exceptionnelle (de période de retour fixée par la classe du barrage traversé) est évacuée sans dommages aux ouvrages ; la crue extrême est évacuée sans mise en danger du barrage traversé. Dans certains cas cependant, les crues des thalwegs se déversent tout ou partie dans le Canal, via des ouvrages hydrauliques spécifiques, et contribuent alors aux crues du Canal.

Les crues du Canal (aléas internes) sont évacuées, de bief en bief, vers les cours d'eau exutoires : l'Oise au sud, et le canal de la Sensée au nord. Cela est réalisé : par des conduites de bypass sur chacun des sites éclusiers (capacité unitaire 15 m3/s vers le sud et 4 m3/s vers le nord) et, pour les crues les plus fortes, en utilisant les écluses en mode « fausse bassinée ».

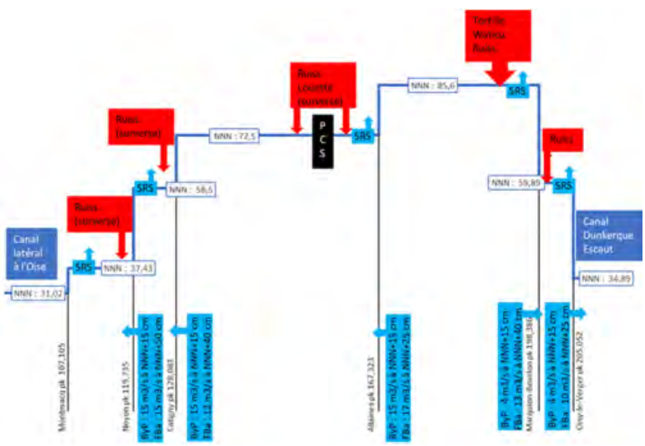

Fig. 9
Schéma d'évacuation des crues (ByP : bypass des stations de pompage ; FBa : fausses bassinées aux écluses ; SRS : sections résistantes à la surverse)
Flood routing diagram (ByP : bypass at pumping stations; FBa : locks used for false lockings; SRS : overtopping-resistant sections)

La sécurité ultime est assurée, sur chaque bief, par une Section Résistante à la Surverse (SRS), qui est un seuil passif déversant de longueur environ 50 m, calée un peu au-dessus des PHE.

Les principes permettant de garantir la sécurité en crue sont les suivantes :

- En crue exceptionnelle, les ouvrages permettent de passer la crue sous la cote des PHE, NNN+70 cm. Les SRS ne sont pas utilisées. La revanche disponible sous la crête est 80 cm, ce qui suffit pour contenir les vagues dues au vent de période de retour 50 ans.
- En crue extrême, les ouvrages (SRS) permettent de passer la crue sous la cote de danger, NNN+140 cm. Ce qui laisse une garde de 10 cm sous la cote de crête des remblais non déversants.
- En crue exceptionnelle, et si les bypass et fausses bassinées sont inopérants, les SRS permettent de passer la crue sous la cote de danger, NNN+140 cm.

Par ailleurs, le phasage des travaux est conçu de sorte à laisser le libre passage des crues des thalwegs et à limiter autant que possible le recours à des batardeaux de chantier en travers des écoulements. Des « sections de passage » (échancrures dans les remblais) sont maintenues dans les remblais des biefs, tant que les bypass ne sont pas opérationnels. L'objectif visé est que les crues de chantier ne puissent pas provoquer de montée de niveau d'eau dans les biefs en cours de chantier.

4.4. Resistance aux accidents de navigation

Depuis 2009, la SCSNE a conduit plusieurs études de recensement de l'accidentologie des canaux de navigation. Ces études se sont basées sur la bibliographie et les bases de données (AIPCN, Erinoh, Bureau d'Enquête des Accidents de Transport Terrestre, BARPI, USACE), ainsi que des enquêtes auprès des exploitants de canaux européens. Ces résultats ont été synthétisés dans les Etudes de Dangers des différents barrages du CSNE.

La probabilité des accidents de navigation est d'abord liée aux conditions de navigation sur le canal. La géométrie du canal (largeurs, surlargeurs dans les courbes, conditions de visibilité) a été choisie de sorte à permettre des conditions de navigation adaptées. Des études de trajectographie sous différentes situations de vent ont été mises en œuvre pour vérifier que cet objectif est atteint.

Cependant, des accidents ne peuvent être exclus.

Un dispositif de protection est mis en œuvre en face amont de l'étanchéité du canal. Il protège suffisamment contre les agressions mineures : chute d'ancre, perte d'un colis, jet d'hélice. En revanche, les accidents majeurs de type collision de navire ou explosion peuvent détruire la protection de l'étanchéité et l'étanchéité elle-même. La conception des remblais permet de limiter les conséquences de ce type d'accident : la moitié amont des remblais assure une étanchéité secondaire dans le cas de la disparition de l'étanchéité de performance, et la cheminée drainante dans l'axe de la digue collecte les infiltrations ; ainsi les barrières de défenses habituelles (étanchéité / filtration / drainage) restent en place y compris dans ce cas.

Une attention particulière est portée aux ponts-canaux. L'exemple illustré ci-dessous est le pont-canal qui franchit l'autoroute A29.

Fig. 10
Pont-canal, autoroute A29
Canal bridge, A29 freeway

Les situations accidentelles d'échouage de bateau, de collision sur les bajoyers, de perte de colis sont prises en compte dans la justification, par le biais des indications de l'Eurocode. Le dimensionnement de l'ouvrage utilise les règles de l'Eurocode en considérant la classe de conséquence la plus élevée : CC3 et la classe de robustesse RC3, qui correspondent en théorie à une probabilité de défaillance inférieure à 10^{-7} par an.

Les bateaux peuvent également provoquer des accidents au passage des écluses. La plupart des accidents passés ont entraîné des conséquences limitées, au sens où ils n'ont pas mis en péril des personnes tierces (ce qui n'empêche pas que ces accidents ont pu avoir des conséquences graves pour les navigants concernés, ou des conséquences graves pour le fonctionnement de l'écluse). Mais certains accidents peuvent provoquer des libérations incontrôlées et dangereuses de l'eau contenue dans le sas ou dans le bief amont. Ces accidents, et les parades retenues, sont les suivants :

Tableau 2
Accidents de navigation et parades
Navigation accidents and defences

Bateau sens	**Accident**	**Parade**
Montant	Collision porte aval	Porte aval suffisamment résistante pour se déformer sans rompre
Montant	Collision mur de chute dans l'écluse	Dispositif amortisseur pour limiter les conséquences sur le génie-civil
Avalant	Collision porte amont	Poutre pare-choc intégrée à la porte, pour limiter les dégâts sur la porte. Mais ne protège pas des collisions majeures.Si porte amont enfoncée : fermeture en charge de la porte aval.
Avalant	Collision mur de chute de la tête aval, dans l'écluse	Tête aval rendue solidaire du sas, par la conception monolithique de l'écluse (continuité du ferraillage entre le sas et la tête aval). Dispositif amortisseur pour limiter les conséquences sur le génie-civil.

4.5. Conduite des ecluses

La conduite des écluses consiste à opérer les portes et vannes, pour le passage des bateaux. Ces opérations peuvent conduire à des fausses manœuvres dangereuses, par exemple :

Tableau 3
Exemples de fausse manœuvre des écluses
Examples of incorrect lock operation

Fausse manoeuvre	**Conséquence**
Ouverture porte aval ou vanne aval, alors que le sas est haut	Libération rapide de l'eau du sas : intumescence dangereuse
Ouverture porte aval ou vanne aval, alors que porte amont ou vanne amont non refermée	Mise en communication du bief amont et du bief aval. Peut conduire à une élévation des eaux puis une surverse du bief aval.
Mauvaise temporisation de l'ouverture des vannes des bassins d'épargne	Débordement d'un bassin d'épargne, et dans certain cas, risque de rupture des remblais qui entourent ce bassin.

Il y a lieu de vérifier que ces fausses manœuvres ne peuvent pas se produire, et cela dans chacune des conditions d'exploitation : en téléconduite normale (à distance) ; en conduite semi-automatique locale ; en conduite manuelle lors d'opérations de maintenance. Les parades mises en œuvre résultent de la prise en compte du retour d'expérience sur de grandes voies navigables européennes (Belgique, Allemagne, France) complété par les recommandations récentes en matière de sécurité des automates industriel ([7]) et par des expertises issues du domaine du nucléaire sont les suivantes :

1. Formaliser une configuration de « mise en repli » en cas de défaut. Dans la « mise en repli », les portes d'écluses sont maintenues en position, et les vannes sont toutes refermées. Il n'y a pas fermeture automatique des portes car cela pourrait être dangereux pour les navigants. Cependant, l'opérateur peut enclencher la fermeture des portes, après vérifications que cela peut être réalisé en sécurité,
2. Garantir la fiabilité de l'information fournie par les capteurs. Les capteurs de niveau d'eau et les capteurs de position des vannes fonctionnent en 2 pour 3 voire 2 pour 4. En mode 2 pour 3 : il y a 3 capteurs, l'automate vérifie la cohérence des mesures ; si au moins deux capteurs donnent des valeurs cohérentes, alors il retient la moyenne de ces 2 capteurs. Sinon, il y a « mise en repli » du site éclusier.
3. Prévoir des automates programmables à haut niveau de sécurité (SIL3). Mettre en œuvre un automate de surveillance indépendant. L'automate de surveillance dispose de ses propres capteurs, de ses propres câblages et de son propre outil d'analyse. Il empêche que soient exécutées les fausses manœuvres dangereuses. Il ne peut donner aucun ordre d'opération, en dehors de l'interruption de la séquence dangereuse. Il est actif dans toutes les configurations d'opération, y compris en mode maintenance.
4. Tester le système sur plateforme de simulation. Les tests permettent de vérifier le comportement des automates dans différentes situations de fonctionnement normal ou dégradé.

Un autre aspect essentiel de la sécurité de la conduite des écluses est l'organisation de l'exploitant : personnel qualifié et formé, présence permanente dans la salle de contrôle et d'exploitation, présence sur site pendant les premiers temps de fonctionnement de la conduite automatique, exercices de simulation de crise, partage du retour d'expérience. L'ensemble de ces sujets fait l'objet d'un document détaillant l'organisation qui, au titre de la règlementation barrage, doit être validé par le préfet pour autoriser la mise en eau du CSNE.

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GRANDS BARRAGES

VINGT-HUITIEME CONGRES DES
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POTENTIAL OF ROMANIAN DAMS TO ADJUST TO CHANGING ENVIRONMENT (*)

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ROMANIA

SUMMARY

Presently Romania has more than 2200 reservoirs, storing over 13 km^3 of water. 246 of these are large dams (according to standard ICOLD definition). Most of the reservoirs are designed as multi-purpose reservoirs, to provide various and combined benefits such as: water supply for population, industry and agriculture, hydroelectricity, flood protection etc.

The paper briefly presents some of the main aspects regarding the concept of dams' re-operationalization in Romania.

Among the main reasons for the new concept of re-operationalization one can mention:

- Water demand changes
- Climate change associated phenomena
- Safety issues.

Capacité des barrages roumains pour s'adapter à un environnement changeant

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All above mentioned aspects are presented in the paper, together with the Romanian experience.

RÉSUMÉ

La Roumanie compte actuellement plus de 2200 réservoirs, stockant plus de 13 km^3 d'eau. 246 d'entre eux sont de grands barrages (selon la définition de la CIGB). La plupart des réservoirs sont conçus comme des réservoirs à usages multiples pour fournir des avantages divers et combinés tels que : alimentation en eau de la population, industrie et agriculture, hydroélectricité, protection contre les inondations, etc.

L'article présente brièvement certains des principaux aspects concernant le concept de ré-opérationnalisation des barrages en Roumanie. Parmi les principales raisons du nouveau concept de ré-opérationnalisation, on peut citer :

- Évolution de la demande en eau,
- Phénomènes associés au changement climatique,
- Problèmes de sécurité.

Tous les aspects mentionnés ci-dessus sont présentés dans l'article, ainsi que l'expérience roumaine.

1. INTRODUCTION

Presently Romania has more than 2200 reservoirs, storing over 13 km^3 of water. 246 of these are large dams according to standard ICOLD definition. Romanian Water Authority "Apele Romane" is the owner of 125 large dams while 119 are owned by Hidroelectrica, the largest hydropower producer in Romania. A small number of large dams belong to some private companies.

The official data concerning the benefits provided by hydro development infrastructures are:

- Water supply - 120 m^3/sec for population (domestic use), industry and agriculture
- Flood protection - some 2,13 million hectares and 1,927 localities
- Hydropower - 20,749 GWh/average hydrological year.

The systematic construction of large dams in Romania began after 1950, and in the first period their safety was a national priority. The lack of experience in the dam construction field of Romanian engineers was successfully replaced by a special care for field tests, by a thorough study of the foreign technical reports and by research, discernibly adapting the good international practice. The first large dams built in this period are reference works even by nowadays standards due to a proper design based on the most severe design criteria “borrowed” from more advanced and experienced countries and due to the careful performance at self-imposing quality standards. For each dam the monitoring was initiated during the construction stage and was carried on during the first filling of the reservoir and in operation.

This “pioneering period” was followed by a period of experience consolidation in the field of dams, when standards and technical norms are conceived, and highly qualified dams’ design and construction groups are created in the country. The State is the only owner of dams. The Ministry of Electric Energy and the State Water Committee (subsequently the National Water Council) were the main authorities directly responsible for dam safety. These provided an organized framework for the dam safety management under all its aspects.

In the first years after 1990 a new approach in dam safety management was imposed. The unitary regulation of the dam field and the direct control of the state were the major concerns of the Government and of the Romanian Committee on Large Dams. In the following, there are briefly shown the main aspects referring to legislation, technical regulations, dam monitoring and risk control as they evolved after 1990 as well as the present state.

The National Commission for the Safety of Dams and Hydraulic Works (Romanian abbreviation CONSIB) was created by the Government’s Decree 419/ 1993 as an advisory body for the Ministry of Water, Forests and Environment Protection.

Romania’s Government issues in November 2000 the Emergency Ordinance no. 244/2000 regarding the safety of dams. This ordinance is subsequently approved by Law 466/18.07.2001 and becomes what today is usually called Law no. 466 regarding the dams’ safety or just “The dam safety law”.

Currently, the Dam Safety Law creates a complete and up-to-date legislative framework for dam safety management based on:

- a more transparent dealing with risk associated to dams
- responsibility on the dam owner for the overall management of the dam during all phases of the dam existence
- entrusting of dams’ safety assessment to dam experts with appropriate qualifications and experience in applying good (or best) engineering practice and guidelines in the field of dams; the responsibility concerning the dam operation conditions is placed on the certified expert
- the state control on the safety requirements
- financial and legal penalties for the dam owner or other involved persons in case of non-compliance with the legal provisions.

2. RE-OPERATIONALIZATION OF DAMS IN ROMANIA

2.1. Re-operationalization imposed by demands change

The water demand has steadily decreased in Romania since the 1990s, because of structural changes in economy, including reduction in industrial activity, shut-down of economically unviable irrigation schemes, introduction of metering and tariffs in domestic water supply, and reducing system losses. The total demand, in terms of volume of water made available to users, has decreased from approx. 20 km^3/year in the early 1990s to approx. 8 km^3/year now. As a result, there is currently a degree of over-capacity in the system at the national level.

Irrigated area in Romania has decreased from 2 million ha in the late 1980s/ early 1990s to approx. 0.8 million ha. The corresponding water demand has reduced from about 8 km^3 to 1 km^3 per year.

Romania's hydropower potential is estimated at 36 TWh/year, and currently the total installed hydropower capacity amounts to 6,400MW. Hydropower generation accounts for some 32% of Romania's total electricity generation, and 16% of the total energy use. A modest increase in hydropower generation capacity is expected.

This change of the required storage brings also a change of the amplitude of the filling – emptying cycle of the reservoir.

If the main use of the reservoir water is water supply, as it is the case of Romanian Water Authority dams, the normal operation level may be lowered thus providing additional storage capacity for flood control. The downstream area will be subjected to more reduced discharges. In many cases the operation of the bottom outlets required to provide pre – emptying the reservoir in order to increase flood control capacity will be no longer needed thus protecting the riverbed downstream. An additional benefit could be the increase of the environmental discharge downstream the dam as a consequence of new reduced water demand of the users.

If the main use of the reservoir water is hydro power, the reduction of the amplitude of the filling – emptying cycle of the reservoir brings a higher average level in the reservoir thus increasing the head and consequently the energy output. Preserving the initial water management agreement, the authorities may increase the environmental discharge downstream of the dam on the basis of the lower demand of water supply.

The decrease of the water demand in the basin has created a special situation for existing medium or small storage reservoirs. In many cases there is no longer the need of the storage, water supply being provided by other larger reservoirs. The spending for dam and reservoir maintenance are not balanced by any income. The existing head can be valorized by micro hydro and the water mirror can be a source for recreational facilities but the rigid legislation and bureaucracy are unsurmountable barriers.

2.2. Re-operationalization imposed by climate change

Up to now the climate changes in Romania are evaluated on the basis of general European trends. Precipitation has decreased at a rate of about 30 mm per decade in Romania, between 1961 and 2006. Large changes in seasonality are also projected, with lower flows in summer and higher flows in winter for Romania. As a consequence, droughts and water stress are expected to increase, particularly in summer. Flood events are projected to occur more frequently in many river basins, particularly in winter and spring, although estimates of changes in flood magnitude remain uncertain.

Under these circumstances the new operation rules have to provide enough storage in the future to cover the droughts periods and increased capacity in the reservoirs in order to store the flood volumes.

New hydrological studies are required in order to reevaluate the peak flows corresponding to probabilities in accordance to Romanian standards concerning the dam safety. If the new values are significantly larger than the ones used under design stage an extended study is required to balance between lowering the operational level in the reservoir and the increase of the spillway capacity by adding overflowing sections in the dam or by providing emergency spillways.

New operation rules are imposed by the flush floods, that are a proved part of the climate changes. They are a source of increased silting of the reservoir and some rivulets training works are mandatory.

3. OPERATION AND MAINTENANCE (O&M) OF ROMANIAN DAMS

Regular operation and maintenance as well as thorough inspection is mandatory for all the dams in Romania. Operations and Maintenance (O&M) Program is imposed by law, it is elaborated by the dam owner, and it is approved by Water Authority.

An O&M Plan is a guidance document developed to ensure that a dam is performing safely and according to its design and purpose. As the name suggests, this type of program contains details pertaining to two main administrative matters: operation and maintenance.

Standard practices for both preventive and extraordinary maintenance are established. Preventative maintenance is performed routinely and includes the servicing of the dam and its appurtenances with the intention of avoiding over-vegetation, animal impacts, equipment deterioration, mechanical malfunction, flooding, or failure. Extraordinary maintenance is comprised of the repairs required to correct these damages if they do occur.

By tradition the dam maintenance activity in Romania was a good one. The main activity of the owner operational staff was dam safety. The funds allocated were in accordance to the needs and the staff in charge came from the former contractor's engineers.

However, conducting effective O&M functions requires trained and motivated staff and personnel. It is essential that the organization responsible for O&M has well-qualified, experienced and efficient staff. Human resource assessment, planning, as well as human resources (HR) management and development (training programs, career plans, performance evaluations and adequate salary systems) are crucial to improve performance.

4. MAIN CONCERNS REGARDING OPERATION AND SAFETY OF ROMANIAN DAMS

The incidents or near failure events affecting the Romanian dams have as the main consequence the constrains in the dam operation, in most of the cases restrictions of the maximum level in the reservoir. The constraints do affect the potential benefits of hydro development. If the storage is dedicated to water supply, the available water volume is less than the one planned and implicitly induces shortages in water provided to the beneficiaries. If the reservoir belongs to a waterpower development the imposed lower level in the reservoir decreases the head and implicitly the power and the energy output.

4.1. Large and/or dangerous seepage through the dam foundation

The majority of the seepage incidents are encountered at medium height dams where the reservoir is created by long lateral dams (dikes). The dikes are founded on pervious alluvium and the foundation watertightening is provided by cut-off walls. The particular geological conditions given by the variable depth of the impervious base rock or more frequently by the large boulders disseminated in the alluvial ground led to significant deficiencies of the water tightening system – floating cut-off walls, large windows in the cut-off wall, opened connection between the face concrete slab and the cut-off wall. In all of the cases the seepage itself is not the main issue but the internal erosion induced by the large gradients. A cavern is created, and the stability of the dike body is endangered. In order to reduce the seepage gradient and the seepage flow the reservoir level has to be decreased. The constrain in the storage operation is imposed. The restricted operation may become the new operation rule if the rehabilitation of the watertightening system is very expensive. Sometimes the duration of the reservoir emptying required by the constructive measures lead to loss of income from the energy output that overpasses the loss caused by operating at the lower head.

There are many dams where the seepage issues has imposed reservoir level restrictions. In some case the incident was solved by significant repair works, as it happened at the Galbeni reservoir on Siret River (the watertightening was provided by a new pile cut-off wall more than 1 km long). In other case the reservoir is kept almost empty, the power station is non-functional, or it works with low power output and low efficiency. That are the cases of Lugasu dam and power station on Cris River (nonfunctional), Tileagd dam and power station on the same river (2m restriction) and the cascade hydro power development on Raul Mare River (Ostrovul Mic, Paclisa, Hateg) were the restriction is between 1.5 m to 4 m. The seepage at Ostrovul Mic dam is shown in photos. Over time, various remedial works at the dikes have been realized, but they failed to effectively control the seepage flow.

Fig. 1
Seepage at Ostrovul Mic dam
Fuites au barrage Ostrovul Mic

a.	Seepage chimney at the upstream toe	a.	Cheminée d'infiltrations au pied amont
b.	Seepage springs and slope instability	b.	Sources d'infiltration et instabilité des pentes
c.	Large boulders in foundation	c.	Gros rochers dans les fondations

At some Romanian large dams, the seepage problem is associated to the rock mass foundation. The grout curtain that provides the watertightening of the foundation was not efficient or not enough extended and during the first reservoir filling the seepage flow collected by the drainage system was very large or concentrated on a specific zone. Consequently, the reservoir level was severely restricted for long periods. The remediation of the grout curtain was achieved by extending or doubling the existing one. The measure was usually beneficial and the reservoir started to be operated with no constraints. In some cases, it was a large economic loss along the years when the power head was reduced (more than 65 m during 10 years in the case of Raul Mare dam, a clay core rockfill dam with a height of 167 m). In some other cases the doubts concerning the actual performance of the existing grout curtain do not allow the reservoir to be raised at its normal operation level (the case of Siriu Dam, a zoned embankment dam 122 m height).

4.2. Reservoir sedimentation

A common process that reservoirs undergo once they are placed in a river system is silting. The total erosion rate from Romania's territory is, on the average, 125 million tons/year out of which 45–50 million tons/year are transferred by rivers.

Large reservoirs in the mountainous regions have a low rate of silting and the reservoir operation is not affected. For example, the yearly silting rate registered at the large reservoirs Izvorui Muntelui and Vidraru are 0.03% and 0.04%, respectively, which ensures them with a millenary running.

A totally different situation is encountered at the smaller reservoirs from the sub-Carpathian area with easily erodible rocks (Arges, Siret, Ialomita and Jiu basins). The most notorious examples are the Bascov and Pitesti reservoirs entirely silted in 2 years. This smaller reservoir usually belongs to a cascade arrangement in a hydro power scheme. The associated power station benefits of the large reservoir created in the upper end of the cascade. The reservoir is controlled by a gated dam, and it is bordered by dikes.

There are two kinds of inconveniences created by reservoir siltation. If the reservoir has as the main objective flood control, the available storage for the large inflow attenuation is lost and the downstream area is no longer protected. For the hydro power output, the effect is not so important since the turbine discharge is provided by the reservoir in the upper end of the cascade.

A more serious consequence is related to dam safety. The siltation process is more active in the upstream end of the reservoir. If the intake in the reservoir is blocked by sediments, there is a major risk that the water will by – pass the reservoir in the case of a significant flood eroding the dike face and flooding the all downstream area.

The most evident case is Pucioasa reservoir (Fig. 2) where the sediments are consolidated by vegetation and Pucioasa town (more than 14,000 inhabitants) is threatened.

Fig. 2
Aerial view of the Pucioasa reservoir – reservoir sedimentation evolution between 2002 (left) and 2016 (right)
Vue aérienne du réservoir de Pucioasa - évolution de la sédimentation du réservoir entre 2002 (gauche) et 2016 (droite)

4.3. RIVERBED LOWERING AFFECTING THE DAM STABILITY

Due to anthropic action along the riverbed downstream problems may arise involving both aggradation and degradation of the riverbed. Bed lowering can move in both an upstream direction (as a 'headcut' or 'nick point') and/or downstream, influencing channel stability over an extensive length of the river or stream system. The process is due to the cumulative effects of in stream aggregate mining and lack or decrease of sediment supply from upstream when the natural passage of sediment through the system is interrupted by upstream dam.

In terms of dam safety, the lowering of the riverbed downstream of dam inherently led to the increase of the hydraulic gradient, to the seepage expansion and has a negative impact on the hydraulic jump associated with energy dissipation.

The most dangerous effect on safety is the regressive erosion affecting the foundations of the rear aprons and stilling basins and sometimes even the dam foundation itself. Some recent accidents caused to Romanian dams by downstream riverbed lowering are briefly presented in next figures (Figs. 3, 4).

Fig. 3
Locations of dams affected by riverbed lowering in S-E Romania
Localisation des barrages affectés par l'abaissement du lit des rivières dans le sud-est de la Roumanie

One of the most affected dams is Bilciureşti, a "historic" dam built around 1930s. More than 6 m of riverbed lowering were measured. The main damage took place in the central bay where the rear apron was destroyed and then the stilling basin collapsed (Fig. 4a).

In the case of Movileni dam, the sill of the secondary stilling basin was displaced downstream, and scouring was observed (Fig. 4b)

Fig. 4
Bilciuresti (a) and Movileni (b) dams and effects of the riverbed lowering downstream of dams
Les barrages de Bilciuresti (a) et Movileni (b) et les effets de l'abaissement du lit de la rivière en aval des barrages

5. CONCLUSIONS

Presently Romania has more than 2200 reservoirs, storing over 13 km^3 of water. 246 of these are large dams (according to standard ICOLD definition).

Re-operationalization of storage reservoirs may be a result of several different reasons, such as: water demand decline, climate change, safety issues etc.

The water demand has steadily decreased in Romania since the 1990s, because of structural changes in economy, including reduction in industrial activity, shutdown of economically unviable irrigation schemes, introduction of metering and tariffs in domestic water supply, and reducing system losses.

Climate change related effects in Romania are evaluated on the basis of general European trends. Large changes in the seasonality of river discharges are projected, with lower flows in summer and higher flows in winter for Romania. As a consequence, droughts and water stress are expected to increase, particularly in summer. Flood events are projected to occur more frequently in many river basins, particularly in winter and spring, although estimates of changes in flood magnitude remain uncertain.

Under these circumstances new operation rules have to provide enough storage in the future to cover the droughts periods and increased capacity in the reservoirs in order to store the flood volumes.

New operation rules are also imposed to cope with the flush floods, that are a proved part of climate changes. They are a source of increased silting of the reservoir and some rivulets training works are mandatory.

The incidents or near failure events affecting the Romanian dams have as the main consequence the constrains in the dam operation, in most of the cases restrictions of the maximum level in the reservoir. The constraints do affect the potential benefits of hydro development.

There are many dams where the seepage issues have imposed reservoir level restrictions. In some case the incident was solved by significant repair works. In other cases, the reservoir is kept almost empty, the power station is non-functional, or it works with low power output and low efficiency.

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A CASE OF POTENTIAL BURERA-RUHONDO PSH SCHEME IN RWANDA, AFRICA (*)

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RWANDA

SUMMARY

This report presents a potential PSH scheme in Rwanda. This scheme uses the natural difference of elevation between two natual lakes (Lake Burera and Lake Ruhondo).

RÉSUMÉ

Ce rapport présente le cas d'un aménagement hydroélectrique potentiel par pompage-turbaniage au Rwanda. Cet aménagement utilise la différence naturelle d'altitude entre deux lacs naturels (Burera et Ruhondo).

**Un cas d'aménagement potentiel de pompage-turbinage à Burera-Ruhondo (Rwanda – Afrique)*

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1. INTRODUCTION

At the ICOLD's 91st GENERAL ASSEMBLY held in Gothenburg; 4 main themes were voted to be worked on for the ICOLD conference that will be tenable in Chengdu China in 2025. The main themes are:

- Dams and reservoirs for climate change adaptation (Qn 108)
- Dams and levees fit for the future (Qn 109)
- Earthquake performance and safety of dams (Qn 110)
- Safety of dams and levees facing extreme hydrological events (Qn 111)

Under Question 108, there are five (5) sub-themes, and the author of this report selected one of the sub-themes to focus on. Therefore, this preliminary report will focus on "Dams for Pumped Storage - A Case of Potential Burera-Ruhondo PSH Scheme in Rwanda".

2. DAMS AND HYDROPOWER IN BRIEF

Globally, IHA points out that hydropower accounts for more than 50% of renewable electricity production. In 2022, the hydropower sector produced about 15% of total electricity generation from all sources.

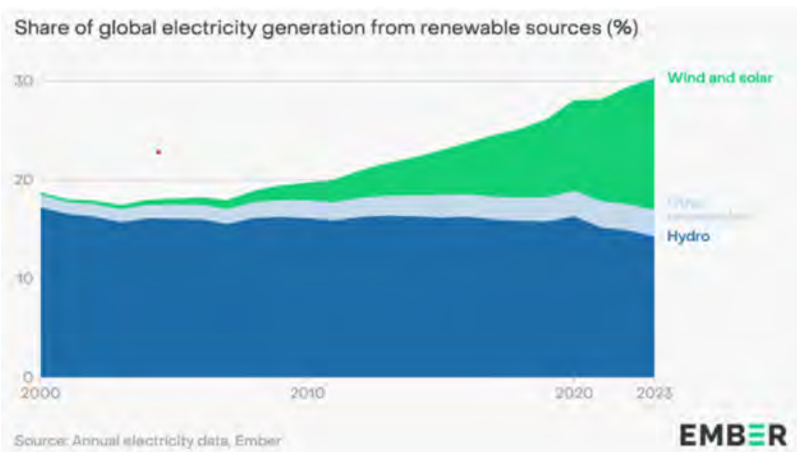

Fig. 1
Share of Global Electricity from Renewable Sources
Part des énergies renouvelables dans l'électricité

In its 2021 Hydropower Special Market Report, the International Energy Agency (IEA) reports that hydropower accounts for nearly a third of the world's capacity for flexible electricity supply and has the potential to provide even more. Hydropower installed capacity reached 1,416 GW in 2023. Conventional hydropower capacity grew by 7.2 GW to 1,237 GW, while pumped storage hydropower grew by 6.5 GW to 179 GW. China, Brazil, the USA, Canada and India are the largest hydropower producing countries by installed capacity. Increasingly, from these growth numbers we can see that investment levels into both conventional hydropower and PSH are more or less similar indicating significant appreciation for PSH. It is reasonable to say that despite the seemingly long-term investment, pumped storage remains a reliable and necessary form of renewable energy.

Hydro Power in Rwanda

Over the last decade, Rwanda's hydropower sector showed a tremendous progress. Overall installed capacity of power is about 390.04MW, hydropower contributing 39.6% of it. This was achieved by involving private investors in the energy sector, Independent Power Producers (IPPs). Equally contributed to achievement in energy sector is a conducive legal and regulatory environment for private investors in this area. Grid connected hydropower plants in Rwanda total 37 hydropower plants. are grid connected and account to 109.7MW as per REG website. They include national and shared regional power plant. Hydropower makes up approx. 39.6% of the total installed capacity.

Hydropower plants are publicly owned and operated, leased to private companies, or privately owned (IPP). The publicly owned power plants are managed by the national utility REG/EUCL. They include larger plants such as Ntaruka, Mukungwa and Nyabarongo I. Currently, other large dams under construction include Nyabarongo II Dam (59 m) and Muvumba Dam (39 m).

3. LOCATION OF THE POTENTIAL PSH SCHEME

Fig. 2
General location of the Potential PSH in Rwanda
Position de l'aménagement potentiel au Rwanda

4. KEY SITE FEATURES

RWANDA'S sister lakes of Burera and Ruhondo were formed as a result of volcanic activity where the largest river Nyabarongo in Rwanda used to flow northward to Ndorwa in Uganda (Reference no.i). The change of flow direction is said to have been caused by volcanic eruption which took place in the northern part of

Rwanda in particular, the eruption of Muhabura volcano. Muhaburara is considered as dormant volcano. The lava from volcanos blocked the Nyabarongo river, hence forming the two lakes.

These two lakes are just perfect natural reservoirs suitable for PSH scheme. Lake Burera, considered to be upper reservoir has an estimated area of about 50 km^2 (rough estimates from Google earth). The Lake Burera water surface is at 1864 masl averagely.

Fig. 3
Google earth imagery showing Lakes Burera/Ruhondo and Muhambura Mt
Image Google Earth montrant les lacs Burera/Ruhondu et Muhambura Mt

Lake Burera inflow is from three rivers, namely Rusumo falls, which is also an outlet of Rugezi wetland lying within the Districts of Burera and Gicumbi, and the other two being Rivers Cyeru and Kabwa. Lake Burera has a catchment area of 580 km^2. The area of appro. 8.5% of it comprises islands.

Lake Ruhondo that would be lower reservoir has an estimated area of about 30 km^2 (rough estimates from Google earth) and its surface water level is at 1759 masl averagely. Lake Ruhondo outflows into Mukungwa River which drains into Nyabarongo River that drains into Akagera river.

5. EXISTING FACILITIES

Currently Ntaruka hydropower plant is harnessing hydro energy from Lake Burera. The plant was commissioned in 1959 by the colonial rulers with a purpose to supply power to mines within the area. The plant has a name plate capacity of 12 MW and it is grid connected. The facility includes a 5.5 m high concrete dam with the reservoir of about 121 Mm^3. The waterways include a headrace tunnel (463m), a surge shaft, penstock (dia 1.8m; 183 long) and a surface powerhouse with 3 generating units. See the figure below for illustrative purpose.

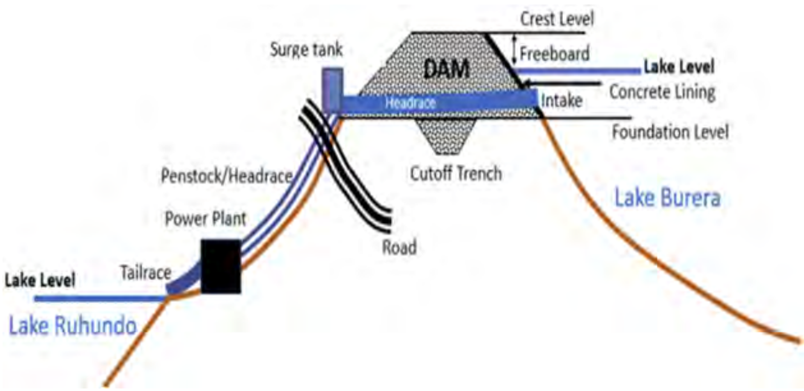

Fig. 4
General Arrangement (not to scale) of Existing of Hydropower Plant (modified after Green Growth Solutions 2021)
Scéma de principe d'un aménagement hydroélectrique (d'après Green Groth Solutions - 2021)

6. PUMPED STORAGE CONCEPT/PRINCIPLES

Pumped storage hydropower (PSH) is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one to the other (discharge), passing through a turbine. See the figure below that demonstrates this type of scheme.

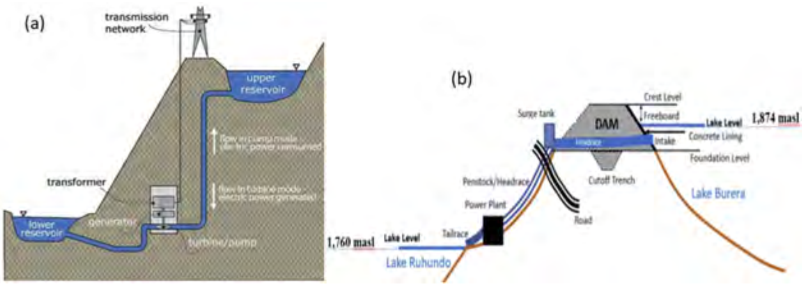

Fig. 5
Schematic of pumped storage hydropower system (a) and General Arrangement of Existing Conventional Ntaruka Hydropower Facility (b).
Schéma du système hydroélectrique de pompage-turbinage (a) et disposition générale de l'installation hydroélectrique conventionnelle existante de Ntaruka (b).

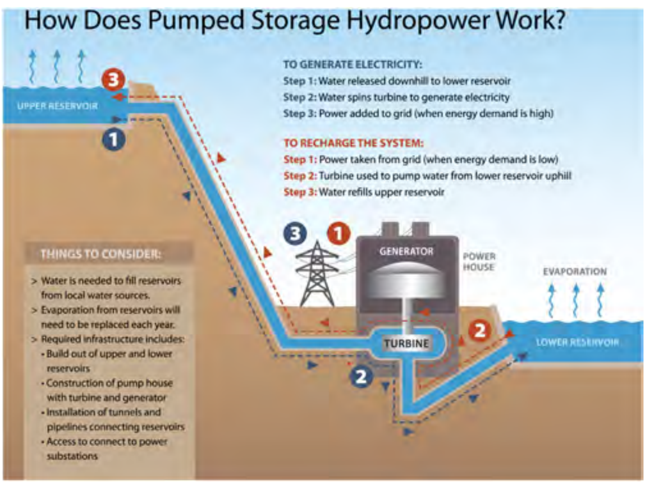

Fig. 6
How Does PSH Work (after Joan Carstensen, Grand Canyon Trust)
Comment fonctionne un pompage/turbinageH (d'après Joan Carstensen, Grand Canyon Trust)

PSH plants operate much like conventional hydropower plants, except PSH has the ability to use the same water over and over again. To generate electricity when power from the plant is needed, water flows from the upper reservoir, because of gravity, through turbine(s) that rotate generator(s) to produce electricity. The figure below demonstrates how PSH works.

PSH can be characterized as open-loop or closed-loop. Open-loop PSH has an ongoing hydrologic connection to a natural body of water. With closed-loop PSH, reservoirs are not connected to an outside body of water.

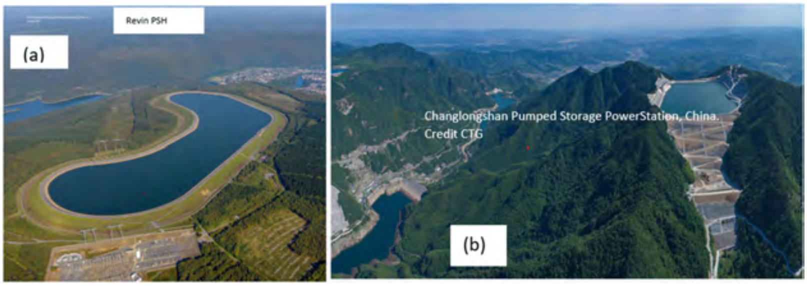

Fig. 7
Photo (a) and (b) Examples of Closed Loop PSH
Photos (a) et (b) : exemples d'aménagement en boucle fermée

Figure 8 depicting a google earth imagery indicating two natural lakes situated at different altitudes creating key features i.e upper reservoir and lower reservoirs and a gross head in the tune of 100m that can be exploited for PSH development.

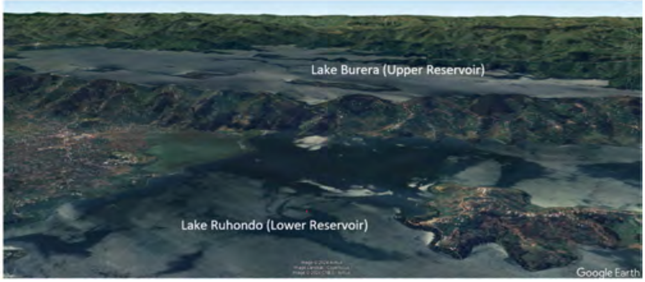

Fig. 8
Existing Natural Reservoirs at different elevations
Réservoirs naturels existants à deux altitudes différentes

7. CONCLUDING REMARKS

Currently, Ntaruka Hydro is producing 12 MW, but the author believes that this figure may be tripled or more if PSH is adopted and developed.

It is also believed that the existence of the two natural lakes (Burera and Ruhondo) will significantly reduce the investment CAPEX since the cost that would have been incurred for reservoirs creation will no longer be needed.

Carry out comprehensive feasibility study for technical, economic, environmental and social aspects to ensure the scheme will be financially feasible and environmentally sustainable. The envisaged study will ascertain which type of PSH scheme to be adopted i.e either closed loop or open loop PSH.

There will also be a need to undertake a tariff study that will setup a tariff differentiation for the PSH operations. This is very important due to nature of the PSH operations. PSH will generate electricity during peak hours i.e when electricity is on high demand by consumers. PSH will buy cheap power which is considered to be available during off-peak times and this energy can be used to pump water from lower reservoir to upper reservoir in future use when demand is so high.

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REFLECTIONS ON THE MANAGEMENT OF ENERGY PROJECTS BASED ON IMMATURE TECHNOLOGIES: THE CASE OF A FPV PILOT PROJECT(*)

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SUMMARY

This document discusses the management of energy projects based on immature technologies, focusing on a Floating Photovoltaic (FPV) pilot project. It highlights the global need to reduce greenhouse gases and the potential of renewable energy sources like FPV in dam reservoirs.

The document is divided into three main sections. The first section describes a pilot project in Europe using membrane technology to install a 2 MWp floating solar plant. The project aims to prove the technical and commercial feasibility of FPV panels. The project was developed by the asset owner (referred to as “Sponsor”) and the technology developer (referred to as “Contractor”). The objective was to demonstrate the technical and commercial viability of floating solar PV panels based on the Contractor’s technology. The second section discusses external factors affecting FPV performance, such as wave action, moisture, dust, debris, biofouling, temperature, and sun conditions. These factors can significantly impact the functionality and performance of the FPV installation. For example, wave action can cause increased movement of the mooring system and added stresses on the floatation modules.

**Réflexions sur la gestion de projets énergétiques basés sur des technologies émergentes : le cas d’un projet pilote FPV*

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Moisture effects, such as rusting, are less of an issue for membrane-based solutions due to the use of synthetic ropes and HDPE piping. However, dust and debris can cover the panels, decreasing their efficiency and increasing maintenance costs. Biofouling, where birds use the FPV to rest and nest, can also result in added cleaning costs. The cooling effect of water on FPV panels can increase efficiency, with studies showing a 5-7% yield improvement for water-cooled panels. The final section reflects on how to scale immature renewable energy types to commercial levels, emphasizing the importance of an ecosystem mindset where various companies and organizations collaborate to innovate and succeed. The document suggests adopting an ecosystem approach to renewable energy innovation, where a group of interacting and code-pendent companies or organizations rely on each other to function and be successful. This approach is particularly suited for renewable energy businesses during the energy transition, as it fosters innovation and collaboration among participants. The Sponsor's role within the ecosystem involves leveraging its financial strength and network while potentially adopting a complementor role to facilitate innovation and manage multiple ecosystems simultaneously.

RÉSUMÉ

Ce rapport traite de la gestion des projets énergétiques basés sur des technologies émergentes, en se concentrant sur un projet pilote de photovoltaïque flottant (FPV). Il souligne la nécessité de réduire les gaz à effet de serre au niveau mondial et le potentiel des sources d'énergie renouvelables telles que le photovoltaïque flottant sur les réservoirs de barrage.

Le document est divisé en trois sections principales. La première section décrit un projet pilote en Europe utilisant la technologie des membranes pour installer une centrale solaire flottante de 2 MW. Le projet vise à prouver la faisabilité technique et commerciale des panneaux FPV. Le projet a été développé par le propriétaire (appelé « Sponsor ») et le développeur de la technologie (appelé « Contractor »). L'objectif était de démontrer la viabilité technique et commerciale de panneaux solaires photovoltaïques flottants basés sur la technologie du contractant. La deuxième section traite des facteurs externes affectant les performances du FPV, tels que l'action des vagues, l'humidité, la poussière, les débris, l'encrassement biologique, la température et les conditions d'ensoleillement. Ces facteurs peuvent avoir un impact significatif sur la fonctionnalité et les performances de l'installation FPV. Par exemple, l'action des vagues peut entraîner un mouvement accru du système d'amarrage et des contraintes supplémentaires sur les modules de flottaison. Les effets de l'humidité, tels que la rouille, sont moins problématiques pour les solutions à base de membrane en raison de l'utilisation de cordes synthétiques et de tuyaux en PEHD. Cependant, la poussière et les débris peuvent recouvrir les panneaux, ce qui réduit leur efficacité et augmente les coûts de maintenance. L'encrassement biologique, lorsque les oiseaux utilisent le FPV pour

se reposer et faire leur nid, peut également entraîner des coûts de nettoyage supplémentaires. L'effet de refroidissement de l'eau sur les panneaux FPV peut augmenter l'efficacité, des études montrant une amélioration du rendement de 5 à 7 % pour les panneaux refroidis à l'eau. La dernière section réfléchit à la manière d'amener les types d'énergie renouvelable immatures à des niveaux commerciaux, en soulignant l'importance d'un concept d'écosystème où diverses entreprises et organisations collaborent à l'innovation et à la réussite. Le document suggère d'adopter une approche écosystémique de l'innovation dans le domaine des énergies renouvelables, dans laquelle un groupe d'entreprises ou d'organisations interdépendantes et codépendantes s'appuient les unes sur les autres pour fonctionner et réussir. Cette approche est particulièrement adaptée aux entreprises du secteur des énergies renouvelables pendant la transition énergétique, car elle favorise l'innovation et la collaboration entre les participants. Le rôle du Sponsor au sein de l'écosystème consiste à tirer parti de sa puissance financière et de son réseau, tout en adoptant éventuellement un rôle de complément pour faciliter l'innovation et gérer simultanément plusieurs écosystèmes.

1. INTRODUCTION

The need to reduce the presence of greenhouse gases in the atmosphere through the capture and reduction of emissions is placed on the global agenda as an emergency. Renewable energy generation is an important part of this equation. Power generation from hydraulic, wind and solar sources are mature and consolidated technologies, but their joint use through hybrid or alternative solutions are developing areas that deserve increasing attention. One example is the use of floating photovoltaic (FPV) in dam reservoirs, which can represent a significant competitive advantage for dam owners. An FPV installation is comprised of photovoltaic solar panels (identical to those used on land), mounted on a floating structure which is moored to the lake- or riverbed. While several technologies and prototypes for FPV alternatives exist on the market, most are not yet fully adapted to high-energy forces (such as open ocean wave action), making implementation in connection with dammed reservoirs suitable.

FPV might be coupled with hydropower reservoirs in several different ways: as a stand-alone system, where the FPV occupy the reservoir surface in co-location but have separate connections to the grid; as a “hybrid” solution where the FPV units are fully interconnected with the hydropower dam and share the same substation, and the power generated by both is transmitted jointly to the grid. A third possibility is the use of FPV as an alternative power source for pumped hydropower storage. Particularly the implementations of FPV in a hybrid context with common connection to the grid can result in reduced operation and maintenance costs and more efficient utilization of existing infrastructure and grid connections, compared with having separated hydroelectric and solar power installations.

In all three potential implementations, the physical coverage of the surface of the water is predicted to prevent some degree of water evaporation from the reservoir, which can be especially beneficial in arid regions with high evaporation rates and periods of low precipitation, where reservoir water conservation is an issue. Further secondary benefits for multi-use reservoirs may include water quality improvements derived from algae bloom reduction. The mindful design of the floating solar PV instalments might provide new possibilities for recreational use or at least provide fewer disadvantages to local populations who use the reservoir for fishing or recreation. Present-day drawbacks of FPV in dam reservoirs include several aspects of regulatory challenges, uncertainties due to new and relatively little-tested or regulated technologies, HSE risks, potential unpredicted negative environmental impact, and negative perception by stakeholders. These challenges and risks will need to be mitigated by continued testing of FPV technologies, and more and better certification and regulation.

This paper is divided into three sections around the FPV theme. The first describes, as clearly as possible, observing confidentiality issues, a pilot FPV project developed in Europe, based on membrane technology, and which served as the motivation for carrying out this work. The following section discusses the common external factors related to an FPV project, namely those of a local nature that influence the performance of the power station. The last section deals with the management issues of pilot projects, namely the leveraging of solutions based on immature technologies.

2. THE FPV PILOT PROJECT

The project was developed by the asset owner (hereinafter referred to simply as “Sponsor”) and the technology developer (in the rest of the text referred to as “Contractor”) to install four units of 500 kWp, totaling of 2 MWp, floating solar plant at a dam reservoir using experience from Norwegian fish farming industry, to deliver a floating system of PV panels cooled through thermal connection with water over a membrane (Table 1). The objective of the project was to prove technical and commercial feasibility of floating solar PV panels based on Contractor’s technology. The Contractor was the key partner in the project and the supplier of DC systems including the floaters and was responsible for the overall design, and Sponsor procure directly inverters, transformer, construct the transmission line, and be responsible for balancing of plant.

The project delivery was split in two, whereby the learning from the first unit should be applied for the installation of the remaining three 500kWp units. If the performance criteria of Unit # 1 were not met, the Sponsor would abort the project with the Contractor and proceed with an alternative solution for the remaining 1.5

MWp. A change to a different technology would require re-applying to authority and issuance of revised construction permits.

Typically, membrane-based solutions like the one proposed by the Contractor use reinforced polymer or rubber membranes as the floating base for solar panels. These membranes are designed to float and support the panels, offering flexibility to fit different shapes and sizes of water bodies. They are lightweight and easy to transport and install, providing versatility for various configurations and installation requirements. However, membranes may be less durable than other options, requiring more frequent replacements, and can be challenging to maintain due to continuous exposure to water and sun.

The financial analysis supported the decision to go ahead with the project. The first 15 years are based on a PPA, which brings additional predictability to the project. The sensitivity analysis shows that the main factors will be the investment (CAPEX) and production, which is in line with other similar projects. It is in fact these two factors that raise the most doubt mainly for projects based on immature technologies. Normally, there is a lot of unpredictability regarding the resilience of the material and the setup, which may justify additional reinvestments. The performance of the setup is also unknown in the real world, namely the cooling effect in the case of membrane-based solutions. It is interesting to check Sponsor’s perspective in relation to the risks associated with the project, in a survey carried out even before construction. This information can be consulted in Table 2. There is no doubt that the risk assessment realistically covers the main concerns.

Table 1
Main technical project data

Description	**Data**
Annual production	2,700 MWh
Installed capacity (DC)	2 MWp
AC/DC ratio	1.25
Technology	Floating Photovoltaic
Lake surface	14,000 m2 (4*4000 m2 each unit)
Transmission Line	1 km
Transmission Line	35 kV
Tilt Angle	0 deg
PV modules	6,500 (4 * 1625) units
Inverter	12 x 185 ktl-M1 capacity
Transformer	2 MW
PPA duration	15 years
Project lifecycle	25

Table 2
Risk analysis carried out by the Sponsor before the construction

Risk	Consequence	Mitigation
Contractor bankruptcy due to Covid-19 and no other projects in their portfolio	Project delay, lower return. Possibly project abortion or switch to alternative supplier	Establish a strong local team, build strong competencies and get the sub-supplier contact to follow up the project in case of such scenario, line up alternative supplier to the Contractor
Transportation hazards including from China	Delay	Follow up of Contractor
Local assembly proves more difficult than expected	Delay, added installation cost	Careful monitoring
Success criteria for Unit # 1 not fulfilled	Delay, added cost	Backup solution with another alternative
Output: The power plant produces less energy than anticipated. Long term performance not meeting expectations	Lower revenue	Ensure highest possible availability managing the maintenance operations carefully and reducing unplanned downtime
Shorter plant lifetime than expected	Frequent repairs, increased O&M cost, revenue loss.	Monitoring of defects, careful management of guarantees
Bird soiling proves difficult to manage in a sustainable fashion	Loss of production, higher O&M efforts	R&D, explore innovative methods
Plant not functioning in accordance with expectations (more flooding, more cleaning etc.)	Reduced availability, lower revenue, higher operational costs	Additional O&M focus

The key rationale for Sponsor's involvement in floating solar was based on the potential seen in the segment for floating solar and the opportunities for learning and competence building offered through the implementation of this project. The market for floating solar is expected to grow fast. The opportunity to invest in this project represented an opportunity to gain an early mover advantage on a potential key technology for this market. If successfully industrialized, floating solar may offer particular benefits when combined with hydropower and dam reservoirs. Examples of industrialized applications in the Sponsor context include: (i) Application on reservoirs in combination with existing HPPs utilizing infrastructure such as sub-stations and transmission lines that may have idle capacity in dry and sunny periods; (ii) Application to reduce evaporation from reservoirs in hot climates; and (iii) Application on water surfaces in densely populated areas where access to land and other renewable energy sources are non-existent. The main positive effects on the Sponsor's image are: (i) Adds installed PV capacity with 2MWp; (ii) Demonstrates the Sponsor as innovative company; and (iii) Develop capabilities and experience in floating solar.

3. FACTORS CONTROLLING THE PROJECT PERFORMANCE

One key objective of a pilot project should be to gain an understanding of the external controls, present at the pilot location and that will be relevant to commercial projects, that impact the functionality and performance of the FPV installation. External controls will be different from one location to the next, due to an intricate interplay of climatic, geographic, socio-political, and anthropogenic factors. Choice in design and technology of the FPV installation should reflect the local conditions at hand. Studies indicate that design elements and the way the installation affects and is affected by the environment and conditions has an impact on performance and longevity. In studying external controls on FPV performance, the objectives have been to glean from other case studies or modelling which conditions have documented effects on improving or decreasing FPV performance, and why.

Numerous studies have addressed both the impact that FPV installations have on the environment [1–6], as well as the effects that surrounding environmental conditions can have on the FPV. In this paper, the focus is on the conditions that can have an impact on the performance of the FPV installations. However, mitigation of negative environmental impacts of the FPV on the surrounding environment is an important aspect of bringing commerciality to a pilot FPV project. A good summary of these factors can be found for example in [2]. Table 3 summarizes the primary environmental and external factors that affect FPV performance, focusing on settings where the FPV is installed in a freshwater body of water, such as a dammed reservoir. Each factor will be described below.

Waves cause increased movement of the mooring system and FPV floatation system. In addition, the connection points between the mooring system, and between the floatation modules, experience added stresses. Flexing of the floatation modules and PV mounts additionally causes bending of the PV panels. The degree and type of stress and flexure will depend on the particular FPV solutions chosen for a particular location [7,8]. In membrane-based solutions, the FPV installation comprises a rope mooring system secured to the lake floor with anchors, synthetic ropes connected to moorings, HDPE piping rings that hold the modules buoyant and to which a membrane is attached. The PV panels are mounted directly onto the floating membrane. The mooring ropes are connected to the floatation rings with thinner, secondary synthetic ropes. Ropes and elastic cords connect the membranes to the rings, and the rings to each other, and ropes hold the electrical elements in place on the structures.

Moisture effects such as rusting are less of an issue for the membrane-based solutions due to materials choices including synthetic ropes, HDPE piping and membrane. Corrosion of metals is expected to be minimal, however weakening of materials through solar exposure has been observed to be a factor through studies [7]. Other moisture issues have been identified to be larger issues. Due to the membrane technology used, the PV panels sit directly on the water, with only the floating membrane in-between. The membrane is flexible, so when weight is applied differently on the surface of it, it will flex and bend in response. During periods of precipitation, water can collect directly on top of the flat-lying PV panels mounted on the membrane. Pumps are installed to remove collecting water when this occurs. However, when a weight is applied to part of the membrane (in this case, water), it does not distribute itself evenly but collects in pools. Once a pool of water begins to form, it draws the membrane downwards. This is not always in the location of the pumps, so O&M staff need to perform visual inspections of the installations during periods of high precipitation to dissipate pools of water that may be forming and endangering the integrity of the installation. Weights can supplementarily be attached to the pumps (metal chains) to create a draw-down effect, not included in the original design. Inspection protocols include applying extra weight to the pumps (standing on top of it), to drain excess water, which is time-consuming for O&M staff, and adds to the overall operational costs.

Literature comparing FPV with land-mounted PV panels has previously stated that one advantage of floating modules is that they are less dust-prone, thereby improving their overall performance since panel surfaces theoretically remain cleaner [2]. Field observations and interviews with O&M personnel have found the opposite to be true: that dust and debris covering the structures are some of the largest obstacles to performance and costs. Regarding the vegetation, on the one hand, vegetation contributes with soil-binding and prevents erosion, thus limiting some of the soil and fine-grained material that becomes air- and water-borne. On the other hand, the vegetation poses its own threat to the FPV installation, as dead leaves and branches tend to be rinsed down the steep slopes during rainstorms, and into the reservoir, where they float and are transported by wind, waves, and currents. In the case of membrane-based solutions, because the panels are mounted flatly on the membrane, and the low profile of the surrounding HDPE pipes, debris-bearing water easily splashes onto the panels. Once the panels have been splashed with water, after the water evaporates, a residual film remains.

One of the commonly cited disadvantages of floating PV compared to land-mounted PV is biofouling, which is when especially birds use the FPV to rest on, nest on, and which as a result is excrement on. Biofouling also includes microbial growth. [8–10].

The supposed cooling effect that water has on the PV panels, either via convection in the air between the water surface and the panels in raised floating structures, or via near-direct water-panel contact – as with the membrane model – is frequently cited as one of the major advantages of floating solar PV technology [7–9,11]. Kjeldstad et al. [12] has tested the performance of air-cooled versus water-cooled PV panels using membrane technology. Their study, performed in mid-Norway, found that the water-cooled PV panels showed averages of 5-7% increased yield, compared to air-cooled panels. The best improvements were seen for greater air-to-water temperature differences.

Table 3
Environmental and external factors affecting FPV performance in freshwater settings

External control	**Environmental factors**	**Negative effects or implications**	**Mitigation**
Wave action and currents	Wind- or current-related in freshwater setting. Differential currents can be due to water flow through gates in a dammed reservoir.	Causes mechanical stress related to activation of moving parts and flexing of stationary parts. Differential currents can especially cause uneven loading on the mooring system. Material fatigue and cracking.	Placement of modules away from the dam, and in wind-protected locations; design of FPV modules that limits friction and material fatigue.
Moisture	Proximity to water.	Chemical reactions of materials with water (e.g. rusting); exposure of electrical units with water (short-circuiting, and HSE risks).	Design of FPV modules that protects the electrical system from water exposure and enables efficient drainage; use of non-corrosive materials such as aluminum, glass and plastics; use of protective barriers that limit splashing onto the module.
Dust and debris	Local environmental conditions: arid regions with air-borne dust; highly vegetated regions with air-borne pollen, seeds, leaves; regions with dense vegetation where plant debris is wind- and water-borne and transported onto the FPV modules (floating leaves, twigs, tree branches, etc.).	Dust covering the PV panels decreases their efficiency. Larger debris can cover the panels, clog the drainage units, and damage various components. Results in added O&M costs for cleaning and replacement of parts.	Module design that encourages self-rinsing of the PV panels during precipitation. Barriers that limit the amount of debris carried onto the structure via wind/waves.
Biofouling	Bird populations that use the floating structures for nesting and other activities.	Bird soiling results in added O&M costs for cleaning.	“Scarecrows” to discourage bird activity; installation of bird habitats that could be preferred over the FPV structure; targeted cleaning schedule.
Temperature	Local climatic conditions.	Adverse high or low temperatures can cause materials damage via freezing or overheating. Overheating can decrease efficiency.	Selection of location taking into account modelled ideal temperatures for highest efficiency.
Sun conditions	Latitude, cloud cover, surrounding terrain	Decreases efficiency	Location selection according to GHI and Global Solar Atlas, e.g.

4. THE ECOSYSTEM APPROACH FOR RENEWABLE ENERGY INNOVATION

Moving forward, this paper aims also to provide some form of reflection on how a Sponsor can best use the experiences from a pilot project to take a new and immature renewable energy type, to a commercial scale. This section has laid out observations relating to the challenges that the pilot project described early has faced, relating to:

- Challenges of the PFV technology,
- The challenges in matching needs versus services provided between Sponsor and Contractor, and
- Specific local conditions that require innovative solutions.

Above these specific hurdles, there is the overall challenge of attempting to hybridize two renewable energy sources, solar PV and hydropower. The motivations for doing so, in line with the Sponsor strategy, are in order to keep market hold and stay abreast of the rapidly changing energy market during the current period of energy transition and digitalization. In this context, the adoption of an ecosystem mindset as the Sponsor further develops its hybridized renewable energy business.

An ecosystem in the business perspective is a group of interacting and codependent companies or organizations that rely on each other in order to function and be successful [13]. BCG's global leader of climate technology Stefan Gross-Selbeck states that the ecosystem model is particularly suited for renewable energy business during the energy transition. It is an iterative and collaborative approach that is conducive to innovation, however requires good cooperation across participants [14]. As with the ecosystem in nature, there will be some larger, more dominant inhabitants, some smaller players, some more passive participants, and some very active ones, but each has its own part to play, upon which the others depend. If one part of the ecosystem is not thriving, it will detrimentally affect the other inhabitants – therefore it's in each participant's best interest to help their co-inhabitants innovate, participate, and succeed. The major difference between a business ecosystem and a wild one, however, is that a good business ecosystem is not an incidental product of evolution – it is carefully curated by the firm(s) that oversee it. There are several different ways one might shape an ecosystem, depending on the needs. Jacobides et al. [13] has subdivided ecosystems into business, innovation and platform styles.

The suggestion is that the innovative ecosystem style could be appropriate for the Sponsor new energy and hybridized energy ventures. Here, the focus is on a particular innovation - in this case, the hybridized floating solar PV-hydropower concept. Contrary to the more classical business-style ecosystem that revolves around one main business architect, the innovation ecosystem focuses even more on the value it creates for the customer, the constellation of ecosystem participants around the innovation they wish to achieve. The ecosystem can also be organized to accommodate complementary innovations that are necessary for the overall innovative goal [13]. For a simplified example, an ecosystem with the Sponsor can be envisioned, and a new renewable energy tech provider (Contractor), as the two main firms in the ecosystem. In a constellation around the Sponsor, there are firms comprising important parts of the hydropower supply chain relevant for the asset location. The constellation around the Contractor involves the supply chains for the mooring, the membrane technology, the electrical equipment, and the PV panels. Notably, the supply chains for these two industries are quite different. Firms responsible for key components, such as the extra-durable solar PV panels critical to making the Contractor design work, are also important parts of the ecosystem. Related tech companies that work with innovative solutions important for operations and maintenance, such as a tech company dealing with PV panel-cleaning innovations, are likewise important to the ecosystem. The inclusion of the tech company into the ecosystem could be a boost for the Contractor, as they would have the opportunity to co-evolve their design to be compatible with advances in automated cleaning. The tech company would likewise be able to innovate at a faster pace, and towards a niche market in membrane-type floating solar design, having better access to data, trial results, and close collaboration with the Contractor. Thus, two unique branches of renewable energy technology could co-innovate within the ecosystem. Furthermore, research and development organizations should also be included within the ecosystem that have close cooperations with each of the main participants. This enhances the ecosystem's emphasis on innovation and the creation of state-of-the-art, hybridized renewable energy solutions. The Sponsor on its part benefits from accessing several innovative technologies that it could not develop on its own. This gives increased likelihoods that future pilot projects in new immature renewable energy connected as hybridized solutions together with Sponsor hydropower might succeed. The Sponsor, from a different perspective, probably poses as an attractive ecosystem partner as they are large, robust, and provide opportunities for scale for smaller tech and renewables companies.

There are several issues regarding the ecosystem that a Sponsor should consider, according to Jacobides [15]: 1) whether the Sponsor can help other firms create value; 2) what role should the Sponsor play in the ecosystem; 3) what the terms for participating in the ecosystem should be; 4) is the Sponsor capable of adapting; and 5) how many ecosystems does the Sponsor want to manage. On point 1, it is clear that the Sponsor has the ability to help others create value. The financial strength, strong existing network, and global position make the Sponsor a strong partner.

Concerning point 2, it is however not a given that the biggest firm in the ecosystem should be the architect. The focus on an immature, new renewable energy type, which has completely different supply chains, different technologies and different structure from hydropower, might suggest that a firm more closely integrated in this new technology takes the lead. It doesn't mean that the Sponsor would lose all control; the assets Sponsor controls are hard to replicate, giving them a good deal of leverage within the ecosystem. However, it is important to avoid trying to exert too much control on the other participants – this can stagnate others' abilities to innovation (Jacobides, 2019). Should the Sponsor accept relinquishing a little bit of control, and accepting a complementor role, they might find more advantages than disadvantages. Complementors may take on less investment in the ecosystem, thus opening up the opportunity to dabble in several different ecosystems simultaneously [16]. If the Sponsor is not yet as committed to other renewable energies as they are with hydropower, thereby not yet willing to commit to major reorganization, new hires and investment in technology, it may very well be that a complementor role in floating solar PV ecosystem (or equivalent) would be the more natural choice.

The terms of participation in the ecosystem will depend in part on whether the Sponsor wants input and participation from many different firms, in an open system, with the disadvantage that they would be less committed and more likely to come and go more easily. Another issue with an open system is that the quality of deliveries may vary, and there is less ability for quality control [15]. A good middle ground may be to balance control over quality of participants and quality of deliveries, yet with some flexibility and conditionally open doors to encourage vetted entrepreneurs with innovative ideas—a managed system.

Ultimately, the Sponsor will have to evaluate how capable they are of adapting to the changing renewable energy markets, and in what way they wish to do so. Certainly, the fact that the Sponsor is undertaking pilot projects, like the one presented here, indicates that the Sponsor has identified the opening possibilities in the energy transition. Putting some work and thought into what kind of ecosystem the Sponsor would like to have, what kind of participation is feasible for them, and what kind of ecosystem is most conducive to renewable energy innovations and value creation, would be a good next step before trying to bring a new concept – like the FPV pilot project – into commercialization.

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OLIFANTSPOORT OFF-CHANNEL STORAGE DAM – CRITICAL STORAGE TO AUGMENT WATER SUPPLY (*)

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SOUTH AFRICA

SUMMARY

Water supplies to the city of Polokwane, located in the northern part of South Africa, and its environs, which is home to more than 1 million people, have been severely constrained for over a decade, affecting the reliability of water services for human consumption and economic development of the area. Various projects and initiatives have been planned and implemented over the years to address the acute water shortages experienced by the communities in the region. One of these supply projects (Olifantspoort Scheme), entails the transfer of water from an adjoining catchment. Currently, the scheme consists of raw water abstraction works (weir with pump station) from which water is transferred over an escarpment into catchment of the city of Polokwane.

Olifantspoort Off-Channel Storage Dam, as part of the Olifantspoort scheme, was defined at concept design level as part of the studies into the refurbishment and upgrading of an existing raw water abstraction works (weir with pump station) at Olifantspoort. The current river abstraction works is located on the left bank of the Olifants River and has a total duty pump discharge capacity of 64 megalitre/day, based on four pumps operating 24 hours per day. It is planned to be upgraded in future to supply 120 megalitre/day to the water treatment works (WTW) which will also be upgraded.

**Barrage de stockage en dérivation d'Olifantspoort - Stockage critique pour augmenter l'approvisionnement en eau ()*

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The weir impound basin is heavily silted with sediment deposited during floods, reducing the effective storage capacity required for the efficient operation of the raw water pump station. The resulting accumulation of sediment in the pump station also contributes to frequent breakdowns of the pumps. The proposed off-channel storage dam to be constructed will assist with the settlement of silt from the Olifants River as well as provide buffer storage capacity for the WTW and supply system to Polokwane.

During 2022 a Dam Type Selection Study was completed to select the most suitable dam types for the site. The options review for the proposed OCSD demonstrated that a Rubble Masonry Concrete (RMC) dam type with a spillway over the lowest closure wall is the lowest-cost solution. The design was subsequently finalised in 2023, with five closure walls required due to the unique geometry.

This paper discusses the project background, the need for the scheme, constraints such as high sediment load in the river dictating the preference for an off-channel (off-river) storage dam, and design challenges.

RÉSUMÉ

L’approvisionnement en eau de la ville de Polokwane, située dans le nord de l’Afrique du Sud, et de ses environs, qui abrite plus d’un million d’habitants, est gravement limité depuis plus d’une décennie, affectant la fiabilité des services d’eau pour la consommation humaine et développement économique de la région. Divers projets et initiatives ont été planifiés et mis en œuvre au fil des années pour remédier aux graves pénuries d’eau que connaissent les communautés de la région. L’un de ces projets d’approvisionnement (Olifantspoort Scheme) implique le transfert de l’eau d’un bassin versant adjacent. Actuellement, le projet consiste en des travaux de captage d’eau brute (déversoir avec station de pompage) à partir desquels l’eau est transférée via un escarpement vers le bassin versant de la ville de Polokwane.

Le barrage de stockage hors canal d’Olifantspoort, dans le cadre du projet d’Olifantspoort, a été défini au niveau de la conception dans le cadre des études de rénovation et de modernisation d’une usine de captage d’eau brute existante (déversoir avec station de pompage) à Olifantspoort. Les travaux actuels de captage de la rivière sont situés sur la rive gauche de la rivière Olifants et ont une capacité totale de décharge de pompe de 64 mégalitres/jour, basée sur quatre pompes fonctionnant 24 heures sur 24. Il est prévu de le moderniser à l’avenir pour fournir 120 mégalitres/jour aux usines de traitement des eaux (WTW) qui seront également modernisées.

Le bassin de retenue du déversoir est fortement envasé par les sédiments déposés lors des crues, réduisant ainsi la capacité de stockage effective requise pour le fonctionnement efficace de la station de pompage d’eau brute. L’accumulation de

sédiments qui en résulte dans la station de pompage contribue également aux pannes fréquentes des pompes. Le barrage de stockage hors canal proposé à construire contribuera au tassement du limon de la rivière Olifants et fournira une capacité de stockage tampon pour le WTW et le système d'approvisionnement de Polokwane.

En 2022, une étude de sélection des types de barrages a été réalisée pour sélectionner les types de barrages les plus adaptés au site. L'examen des options pour l'OCSD proposé a démontré qu'un type de barrage en moellons et maçonnerie en béton (RMC) avec un déversoir au-dessus du mur de fermeture le plus bas est la solution la moins coûteuse. La conception a ensuite été finalisée en 2023, avec cinq murs de fermeture nécessaires en raison de la géométrie unique.

Cet article discute du contexte du projet, de la nécessité du projet, des contraintes telles que la charge élevée de sédiments dans la rivière dictant la préférence pour un barrage de stockage hors chenal (hors rivière), et des défis de conception.

1. INTRODUCTION

1.1. Existing project background

Water supplies to the city of Polokwane, located in the northern part of South Africa, and its environs, which are home to more than 1 million people, have been severely constrained for over a decade, affecting the reliability of water services for human consumption and economic development of the area. Various projects and initiatives have been planned and implemented over the past years to address the acute water shortages experienced by the communities in the region.

The Olifantspoort Water Supply Scheme (WSS) supplies treated water to Polokwane City, as well as rural communities in Polokwane Local Municipality (LM), Lepelle-Nkumpi LM and Fetakgomo/Greater Tubatse LM. Raw water released from the Flag Boshielo Dam down the Olifants River, is abstracted at the Olifantspoort Weir and pumped to the Olifantspoort Water Treatment Works (WTW).

The existing Olifantspoort Weir is 108 m long, and the low notch height is 2.2 m above the riverbed. The weir was raised in the past with a brick wall, but the brick wall was washed away during a flood.

The current river abstraction works is located on the left bank of the river and has a total duty pump discharge capacity of 64 megalitre/day, based on four pumps operating 24 hours per day. It is planned to be upgraded in future to supply 120 megalitre/day to the WTW which will also be upgraded.

1.2. Need for upgrading the existing scheme

The existing weir impound basin is heavily silted with sediment deposited during floods, reducing the effective storage capacity required for the efficient operation of the raw water pump station. The resulting accumulation of sediment in the pump station also contributes to frequent breakdowns of the pumps. The proposed off-channel storage dam to be constructed will assist with the settlement of silt from the Olifants River as well as provide buffer storage capacity for the WTW and supply system to Polokwane. The increase in water demand in the region necessitates the need for additional storage.

2. CONSTRAINTS TO BE CONSIDERED DURING UPGRADE DESIGN

2.1. Sedimentation

An average of 2351 tons/annum at a density of 1.1 t/m^3 of fine sediment (excluding bedload sediment) was predicted [4]. The current weir is heavily silted up. Silt can be removed from the Olifants River using a gravel trap at the proposed upgraded extraction works/pump station or new abstraction works.

One of the design principles is that the new OCSD's function is a sediment trap for the WTW and for desilting the storage reservoir during operation. The dam can consequently not be allowed to silt up fully nor clog up the intakes to the WTW. Frequent sediment removal is an owner required to ensure that the system functions as intended. The operational requirements must be finalised at a later stage.

2.2. Operational constraints

In addition to the sedimentation issues, the current weir must continue to function and supply water to the WTW while the new works are under construction and until the final commissioning of the various components has occurred.

3. PROJECT COMPONENTS OF SCHEME UPGRADE

Earlier studies in 2016 [4] recommended upgrading the raw abstraction works by raising the existing Olifantspoort Weir while modifying and upgrading the raw water pump station. An updated study was undertaken in November 2021 [5] to investigate the feasibility of either modifying the existing infrastructure (weir and abstraction works) or constructing a new weir and abstraction works downstream of the existing structure to ensure the increased demand is met.

The Olifantspoort Off-Channel Storage Dam, as part of the upgraded scheme, was defined at concept design level as part of the overall project definition. Its main functions include buffer storage and being a silt trap for the WTW.

3.1. WEIR

Initially, the functioning of the existing weir was investigated [4] and it was recommended that the weir be raised by 2.8 m to increase the submergence at the river intakes and trash racks. It was also recommended that a fishway be incorporated into the weir. Following various design iterations [5] and due to the requirement to be fully functional even during the implementation/construction of the upgrade, it was found to be the least risky option from a supply risk point of view to construct a new weir and abstraction works downstream of the existing system. The layout of the proposed weir and surrounding infrastructure is presented in Fig. 1 below.

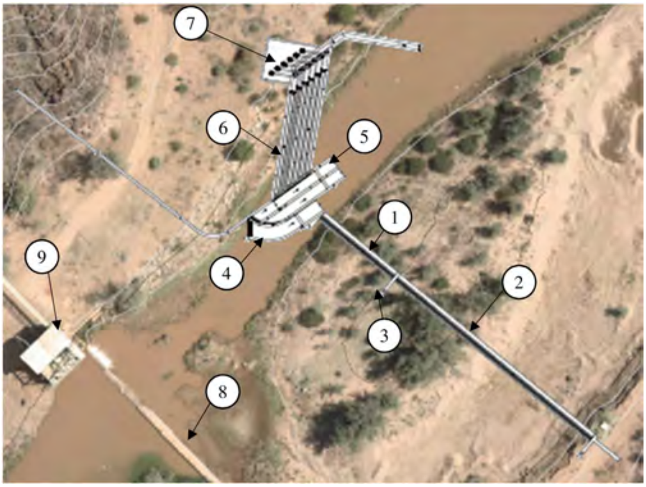

Fig. 1
Proposed Weir and Abstraction Works Layout [5]
Disposition proposée du déversoir et des travaux d'abstraction

1	New weir low notch	1	*Nouveau déversoir à encoche basse*
2	New weir high notch	2	*Nouveau déversoir de grande qualité*
3	New fish ladder	3	*Nouvelle échelle à poissons*
4	Boulder traps	4	*Pièges à rochers*
5	Gravel traps	5	*Bacs à gravier*
6	Pump canals	6	*Canaux de pompe*
7	Pump station	7	*Station de pompage*
8	Existing weir	8	*Déversoir existant*
9	Existing abstraction works	9	*Œuvres d'abstraction existantes*

3.2. New abstraction works

Following detailed hydraulic modelling ([4] and [5]), the proposed abstraction works will be self-scouring at the river intake (gravel trap gate closed) during floods larger than about 400 m^3/s (a 1-year flood), while secondary currents should keep the intake open. The local scour of the gravel trap would, however, improve by opening the gravel trap gate (automatic) when the discharge exceeds the 2-year flood when the weir is submerged while continuing to pump to the WTW. The abstraction works design is similar to other completed structures in Southern Africa [5].

Trash racks are proposed to be located under water, and generally, debris would not reach the trash racks. The trash racks could be cleaned by flushing the gravel trap near the end of a flood, which will drain the hoppers by reversing the flow or by raising the trash racks for cleaning during floods. Vertical sluice gates at the river intakes should be closed when the trash racks are raised for cleaning.

The gravel trap could be flushed manually during frequent small (frequent) floods (1-year floods) or at the end of large floods. The tailwater level downstream of the weir should be low enough so that free outflow conditions occur for maximum flushing efficiency of the sediment. Gravel trap canal flushing would be for short periods only (about 20 minutes) and during small floods or at the end of large floods. Manual operation of the gravel trap for flushing could be done for river flows below 200 m3/s.

Sedimentation to within 1 m of the weir crest is expected to occur during the first flood season following the upgrade construction and should not impact the normal operation of the abstraction works.

3.3. Off-channel storage dam

3.3.1. *Dam type selection*

A Dam Type Selection Study was completed in 2022 [1] to select the most suitable dam types for the site. The design was subsequently finalised in 2023. Construction is yet to commence.

After evaluating various dam type options, such as Hardfill (gravity) Dam, Concrete Faced Rockfill Dam (CFRD) and rockfill with geomembrane face, in relation to site conditions, the Rubble Masonry Concrete (RMC) multiple arch buttress dam type was selected. The abundant supply of rock material, scarce supply of clay or impermeable material, as well as the low construction and material cost using labour-intensive construction methods, make it an appropriate choice. Fig. 2 shows the layout.

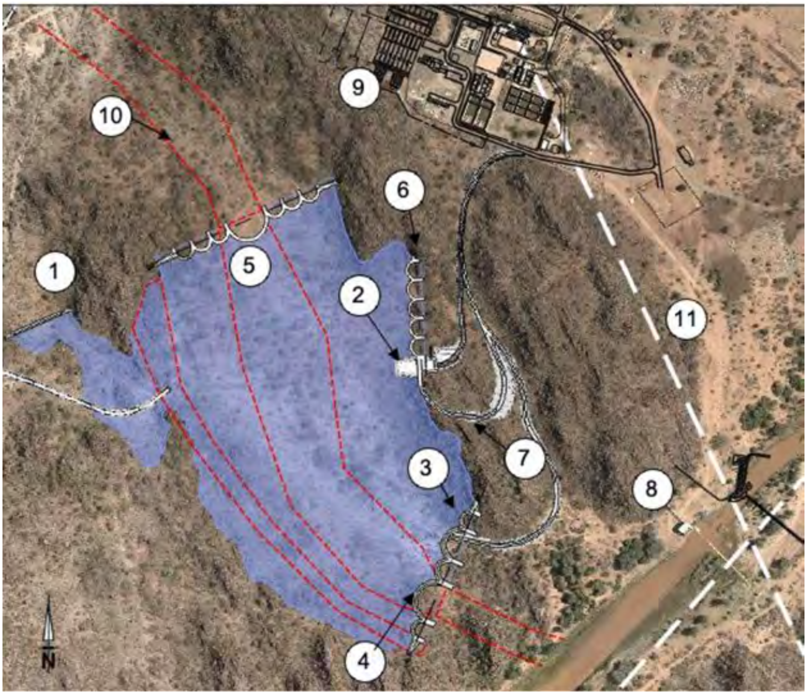

Fig. 2
Dam ring structure layout indicating 5 closure walls
Disposition de la structure en anneau du barrage indiquant 5 murs de fermeture

1	Spillway	1	*Déversoir*
2	Inlet/Outlet Works	2	*Ouvrages d'entrée/sortie*
3	Low-level Outlet	3	*Sorties de bas niveau*
4	Southern Wall	4	*Mur Sud*
5	Northern Wall	5	*Mur Nord*
6	Eastern Wall 1	6	*Mur Est 1*
7	Eastern Wall 2	7	*Mur Est 2*
8	Existing weir	8	*Déversoir existant*
9	WTW	9	*Travaux de traitement de l'eau*
10	Lineations	10	*Linéations*
11	Regional lineations	11	*Linéations régionales*

3.3.2. *Configuration*

The dam was designed as a ring structure incorporating five enclosure walls (including the spillway), as shown in Fig. 2, to enclose a valley to the west of the abstraction weir. The southern enclosure wall is the highest, and it comprises a 22 m high RMC multiple-arch buttress dam with a crest length of 230 m. The OCSD Dam is classified as Category II in terms of the South African Dam Safety Regulations [7]. The foundation comprises slightly weathered, moderately jointed hard igneous rock formations of Gabbronorite and Anorthosite.

Multiple-arch buttress dams comprise a hybrid of arch and gravity components. The stiff, bulky buttresses provide stability in the form of self-weight whilst the arches transfer the majority of their loading into the buttresses via compressive arch thrusting along the arch axis. The layout of the dam structure has been proportioned and aligned to best fit the site topography and geology, incorporating the precedent of similarly sized structures [3]. Two local lineations of thickened fractured rock pass through the dam site from the Northern Wall to the Southern Wall. The Southern Wall was configured to have a small arch in the centre to allow for two larger arches to span across the lineations, ensuring the buttresses are all founded on the competent rock.

Fig. 3 shows the arch and buttress configuration adopted for the Southern Wall. The arch thickness is 2 m and the buttress width ranges from 6.6 m to 8.1 m.

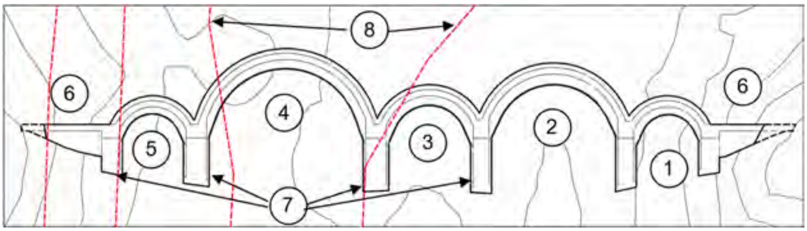

Fig. 3
Southern Wall Layout
Définition du mur sud

1.	Arch 1: inner radius = 11.2 m	1.	*Voûte 1*
2.	Arch 2: inner radius = 21.6 m	2.	*Voûte 2*
3.	Arch 3: inner radius = 14.7 m	3.	*Voûte 3*
4.	Arch 4: inner radius = 26.1 m	4.	*Voûte 4*
5.	Arch 5: inner radius = 11.2 m	5.	*Voûte 5*
6.	Gravity Wall	6.	*Mur poids*
7.	Buttress	7.	*Contrefort*
8.	Lineations	8.	*Linéations*

3.3.3. *RMC*

Rubble Masonry Concrete (RMC) is a combination of labour-based construction and mid-eighteenth-century concrete technology, brought into the 21st century through the application of Finite Element structural analysis. The first RMC dams were developed in Zimbabwe in the mid-1980s, and new-generation RMC arch dams were introduced in South Africa in 1995. The technology has proved very successful in offering an effective means of constructing durable, small to medium-sized dams at a particularly low cost. On a small scale, RMC dam construction has been demonstrated over and again to offer the lowest cost solution for a dam on competent foundations.

RMC comprises a monolithic matrix containing large stones or plums within a body of mortar. To minimise cost and optimise structural properties, it is necessary to ensure the maximum possible rock or stone content. The mix normally comprises 50 to 60% rock with 40 to 50% mortar. The mortar normally comprises 1 part cement to 4-6 parts of sand by volume. The stone sizes range from 50 mm to 300 mm in diameter, with a maximum stone size used in the RMC mix normally limited to one-third of the thickness of the member at the point of placement and/or the maximum weight that can be manhandled [9].

RMC dams have the highest opportunity to employ local labour compared to other dam types and thus offer an excellent opportunity for community involvement and development. RMC construction is labour-intensive and utilises hand tools instead of heavy machines and equipment. The RMC construction process involves a limited number of individual activities, namely stone collection, mortar mixing and RMC placement. The majority of labourers are engaged in RMC placement. If properly done, construction can progress relatively quickly. RMC offers the opportunity to increase the labour component of a project without a reduction in quality or design.

4. OFF-CHANNEL STORAGE DAM DESIGN CHALLENGES

4.1. Lineations

Evaluation of the geotechnical investigation results [2] indicated the presence of two prominent lineations within the basin extending through the northern and southern closure walls. These lineations were anticipated to be a reappearance of the typical N-S trending regional lineation observed in this area (Refer to Fig. 2).

The configuration of the southern and northern multiple arch closure walls was adapted to ensure the structural integrity of the closure walls. The radius of the arch in the particular location was increased which allowed the arch to span across the lineation while the buttresses were founded on a competent rockmass adjacent to the lineations. Consolidation on the footprint of the arch (spanning across the lineation) will provide additional foundation integrity.

4.2. Permeability of ridges

Basin impermeability, including the basin's upper reaches, is required to ensure that significant seepage does not occur. The formation of the highly permeable jointed rockmass outcroppings at the ridges is described in [6]. Cooling joints formed during the process of cooling subdivided the rock into a number of intact rock blocks, consequently forming highly permeable jointed rockmass ridges. Permeability testing (water testing) at the ridges indicated various localised permeable areas.

Extensive grouting curtains along the ridges (forming the basin of the OCSD) were consequently recommended [3]. While the provision of a grout curtain will decrease the permeability of the ridges, the rockmass will never be completely impermeable. The grout curtain depth was consequently extended to a depth where an insignificant change in anticipated seepage was noted with an increase in grouting depth.

4.3. Structural behaviour

The three multiple-arch buttress configurations forming part of the Olifantspoort OCSD were analysed using the finite element analysis (FEA) method to evaluate the dam for structural integrity against a material failure. Under the critical load case and the assumptions of a linear elastic material model for RMC, the FEA of the Olifantspoort Dam indicated that a localised portion of the dam heel is expected to undergo yielding, as the computed tensile stresses exceed the RMC material strength.

Subsequent nonlinear analyses indicated that these localised high tensile stresses are expected to redistribute due to the nonlinear elastoplastic nature of RMC. Three nonlinear material model approaches were adopted for comparison, all having a positive outcome in relation to the alleviation of local tensile stress concentrations output by the linear elastic analyses and computation of realistic values synonymous with the material behaviour of RMC [8]. Fig. 4 shows the finite element model.

The outcome of the FEA provided confidence in the ability of the structure to safely transfer all defined loadings to the foundation without the development of internal stresses that exceed the specified RMC material strength criteria.

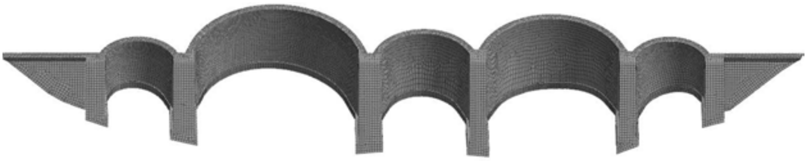

Fig. 4
Finite element model of Southern Wall showing the downstream face
Modèle par éléments finis du mur sud montrant la face aval

4.4. Outlet works

Various options for the location of the inlet/outlet works were investigated. These were evaluated in terms of access, bridge length, pipe hydraulics (supply to the WTW), operation and maintenance requirements, and excavation quantities. Excavated material from the outlet foundations is earmarked for the RMC construction. Cut volumes were optimised together with the inlet/outlet works layout.

The design of the inlet/outlet system must be of adequate capacity to meet the full supply demand, even during periods of extended maintenance. It is consequently the accepted practice for primary water supply dams in South Africa that a full system duplication is provided, with twin stacks, twin conduits through the dam and twin outlets, etc. The benefits of this policy have been proven in practice at many projects over many years.

Due to the relatively shallow dam basin, large outlets were required to meet the demand supplied under gravity to the WTW. 1.4 m diameter pipes were selected to meet the demand of 3.9 m3/s. It was also necessary to ensure that sufficient submergence was provided at the bottom intakes to limit vortex formation. The inlet/outlet works could not be used for emergency drawdown as it was located higher in the dam basin. A second outlet for the OCSD was provided, comprising an outlet pipe cast into the second arch section of the Southern Wall, which will ensure a low invert level. A 400 mm diameter pipe, with an upstream coarse screen, wall-mounted sluice for isolation, and downstream gate valve (control valve), was proposed.

5. CONCLUDING REMARKS

This paper discusses the Olifantspoort project background, the need for the scheme, constraints such as high sediment load in the river dictating the preference for an off-channel (off-river) storage dam, operational constraints, and design challenges related to the dam.

The advantages of using RMC for the dam especially when typical embankment material is not available as well as providing appropriate solutions for tricky foundation conditions were discussed. Additionally, the importance of considering de-silting at the abstraction point in the river and at the storage facility was stressed. Considering existing operational requirements during implementation at an early project stage may lead to new infrastructure instead of only upgrading existing infrastructure.

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QUANTIFYING THE IMPACT OF CHANGING CLIMATE ON DAM OPERATION: A REVIEW FOR ENGINEERING PRACTITIONERS (*)

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CANADA

SUMMARY

Currently, dams control and regulate the flow of approximately half of the planet's major river systems. Climate change is expected to increase the global risk of flooding, primarily due to shifts in spatial distribution, temporal distribution, and intensity of precipitation events. The operation of dams typically alters the frequency, duration, and timing of flooding events. However, reservoir water surfaces emit about a billion tonnes of greenhouse gases each year, primarily through the release of methane from decaying vegetation. This accounts for 1.3% of the total annual anthropogenic greenhouse gas emissions globally, making dams a significant contributor to climate change while also being impacted by it.

Climate change could affect various aspects of dam operation and maintenance, which heavily rely on the water balance comprising inflow, outflow, and storage. It is vital to understand the reciprocal implications of climate change and dam operations for implementing appropriate adaptation and mitigation strategies. This paper reviews various factors affecting these water balance components and highlights potential risks and impacted areas.

**Quantifier l'impact du changement climatique sur le fonctionnement des barrages : une étude pour les praticiens de l'ingénierie*

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The study explores available literature and compares it with mandates and instructions from acts, guidelines, and standards provided by local, national, or international entities. While managing extremes is part of the operator's concerns, the review suggests that operators are more focused on daily operations. Therefore, practical methods to evaluate these impacts on daily dam operations are provided. Additionally, various gaps in the state of the art are identified, which require further research to be addressed.

RÉSUMÉ

Les barrages contrôlent et régulent le débit d'environ la moitié des principaux systèmes fluviaux. Le changement climatique devrait accroître le risque d'inondation au niveau mondial, principalement en raison des changements dans la distribution spatiale, la distribution temporelle et l'intensité des précipitations. L'exploitation des barrages modifie généralement la fréquence, la durée et le moment des inondations. Cependant, les surfaces d'eau des réservoirs émettent environ un milliard de tonnes de gaz à effet de serre chaque année, principalement par la libération de méthane provenant de la décomposition de la végétation. Cela représente 1,3 % du total des émissions annuelles de gaz à effet de serre d'origine anthropique dans le monde, ce qui fait des barrages un contributeur important au changement climatique, tout en subissant son impact.

Le changement climatique pourrait affecter divers aspects de l'exploitation et de l'entretien des barrages, qui dépendent fortement du bilan hydrique comprenant l'afflux, l'écoulement et le stockage. Il est essentiel de comprendre les implications réciproques du changement climatique et de l'exploitation des barrages pour mettre en œuvre des stratégies d'adaptation et d'atténuation appropriées. Ce document passe en revue les différents facteurs qui affectent ces composantes de l'équilibre hydrique et met en évidence les risques potentiels et les zones touchées.

L'étude explore la littérature disponible et la compare avec les mandats et les instructions des lois, des lignes directrices et des normes fournies par des entités locales, nationales ou internationales. Bien que la gestion des extrêmes fasse partie des préoccupations de l'opérateur, l'étude suggère que les opérateurs se concentrent davantage sur les opérations quotidiennes. Par conséquent, des méthodes pratiques pour évaluer ces impacts sur les opérations quotidiennes des barrages sont fournies. En outre, diverses lacunes dans l'état de l'art sont identifiées et nécessitent des recherches supplémentaires.

1. INTRODUCTION

Currently the flow of about half of the planet's major river systems is controlled and regulated by dams (Grill, *et al.*, 2019). These dams control one-sixth of the annual continental discharge to oceans (Hirabayashi, *et al.*, 2013) and (Jongman, J. Ward, & C.J.H. Aerts, 2012). Climate change is expected to increase the risk of flooding globally, and this is mainly due to the changing spatial /temporal distribution and intensity of precipitation events (Prein, *et al.*, 2017) and (Milly, Wetherald, Dunne, & Delworth, 2002). Dam operations generally alter the frequency, duration, and timing of flooding events. Various techniques used to assess global flooding risk have demonstrated that the total global exposure to river and coastal flooding would increase threefold from 2010 to 2050 based on population density at risk, and by 2.5 times based on land use (Jongman, Ward, & Aerts, 2012).

While climate change impacts flooding and dam operations, dams also contribute to climate change since reservoirs emit a billion tonnes of greenhouse gases each year, mostly through the release of methane from decaying vegetation. This equates to 1.3% of the total annual anthropogenic greenhouse gas emissions globally (Deemer, *et al.*, 2019) and ensures that dams are a major contributor to climate change. Therefore, understanding the implications of a changing climate on the operation of dams, and vice versa, is vital in identifying appropriate adaptation and/or mitigation strategies.

This literature review examines the impacts of climate change on dam operation, with a focus on engineering practices. It begins by highlighting key research into the influence of climate change on reservoir balances, including inflows, outflows, changes in storage, spills, and other variables. The impacts of climate change on dam operational models are analyzed and discussed. Finally, the review explores how climate change considerations have been incorporated into regulatory frameworks. Overall, this review offers a comprehensive summary of the progress in dam operation in the context of climate change.

2. CLIMATE CHANGE'S IMPACT ON RESERVOIR WATER BALANCE

Climate change affects a reservoir's water balance and, in turn, various ensuing aspects of dam operation and maintenance. The reservoir water balance has three components: inflow, outflow and storage. The various factors affecting these components and their potential risks and impacts are reviewed in detail below.

2.1. INFLOW

Climate change is expected to have a significant but varied impact on inflows by altering precipitation, snowmelt, and hydrological regimes. According to the Intergovernmental Panel on Climate Change (IPCC), annual mean precipitation has increased in most mid-latitude regions in the Northern Hemisphere, parts of the Southern Hemisphere such as the west coast of South America, and in the Arctic. Mean annual precipitation decreases have been observed in many subtropical and temperate land regions, such as the Mediterranean, southwest North America and southern Africa. IPCC's long-term projections (2081-2100) expect over 30% increase in annual precipitation in Artic regions and over 30% decrease in areas such as Mediterranean, southwest US and southern Africa under high emission scenarios (IPCC, 2023). Shifts in precipitation intensity, and timing, are also expected to be significantly impacted due to climate change, with more extreme rainfall events and shifting seasonal rainfall patterns. In regions where snowmelt contributes to inflow, rising temperatures are expected to lead to earlier snowmelt and reduced snowpack accumulation (IPCC, 2023). Climate change is also expected to impact the hydrological regimes of some areas, affecting soil moisture levels and groundwater recharge rates, impacting fluvial patterns and thus inflows to reservoirs behind dams.

A number of case studies have sought to evaluate the impact of climate change on resevoir inflows. For example, (Zabalza-Martínez, *et al.*, 2018) evaluated various future land cover and climate change scenarios and their effect on Boadella-Darnious reservoir inflow in Spain. That study used the regional hydro-ecologic simulation system (RHESsys) to analyze impacts from 2021 to 2050 and found a clear decrease (i.e., -31%) in inflow over that period. (Norouzi, 2020) used non-parametric Mann-Kendal trend analysis to show that inflow to the upstream basin of the Dez Dam in Iran would decrease significantly, compromising its performance if a water resource management plan was not implemented. In another study, (Zareian, Eslamian, & Hosseinipour, 2014) used 15 Atmosphere-Ocean General Circulation Models to predict the inflow to the Zayandeh-Rud dam from 2015 to 2074 as compared with observed data from 1971 to 2000. Their comparison revealed that the maximum reduction in runoff would occur in fall while the minimum reduction would occur in winter, pointing to a seasonal shift of inflow in addition to an overall annual reduction. Generally, inflows are expected be significantly impacted by climate change. However, these impacts will be varied and will depend on the specific location of each dam.

2.2. OUTFLOWS AND DEMANDS

Water stored behind dams is often used in to serve multiple purposes, including for drinking (municipal water supply), agricultural consumption, hydropower, etc. Climate change is generally understood to augment these demands. Increases in municipal water demand due to climate change have been documented in many studies for various regions. This could range from 2% (Roshani, Kleiner, Colombo, & Salomons, 2022) to more than 10% of daily per capita consumption per degree of increase in the daily temperature (Staats, 2018) and (Akuoko-Asibey, Nkemdirim, & Draper, 2013) in the Canadian context. Such an observation has been discussed many [(Maidment & Miaou, 1986), (Mote, *et al.*, 1999), (Protopapas, Katchamart, & Platonova, 2000), (Downing, *et al.*, 2003), (Sadiq & Karney, 2004), (Neale, Carmichael, & Cohen, 2007), (Praskievicz & Chang, 2009), (Dimkić, 2020), and (Rasifaghihi, Li, & Haghighat, 2020)]. More than 27% of the 482 world's largest cities (i.e., 233 million people) will experience water demands that exceed their available surface water by 2050 by (Flörke, Schneider, & McDonald, 2018). An additional 19% of the world's largest cities have a high potential for conflict between the urban and agricultural sectors since both sectors cannot obtain their estimated future water requirements[†]. Crop yield has declined by 11% to 21% of the total irrigated acres in the southwestern US mostly due to surface water shortages (Elias, *et al.*, 2016). The North China Plains will witness a 6% increase in agricultural water consumption for wheat under the Intergovernmental Panel on Climate Change's (IPCC) A2 and B1 scenarios (Mo, Liu, Lin, & Guo, 2009).

Hydropower plants account for 15% of worldwide electricity production (World Energy Council, 2013). Significant warming (i.e., 6.25°C) is projected to result in a decline of hydropower production in May-June for snow-dominated hydropower plants in India (Ali, Aadhar, Shah, & Mishra, 2018). The annual mean hydropower would change by -12% to +2%, and spills are projected to change from -49% to +152% in the Peribonca water resource system in Quebec under climate change scenarios by 2050 (Minville, Brissette, & Leconte, 2010). Dams located in colder climates that rely on glacier meltwater might experience an increase in their hydropower production sooner than that. Iceland's National Power Company has already implemented measures to increase its hydropower production due to increased glacier meltwater (Braun & Fournier, 2016). It is worth noting that the glacier-melting rate is expected to plateau in 2030, remain constant until 2080 and decrease after that.

2.3. Storage, spillover, and other parameters affecting dams operation

Although the exact mechanism is still uncertain, climate models indicate that a high number of extreme events such as urban flooding and droughts are expected to occur, although this expectation does not include all the regions in Canada. The models also predict increased coastal flooding in many areas such as Canada due to local sea level rise with high certainty (Bush, 2019). There is a good possibility that the change in the distribution, magnitude and frequency of these extreme

[†]The cited reference is silent on whether agricultural technological advance (e.g., hydroponics, etc.) have been considered in their predictions.

events will directly influence the hydrological and geological variables used to estimate a reservoir volume, and/or the capacities of spillways or other appurtenances (Ouranos, 2015) (Turcotte, Burrell, & Beltaos, 2019) (BC Hydro Generation Resource Management, 2012) (ICOLD, 2016). These changes especially affect hydropower dams.

(Blackshear, *et al.*, 2011) studied the impact of climate change on various types of hydropower production, where they compared dam types, reservoir sizes and the area to volume ratio of the reservoirs under four climate trends, while accounting for evaporation, discharge, temporal variability of climate variables, and glacier melt. The results indicated that pumped-storage hydro dams were only vulnerable to evaporation and, although dams with larger reservoirs were more resilient to temporal variability of precipitation (i.e., floods, droughts, etc.), these dams were mostly affected by changes in evaporation, discharge and glacier melt. Contrary to storage dams, run-of-river dams were mostly vulnerable to the temporal variability of climate variables, which is expected since these dams often have minimal storage capacity. Also, dams with a high area-to-volume ratio are more vulnerable to evaporation than dams with a lower area-to-volume ratio.

Changing climate has been shown to affect sediment production and transfer processes on hillslopes and through channels, possibly due to changes in precipitation, runoff, temperature and land cover. The projected changes in precipitation and air temperature lead to a decrease in sediment yield (-48%) and debris-flow occurrence (-23%) in the Swiss Alps (Hirschberg, *et al.*, 2020). In this study, the authors combined a hillslope-channel sediment cascade model with a weather generator based on the climate change projections, which allowed them to quantify the climate change impacts and their uncertainties on sediment yield.

Although the mechanism of how climate change would affect the stability of slopes is still debated, it has been discussed in detail by (Chiarle, Geertsema, Mortara, & Clague, 2011) The authors claim that slope stability is affected by the presence of the cryosphere and its degradation in mountain regions (e.g., the Western Cordillera in Canada and the European Alps). The authors also indicated that, in lower elevations in the mountains, changes in seasonal frost activity, snowmelt and rain could modify the frequency of debris flows.

The gate equipment operation could be affected by cold and ice, as mentioned in the Dam Safety Guidelines (Canadian Dam Association, 2013). In fact, icing was one of the contributing factors leading to the Spencer Dam break in Nebraska, USA, in 2019, preventing the operators from removing the stop logs from the gates (Association of State Dams Safety Officials, 2020). It is difficult to quantify the impact of climate change on the production of frazil ice, however, delayed formation of frazil ice or the absence of ice cover on rivers could potentially cause ice jams and clog intakes and turbines. This could jeopardize the infrastructure and compromise their performance (Turcotte, Burrell, & Beltaos, 2019) (BC Hydro Generation Resource Management, 2012) (ICOLD, 2016) (Andrishak & Hicks, 2005) (GENIVAR, 2010).

In the previous sections, most parameters that affect a dams' water balance were discussed. However, other dam-related factors could be impacted by climate change and could indirectly influence dam operation. These include, but are not limited to, the following (please note that the literature covering these parameters is either too scant to warrant their own section or their effect on operation is indirect):

- *Water quality:* Temperature (Messina, Couture, Norton, Birkel, & Amirbahman, 2020) and precipitation (Mosley, 2015) have been shown to impact water quality in lakes and reservoirs through changes in turbidity (Lee, Kim, Park, & Choi, 2015), nutrient loading (Salila, Sharma, & Singh, 2020), and wind (Beaver, *et al.*, 2013). Various operation strategies (e.g., releasing times and volume) could affect the water quality as well.
- *Environmental water rights:* Most large dams are required to release their main river's base flow to satisfy downstream water rights and environmental requirements. Environmental demands could be affected by temperature and precipitation; therefore, these requirements could impact the dam's outflow.
- *Pore water pressure in earthen dams:* Extreme climatic events (e.g., flooding) are expected to increase due to climate change. Many reservoir dams are designed to capture these floods and store the water for summer and fall use when the precipitation volume is lower. If a dam is expected to overflow during a flood, dam owners often choose to release part of their existing stored water to create room to capture the new flood runoff. This is often performed in a short period and could lead to a rapid drawdown of the reservoir water level. Pore pressure in earthen dams could increase significantly with rapid draw-down events, which has the potential to jeopardize the dam's stability. Climate change could increase the probability of these events, and a reliable fore-casting system could reduce this probability by providing enough time to per-form the drawdown over a longer period of time.

3. CLIMATE CHANGE IMPACT ON DAM OPERATION MODELS

Dam operation models are a key resource for engineering practitioners to assist in identifying optimal dam operations to help manage their water resources. Fundamental to an effective dam operation model is an accurate prediction of the overall reservoir water balance which includes the storage volume of water in the reservoir, projected inflow and the water demands of various users (Loucks, Water Resources Planning. Analysis, 1981). Once an effective water balance model is developed for a dam, an operation model or set of rules/guidelines can be devel-oped. These rules help engineers satisfy various water requirements such as irri-gation, electricity generation, domestic water use, environmental stream flows, flood protection, etc. (Fallah-Mehdipour, Bozorg Haddad, & Mariño, 2012).

Significant advances have occurred in dam operation models, in large part due to improvements in computational power and artificial intelligence. However, the impact of climate change poses new challenges to these models. The following sections aim to explore the effects of climate change on key components of dam operation models, including climate variable prediction, inflow and outflow prediction, and overall reservoir operation optimization. By examining how climate change is expected to influence each model component, this review provides insights into the future resilience and adaptability of dam operation models in the face of changing environmental conditions.

3.1. Estimating climate variables

(Němec & Schaake, 1982) and (Klemes, 1985) were among the first who raised the issue of sensitivity of water resource systems to climate variations and evaluated the anticipated sensitivity. They showed that reliability (i.e., the probability of successfully satisfying demand) decreases much faster than any decrease in precipitation or increase in evapotranspiration losses. Later (Cohen, 1986) and (Gleick, 1987) used water balance models to simulate the system response to various climatic scenarios. (Kaczmarek, 1990) produced a set of scenarios by changing runoff parameters stochastically and measured reservoir's reliability and resilience (i.e., a measure of how quickly a reservoir will recover from afunctional failure). Kaczmarek showed that, despite moderate changes in inflow, the values of the performance criteria are substantially different. The main issue with these studies is the use of General Circulation Models (GCMs) to estimate hydrological processes at the spatially smaller catchment level (Wilby, 1994). To solve this issue (Hughes & Guttorp, 1994), (Nkemdirim & Purves, 1994) and (Burn & Simonovic, 1996) used temperature as a climate change indicator variable and partitioned their data to warm years (representing the climate change condition) or cool years (representing the status quo) based on average annual temperature. This removes the difficulties of down-scaling GCMs; however, it significantly relies on past data which does not permit extrapolation of potentially more extreme conditions, something which can result in the underestimation of such events (Burn & Simonovic, 1996).

Downscaling refers to techniques that bridge the gap between what climate modellers are currently able to provide using GCMs and what engineering practitioners require at a smaller scale to evaluate localised impacts. Downscaling methods (DSMs) are especially important for estimating rainfall and runoff (Keteklahijani, Alimohammadi, & Fattahi, 2019). Two main methods for downscaling are statistical and dynamical approaches. Regression methods, weather pattern circulation-based approaches, and stochastic weather generators are all considered statistical downscaling methods (Wilby & Wigley, 1997). Empirical statistical downscaling (ESM) methods are commonly used in this category. ESM often includes a statistical transformation function to adjust observation or raw climate model outputs to generate future climate scenarios at the local scale (Chiew, *et al.*, 2009) and (Wang, Ranasinghe, Maskey, van Gelder, & Vrijling, 2016).

With dynamic approaches, physical processes are simulated at a local scale using regional climate models (RCMs). The main issue preventing their wider adoption is their complexity and the significant computational requirements inherent in their application (Maurer & Hidalgo, 2008) and (Tabor & Williams, 2010). Although RCM based techniques are more precise than GCMs they often require bias correction (Durman, Gregory, Hassell, Jones, & Murphy, 2001) which adds to their complexity. Considerable research has been done to understand how uncertainties associated with various DSMs impacts temperature and precipitation estimations (Wang, Ranasinghe, Maskey, van Gelder, & Vrijling, 2016), (Gudmundsson, Bremnes, Haugen, & Engen-Skaugen, 2012), and (Vrac & Ayar, 2017), and how they affect runoff (Hawkins & Sutton, 2011), (Asadieh & Krakauer, 2017), (Milly, Dunne, & Vecchia, 2005), (Gizaw, Biftu, Gan, Moges, & Koivusalo, 2017), (Mandal & Simonovic, 2017) and (Keteklahijani, Alimohammadi, & Fattahi, 2019). These uncertainties are often minimized using an ensemble of various DSMs (Hawkins & Sutton, 2011), (Knutti, Furrer, Tebaldi, Cermak, & Meehl, 2010) and (Eisner, *et al.*, 2017).

Various organizations such as the U.S. Geological Survey (USGS, 2023), and Pacific Climate Impacts Consortium (PCIC, 2023), provide downscaled climate projections under different scenarios. They also offer recommendations on the proper DSMs for the locale under study. This effectively eliminates the burden of downscaling and yields watershed level climate data. The predicted temperature and precipitation resulting from DSMs are fed into hydrological models to estimate runoffs.

3.2. Inflow prediction

Dam operation depends heavily on the inflow to the reservoir. An efficient reservoir management system requires an adequate water level in the reservoir, protection of the environment downstream, safety of people and goods, and flood and drought mitigation (Souza, Martinho, Rocha, Christo, & Goliatt, 2022). Having a relatively accurate prediction of the inflow for a reasonable time ahead can help in making the most effective decisions for balancing reserves and outflow. Reservoir inflow prediction has been studied over the last few decades (Esmaeilzadeh, Sattari, & Samadianfard, 2017); (Bashir, Shehzad, & Hussai, 2019); (Allawi, *et al.*, 2019). Physically based models aim to predict inflow by using a set of equations that represent conceptual models and physical laws, such as conservation of mass and momentum (Chua, 2012). Data-driven modelling approaches, like machine learning, aim to identify patterns underlying observed information that reveal the relationships between different variables and inflow, often without explicitly identifying the physical processes that occur within the watershed. Although complex data-drive models can produce accurate inflow predictions, they typically lack transparency and are not well suited to the reproduction of results (Elshorbagy, Corzo, Srinivasulu, & Solomatine, 2010).

Among data-driven methods, machine learning techniques have demonstrated their ability to model hydrological variables. Recent studies such as (Nearing, Klotz, & Sampso, 2021) and (Zounemat-Kermani, Batelaan, Fadaee, & Hinkelmann, 2021) have shown the proficiency of machine learning methodologies in capturing intricate and non-linear patterns in data, making them a promising alternative to current prediction methods for diverse hydrological applications. Machine learning has been used to predict rainfall forecasting, river flow forecasting, and overall reservoir inflow (Yaseen, Sulaiman, Deo, & Chau, 2019); (Ehteram, *et al.*, 2019); (Allawi, *et al.*, 2019); (Singh & Ray, 2021).

Rainfall is a key variable governing reservoir inflow. Thus, a rainfall forecast is important for predicting inflow. A variety of machine learning models and methods have been applied to predict rainfall data, including Bayesian Linear Regression (BLR), Boosted Decision Tree Regression (BDTR), Decision Forest Regression (DFR), Neural Network Regression (NNR), and Extreme Learning Machine (ELM) (Ridwan, *et al.*, 2021); (Kalteh, 2019). These models have exhibited high accuracy in predicting rainfall over different time horizons, from short-term (e.g., hourly or daily) predictions (Zhou, Ren, He, & Liu, 2021) to long-term (e.g., seasonal or yearly) (Feng, Wang, Liu, Ji, & Ni, 2020). The combination of wavelet analysis and ELM has been proposed to capture different patterns in rainfall data and improve forecast accuracy (Kalteh, 2019). Support Vector Machine (SVM) is also used to develop a supervised learning algorithm for hourly rainfall forecasting, considering the time autocorrelation of rainfall (Zhou, Ren, He, & Liu, 2021). Random Forest (RF), Support Vector Machine (SVM), and artificial neural network (ANN), have been used to develop probabilistic seasonal rainfall forecasting models. An ensembled version of these models, combined with the majority voting strategy, has also been shown to be effective in boosting the performance of rainfall prediction (Sani, Abd Rahman, & Ad, 2020). Although all of these models implicitly account for climate change, several have developed techniques to explicitly incorporate climate change into their rainfall predictions. These techniques include using large-scale climate pattern indices such as El Nino-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Madden-Julian Oscillation (MO) as modelling input variables, integrating outputs from GCMs to reflect future climate projections, using machine learning to bias-correct precipitation predictions from GCMs, or combining multiple GCMs into a single model (Anaraki, Kdkhodazadeh, Morshed-Bozorgdel, & Farzin, 2023) (Le P. V.-G., 2023). Future research is needed to better understand and compare which models accurately account for climate change and improve both short- and long-term precipitation prediction for reservoir operation.

Streamflow prediction has also benefitted from advances in machine learning. Machine learning algorithms such as emotional neural network (ENN) (Cui, *et al.*, 2020), random forests, gradient boosting machine, extreme learning machine, M5-cubist, elastic net (Tian, He, Srivastava, & Kalin, 2021), feed-forward neural network (FFNN), convolutional neural network (CNN), long short-term memory (LSTM), and gated recurrent unit (GRU) (Le, *et al.*, 2023), have been used to translate the rainfall forecast and other variables into streamflow forecasting. These studies have shown that recurrent models, such as LSTM and GRU, exhibit better performance and stability compared to other models.

Reservoir inflow models typically incorporate streamflow and river forecasts, alongside various other input variables, to forecast the net water inflow into a reservoir. Due to the multitude of input variables and their non-linear correlation with net inflow, reservoir inflow models are excellent candidates for machine learning algorithms (Hong J, 2020). A study conducted by (Huang, Chang, & Lin, 2022) compared seven machine learning algorithms for predicting reservoir inflow during extreme weather events. The results indicated that, while specific algorithms proved effective for short, medium, and long-term forecasts, not all individual algorithms consistently performed well across all events. To address this, the researchers utilized ensemble methods and the Switched Prediction Method (SP) to integrate multiple machine learning techniques, resulting in improved accuracy of inflow forecasting. In their work, (Herbert, Asghar, & Oroza, 2021) introduced a method for long-term forecasting of water supply and inflow volumes using deep learning algorithms. They trained an encoder-decoder algorithm with historical snow water equivalent (SWE) and reservoir inflow time-series data, enabling predictions of reservoir inflow for future time steps during the April-July runoff period. The study assessed the proposed method using 30 years of reservoir inflow and SWE data from the Upper Stillwater Reservoir in Utah. The most effective model was found to be an LSTM encoder-decoder algorithm with 16 nodes per layer. Notably, the long-term water supply forecasts generated by their optimal deep learning algorithm outperformed statistical methods and were comparable to those of the ESP (Ensemble Streamflow Prediction) with a 50% exceedance probability forecast, evaluated over five consecutive hold-out periods. (Yaseen, Sulaiman, Deo, & Chau, 2019)explored the applicability of an enhanced version of the extreme learning machine (EELM) model for predicting river inflow in tropical environments. The EELM model was introduced as a precise alternative for modeling tropical river inflow patterns. The study revealed that the EELM model outperformed both the classical ELM and the support vector regression (SVR) model based on various statistical metrics, including the coefficient of determination (R), Nash-Sutcliffe efficiency (Ens), Willmott's Index (WI), root-mean-square error (RMSE), and mean absolute error (MAE).

In a recent study, (Kim, Lee, & Kim, 2022) used 20 years of precipitation and dam inflow data to identify the best deep-learning model for forecasting the Andong and Imha Dams' inflow. Their findings showed that recurrent neural network-based models provided more accurate predictions compared to traditional models across various scenarios. Additionally, (Kao, Zhou, Chang, & Chang, 2020) introduced an LSTM-ED model for multi-step-ahead flood prediction, which outperformed a feed-forward neural network-based model in terms of accuracy, stability, and reliability. Furthermore, (Chen, Wang, & Tsou, 2013) compared conventional regression and ANN models using data from 27 typhoons in Taiwan's Linbien River Basin, finding that the ANN model produced superior statistical results.

(Saab, *et al.*, 2022) proposed a deep learning neural network (DLNN) using LSTM for inflow prediction. They used a genetic algorithm (GA) to find the best combination of variables with the highest capability of predicting inflow. Their model demonstrated higher accuracy for daily inflow prediction compared to monthly predictions, utilizing a 10-year time series of inflow with a one- to five-month time lag to forecast one month ahead. (Martinho, Saporetti, & Goliatt, 2023) evaluated five machine learning methods for dam inflow prediction in Mozambique. Utilizing extreme gradient boosting (XGB) showed the best performance. They employed autocorrelation functions (ACFs), partial autocorrelation functions (PACFs), and cross-correlation functions (CCFs) to detect influential input variables for inflow prediction. They used 15 years of time series data for streamflow, rainfall, evaporation, and humidity to forecast inflow for the next 1, 3, 5, and 7 days. XGB, XGB-LASSO, and XGB-PMI outperformed the other models, with XGB-LASSO providing similar results with less complexity. (Sharma, Kumar, Padmalal, & Roy, 2023), tested four machine learning models for streamflow prediction in three rivers with different climatic and geological settings. The random forest (RF) model outperformed other models for daily streamflow, while the multivariate adaptive regression splines (MARS) model showed the best performance for monthly streamflow prediction in the Suvarna River. SVM and RF showed the best performance for daily and monthly streamflow, respectively, in the Aghanashini River. For severe and extreme flow simulation, MARS outperformed other models. The models employed various independent variables such as daily streamflow, daily rainfall, and basin-averaged daily maximum and minimum temperature, with specific time lags considered for prediction purposes.

The general formulation for the inflow forecasting model can be proposed as equation 1. A machine learning model must be accurately trained to learn spatial and temporal patterns that exist in the independent variables to be used as a surrogate for estimation function, F.

$$
\begin{aligned}
In_J^{t+k} = F\big(In_J^t, In_J^{t-1}, ;, In_J^{t-L}, \quad R_J^t, R_J^{t-1}, \ldots, R_J^{t-L}, \\
H_J^t, H_J^{t-1}, \ldots, H_J^{t-L}, \quad E_J^t, E_J^{t-1}, \ldots, E_J^{t-L}, \quad T_J^t, T_J^{t-1}, \ldots, T_J^{t-L}\big)
\end{aligned}
\tag{1}
$$

Where, $In_{(lat,lon)}^{t+k}$ is the predicted river inflow at time (t+k) and location (lat,lon), k is the number of steps ahead (forecast horizon), In_J^t, R_J^t, H_J^t, E_J^t and T_J^t are the inflow, rainfall, humidity, evaporation, and temperature measured at time t and at locations J $\in$ {(lat,lon) and its upstream neighbors}, *L* is the number of the time-lags, and F is an estimation function that represents the input/output relationship provided by a machine learning model. Considering equation 1, the key practical challenges for accurate inflow forecasting that must be investigated in any study (aimed at using machine learning for inflow prediction) would be identification of the effective variables, the appropriate time lag, the effective upstream neighborhood, the forecast horizon, and the machine learning model. Furthermore, most of the current machine learning methods are trained on the historical time series of the variables to extrapolate the inflow for the future. However, historical data may not be representative of the current climate. Research must be conducted to include climate change patterns in the training process of the machine learning model.

In general, a variety of machine learning models are investigated to predict inflow. These models range from conventional methods like the random forest, XGBoosting, and support vector machines to the most modern approaches like deep learning using recurrent or convolutional models. Although conventional models like RF showed promising results, modern methods enjoy more flexibility to learn complex spatial and temporal patterns. Specifically, the recurrent machine learning models like LSTM and GRU can model time series effectively and have often showed better results compared to other methods. Variables such as the historical and current rate of inflow, temperature, humidity, and precipitation, with different time lags and horizons, ranging from hourly to daily, have been utilized for these predictions. Overall, to better ensure an accurate inflow prediction, a variety of machine learning models and input variables should be tested and the most accurate combination selected based on these results.

3.3. Outflow demand

Water stored in reservoirs is released for a variety of reasons. This includes hydropower generation, agriculture and municipal use, as well as for environmental and recreational purposes. The amount and timing of these demands can significantly impact operation. Furthermore, these demands are climate dependent. Therefore, climate change is an important factor in their prediction.

A major objective for most large dams is the production of hydro-electricity. A variety of models have been developed to help predict and schedule electricity production from dams, ranging from regression models, to dynamic programming models and machine learning models (Niu, *et al.*, 2019). These models focus on prediction or optimization for electricity production, ensuring that outflow directed through the turbines is a key variable and/or constraint.

(Niu, *et al.*, 2019) compared the performance of three regression methods including artificial neural network (ANN), extreme learning machine (ELM), and support vector machine (SVM) in predicting hydro energy generation. They showed that these methods outperformed linear regression (Niu, *et al.*, 2019). Similarly, (Sattar Hanoon, *et al.*, 2022) showed that ANN and SVM perform better than an autoregressive integrated moving average (ARIMA) model at the Three Gorges Dam in China.

Machine learning has recently demonstrated promising outcomes in forecasting short-, medium-, and long-term deviations in hydropower production. Turkey's hydroelectric generation prediction has been investigated via deep learning models based on long short-term memory (LSTM). Historical power generation data and LSTM models have proven to be effective in long-term prediction (Bulut, 2021). The efficacy of LSTM and gated recurrent unit (GRU) models were also examined to predict wind- and hydro-based renewable energy generation using hourly time series of power generation in Turkey. This study indicated that LSTM models are outperforming others techniques (Gökgöz & Filiz, 2021). A Monte Carlo algorithm was used to create a synthetic power production dataset by (Ying, Liu, & Han, 2020). This synthetic dataset was then used to train an ELM model to predict hydropower production capacity. The ELM model trained using the synthetic dataset outperformed an ELM model trained using the limited observed dataset.

A deep neural network-based approach using residual neural networks (ResNet) and recurrent neural networks (RNN) was used to predict daily and weekly hydropower generation by (Li, Yao, Huang, & Zhou, 2019). The proposed model outperformed the baseline methods such as historical average (HA), ARIMA, seasonal ARIMA (SARIMA), GRU, LSTM, and spatiotemporal residual network (ST-ResNet) by a 2% to 44% improvement in the RMSE. (Javed, Fraz, Mahmood, Shahzad, & Arif, 2020) compared Multiple Linear Regression, K-Nearest Neighbor, Support Vector Regressor, Random Forest, and LSTM performances. However, they considered dam related sources of data in their predictions such as date, reservoir water level (HRL), irrigation release, inflow, total turbine-driven outflow (Total outflow), and energy production (Generation). They also integrated temperature and precipitation data from the dam's basin. Each method was tested across four different dataset configurations: solely dam-related variables, dam variables with temperature augmentation, dam variables with rainfall augmentation, and dam variables with both temperature and rainfall augmentation. They showed that the Random Forest yields the most accurate results when augmented with temperature variables followed by the K-Nearest Neighbor.

Climate change is expected to entail a significant impact on hydropower production (Hamududu & Ngoma, 2020). Therefore, a variety of models have included climate change variables into their hydropower prediction. Some hydropower power prediction models directly incorporate climate change predictions into the modeling inputs (Chilkoti, Bolisetti, & Balachandar, 2017), whereas others use an ensemble approach of multiple climate change models and hydrological parameters to perform uncertainty analyses for deriving policies that perform adequately across a range of plausible futures (Hamududu & Ngoma, 2020). Overall, a large number of modeling techniques have been developed in recent years in order to predict hydropower production. Results indicate that machine learning techniques such as LSTM, SVR, and ELM, combined with dam and climate change related parameters, outperform traditional approaches in short-term, mid-term and long-term hydropower predictions.

Agriculture and municipal demand are also two major users of reservoir outflow. What makes agriculture and municipal demand difficult to satisfy is that they often peak when the water is less available (i.e., during dry seasons). To ensure sustainable irrigation and address the timing mismatches between future water availability and the water requirements of crops, there may be a need for greater water storage. However, reliance on large, centralized irrigation projects can have negative impacts on ecosystems, leading to unsustainable water use and increased vulnerability to climate extremes. For these reasons, the impact of climate change on inflows and demands must be considered when devising dam operations (Rosa, 2022). While climate change puts pressure on agriculture and the irrigation that supports it, Lam (2011) noted that, despite global population more than tripling in the last 75 years there was a commensurate increase in food production, suggesting that agrotechnical and agri-business practices have been able to adapt to emerging challenges through technological innovation (Lam, 2011). Although difficult to predict, projections that ignore possible technological advances in managing climate change impacts may miss important considerations.

3.4. Reservoir operation

Reservoir operation follows the application of a collection of guidelines/rules that regulate the release of water. These rules consider different factors, including the current water level in the reservoir, the projected inflow, and the water demands from various users (Loucks, 1981). Optimizing these rules is a procedure that aims to achieve the greatest possible advantages from the reservoir while reducing adverse side affects. The goal of this process is to make sure that the reservoir can fulfill different goals, such as irrigation, electricity production, etc., while also ensuring the entire operation remains sustainable (Fallah-Mehdipour, Bozorg Haddad, & Mariño, 2012). This requires the use of mathematical models and algorithms to assess multiple factors and devise the most suitable set of rules.

If the reservoir's downstream demand is assumed to be fixed, the result is a set of rules known as standard operating policy (SOP) (Alrayess, Zeybekoğlu, & & Ulke, 2017), (Loucks, Water Resources Planning. Analysis, 1981), (Maass, *et al.*, 1962), and (Stedinger, 1984). These rules release water as close to the downstream demand as possible and only reserve surplus water for future deliveries. When the goal of reservoir operation is to minimize water deficits over a set-period of time, and all deficits are considered equal, SOP is considered the optimal policy (Klemeš, 1977) (Burness & Quirk, 1981; Hashimoto, Stedinger, & Loucks, 1982). However, the main weakness of SOP is that it does not have a mechanism to ration supplies for future demand in times of water scarcity or to release excess water in times of surplus (Klemeš, 1977), (Hashimoto, Stedinger, & Loucks, 1982), and (Stedinger, 1984). Whenever dry periods are persistent, hedging is a good strategy that combines economic principles and physical conditions in the operation planning of water resources to enhance their efficiency. Hedging often includes explicit considerations of hydrologic and engineering constraints such as water delivery not exceeding the long-term available water supply (outflows can have short durations of exceeding inflows, e.g., when reducing storage volume to attenuate an imminent rainstorm). It should be noted that a hedging rule closely adheres to the SOP; however, the hedging rule results in a release that is lower than the SOP, which reflects the current demand level.

Methods such as SOP or hedging do not consider other reservoir functions (e.g., recreation, hydropower, flood control . . .) (Raman & Chandramouli, 1996). Optimizing reservoir releases requires considering various hydrologic conditions across all goals for which the reservoir was designed. This process is known as reservoir operation optimization and involves maximizing reservoir benefits without violating operational constraints. Various methods have been documented in the literature to achieve this goal. These include linear programming (LP) (Becker & Yeh, 1974), non-linear programming (NLP) (Chang, Chen, & Chang, 2005), dynamic programming (DP) (Chu & Yeh, 1978), Lagrange relaxation (Finardi, Silva, & Sagastizábal, 2005), and network optimization (Kuczera, 1989).

The start of the 21st century was accompanied by the advancement in high performance computation and artificial intelligence, both of which led to improvements in some of the most popular models, especially in their precision. Genetic algorithms (GA) (Mitchell, 1988), genetic programming (GP) (Koza, 1994), and differential evolution (DE) (Storn, 1997) are some of the evaluation algorithms that have been refined. Recently, meta-heuristic optimization algorithms, such as particle swarm optimization (PSO), have become the preferred optimizer engine for reservoir modeling. Furthermore, hybrid algorithms that combine these methods have been widely adopted to overcome issues such as premature convergence, high computational burden, parameter tuning, and complexity in optimization problems.

In general, the available methods to optimize reservoir operation can be classified broadly into traditional and metaheuristic methods, for which each may involve subcategories. Traditional approaches rely on mathematical methods such as linear/nonlinear maximisation/minimisation, whereby deviations from the perfect (theoretical) value. Historically, dams have been designed for the worst-case drought scenarios using Rippl's method (Rippl, 1883), which determines the smallest reservoir capacity required to fulfill the design water demand. The traditional approaches are difficult to apply to more complex systems such as multi-objective reservoirs. To address this, a reservoir system is simulated against a long-term series of inflows, and iterations are employed until the minimum reservoir capacity that meets the target objectives is achieved. This results in two conventional optimization techniques: Implicit Stochastic Optimization (ISO) (Simonovic, 1987) and Explicit Stochastic Optimization (ESO) (Celeste & Billib, 2009).

The ISO uses historical data and statistical modeling to generate a diverse range of scenarios, similar to Monte Carlo optimization. This approach employs a deterministic optimization model based on historical data to estimate the most effective reservoir releases under various inflow conditions (Celeste & Billib, 2009).

The ISO optimizes over a long continuous series of historical or synthetically generated unregulated inflow time series (e.g., natural, unmanaged flow upstream of dam), or many shorter equally likely sequences. Consequently, most stochastic elements of the problem, including spatial and temporal correlations of unregulated inflows, are inherently integrated, allowing deterministic optimization techniques to be directly applied. Despite this, ISO relies on the specific hydrologic timeseries modelled, and therefore may perform poorly if modelled time series differs substantially from observed data (Labadie, 2004).

Contrary to ISO methods, the ESO models rely on the statistical model directly in the optimization process, making it a more reliable approach for reservoir operation optimization. The ESO system is intended to function based on probabilistic representations of random streamflow patterns and other stochastic variables, as opposed to relying on deterministic hydrologic sequences. Therefore, optimization is carried out without assuming complete knowledge of future events. Moreover, ESO can reduce computation requirements by directly optimizing expected performance over the probability distribution of uncertain variables, without the need for simulation-based policy evaluation. The ESO method is more suitable for simple cases with a single input reservoir system where probability distributions can provide an accurate interpretation of inflow uncertainty (Labadie, 2004). For more complex water resources network planning using ESO, it is crucial to consider the spatial and temporal scales of these trade-offs to ensure clarity and understanding, as stated by Loucks (1993).

Evolutionary-based techniques, such as Differential Evolution (DE), Genetic Algorithm (GA), and Genetic Programming (GP)) are a subclass of a broad range of metaheuristic methods to minimise/maximise an objective function. They follow similar principles as Darwin’s theory of evolution that has allowed various biological species to adapt to changes. In these methods, a pool of possible solutions is created through selective mechanisms like natural selection (survival of the fittest), evolution, and reproduction, ultimately leading to improved solutions (Lambora, Gupta, & & Chopra, 2019). By repeating this process iteratively, a near-optimal solution can be achieved. GA is an excellent example of this set of methods that has been used due to its simplicity and problem independent application. Numerous studies have reported GA’s applicability in optimizing hydro-systems. For example, Chang and Chang (2005) demonstrated the effectiveness of the GA in optimizing the Shihmen Reservoir for irrigation purposes. The study revealed that while the GA can effectively solve reservoir problems, it often faces difficulties in breaking down large-scale problems into smaller sub-problems. Decomposing complex problems into more manageable components could potentially accelerate the search process and enhance the quality of the solutions found. Wang *et al.* (2011) developed an interactive multi-tiered GA (MIGA). Their study showed that a 20-year operation utilizing the blended or hybrid model resulted in a 25% decrease in the objective function (e.g. 10-day water shortage rate average) and an 80% reduction in computation time required by MIGA. Moreover, another popular modified GA, known as the non-dominant sorting GA II algorithm (NSGA-II) (Deb, Pratap, Agarwal, &

Meyarivan, 2002), has been implemented in the multi-objective optimization of reservoir operation.

Hybrid algorithms can offer the benefit of addressing the limitations of a standalone algorithm. A multi-level hybridization approach involves alternating between a stochastic/deterministic method and passing the outputs of the preceding algorithm to the next hybridized algorithm for further optimization processing. Simultaneously, a stochastic/deterministic embedded algorithm is executed independently in parallel (Van Zyl, Savic, & Walters, 2004). Both optimization methods can be utilized in various fields, but hybrid algorithms can be particularly advantageous in studying multi-objective (MO) trade-offs, such as flood control, hydroelectricity generation, and water supply. Numerous studies have revealed that hybridized algorithms can confer benefits on reservoir operation. For instance, (Wu & Chau, 2010) demonstrated the integration of data-driven techniques and optimization modeling for streamflow forecasting. By combining accurate reservoir inflow forecasting using artificial neural networks with efficient optimization through Pareto multi-objective differential evolution, daily hydropower generation at the Vanderkloof Dam could be improved (Olofintoye & Otieno, 2016). Studies have also been conducted on blending neural network and evolutionary algorithm (EAs) approaches to optimize reservoir operation and obtain the best reservoir policy (Ladanu, Akanmu, & Adeyemo, 2020).

Reservoir model optimization has made significant strides with the application of Swarm Intelligence techniques such as Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and other Nature-inspired metaheuristic methods. PSO is a well-established method that found widespread use in various engineering disciplines. (Al-Aqeeli & Mahmood Agha, 2020) demonstrated the efficacy of PSO in striking a balance between maximizing hydropower and mitigating floods in the Mosul and Badush Dam case studies. The authors conducted several case studies to benchmark and explore the utility of PSO. The first model they developed was the PSO algorithm for a single reservoir system (PSOS) to validate the optimization model. The second model was the PSO algorithm for a multi-reservoir system (PSOM) used to identify the best operating policies that offer the most favorable trade-offs for complex reservoirs. The PSOM proved efficient in delivering optimal trade-offs even under different constraints and inflow conditions. Another prevalent technique for enhancing optimization is the chaotic PSO (CPSO), which uses an improved logistic map and employs the discharge flow process as decision variables along with the death penalty function (PF).

Traditional reservoir models typically require multiple iterations and perform poorly if parameters are not adequately tuned. While metaheuristics are not guaranteed to provide the optimal solutions, they are designed to find near-optimal solutions and offer advantages when used alone or in combination with other traditional techniques. To evaluate the effectiveness, robustness, and performance of each reservoir model, researchers have employed various evaluation methods. These include assessing model performance, such as convergence rate and run-time, to evaluate the performance of standalone algorithms, as well as testing the robustness of each algorithm in solving high-dimensional complex problems. A detailed comparison of various reservoir operation optimization algorithms could be found in (Lai, F., Koo, Ahmed, & El-Shafie, 2022).

Optimal (or near-optimal) solutions often depend on problem formulations, and if the formulation is incorrect or assumptions are flawed, the results may be oversimplified or inadequate. Hence, it is crucial to meticulously consider the problem formulation's impact when defining objective function(s) and constraints for optimization (Al-Aqeeli & Mahmood Agha, 2020) and (Labadie, 2004).

3.4.1. *Key performance indicators: operation resilience and reliability*

In the context of climate change, the resilience and reliability of dam operations become crucial in ensuring the continuous functionality and safety of these assets (Singhal, Gottumukkala, & Sharma, 2019). While climate change poses significant challenges to the resilience and reliability of dams, proactive measures can alleviate these challenges. Embracing a design that is resilient to climate change, employing adaptive management strategies, and prioritizing long-term reliability are essential measures in preserving the indispensable benefits of dams, while simultaneously safeguarding downstream communities and ecosystems (Fluixá-Sanmartín, Altarejos-García, Morales-Torres, & Escuder-Bueno, 2018).

The resilience of a system pertains to its capacity to absorb, adapt to, and recover quickly from disturbances, shocks, or stressors while maintaining its central functionalities and structure. Essentially, it is a measure of a system's ability to endure external pressures or internal disruptions without substantial, protracted harm. Dam operation resilience has become even more complicated, having to absorb and adjust to disturbances brought about by climate change, such as increased precipitation, temperature fluctuations, or extreme meteorological events (Argyroudis, 2022).

Reliability analysis refers to the quantitative assessment of the probability of failure, where failure is defined as the exceedance of demand over supply. In our context we interpret structural failure as when the loading on a structure exceeds its strength (or capacity to resist), and functional failure as when the structure is incapable of providing the service or function for which it was intended. Structural reliability is therefore the probability of not experiencing structural failure. Since functional failure can be partial or complete, functional reliability requires qualification of the level of functionality at hand. In the context of dams, functional reliability refers to the probability of the dam to meet downstream demands. The period during which the reservoir system is able to meet all downstream demands is called success state, and the period during which the reservoir system is unable to satisfy demand is the failure state. The functional reliability of a dam is then denoted using the following equation:

$$X(t) = \begin{cases} 1, if\, R_t \geq D_t \\ 0, otherwise \end{cases} \tag{2}$$

Where X_t is a binary value indicating the state of the reservoir system (1 – meaning success state, and 0 meaning failure state) at time t, R_t is the release made from reservoir at time t, and D_t is the demand at time t (Hashimoto, Stedinger, & Loucks, 1982).

Reservoir Operation Time Scales

Reservoir operation models can be typically described in two distinct time scales, short-term (e.g., hourly to daily) operational models and long-term (monthly, seasonally, to yearly) schedule models.

Short-term operational models focus on hourly and daily operational planning for relatively fast process, such as maximizing daily electricity production and flood control (Xu, Zhong, Stanko, Zhao, & Yeh, 2015). Short-term operational models utilize short-term inflow forecasts to determine water release strategies. Some short-term inflow forecasts explicitly incorporate climate change impacts on weather patterns; however, it is more typical to implicitly capture current climate change impacts through observations and trend analyses. Overall, the short-term inflow forecasts are considered more accurate than long-term forecasts, resulting in more accurate and detailed release strategies from the short-term operational model output (Xu, Zhong, Stanko, Zhao, & Yeh, 2015). However, due to the short-time horizon, the short-term operational models are ill-equipped to obtain long-term operational goals such as meeting electricity demand over the entire year, and handling longer climate processes needed for things like drought management. For these processes, long term scheduling models are called for.

Long-term scheduling models focus on extended processes and goals, such as maximizing annual electricity production or meeting downstream water requirements (e.g., agriculture and municipal demand, and environmental stream flows). These long-term scheduling models require much longer inflow forecasts, from monthly up to yearly inflow forecasts. Explicitly incorporating climate change variables into these forecasts becomes increasingly important as the time horizon extends. Using these long-term horizon inflow forecasts, the long-term scheduling models aim at optimizing long-term goals such as ensuring water demands are met during droughts, and maximizing annual hydropower production. A key consideration, however, is that longer inflow forecasts entail greater uncertainty, rendering it difficult to devise hourly operational strategies based on long-term predictions (Shang, *et al.*, 2022).

Several combination models have been developed with the objective of improving daily operational strategies, while still optimizing for long-term objectives.

Nesting long-term operational models to guide short-term operation is one such strategy. This approach typically uses outputs from a longer-term model (e.g., end-of-month storage level) as inputs to short-term models, iterating and updating both models when new data become available (Georgakakos, 2006) (Batista Celeste, Suzuki, & Kadota, 2008). This nesting approach often has a hierarchy of priority – placing more emphasis on the long-term objective rather than the short-term objective (Xu, Zhong, Stanko, Zhao, & Yeh, 2015). Another modelling approach is to use an infinite horizon model predictive control (MPC). The infinite horizon MPC reduces computational complexity through basis functions, allowing for short-term operation and long-term reservoir management considerations. However, a trade-off between computation time and performance has been noted, with more basis functions reducing computation time but also decreasing performance (Raso & Malaterre, 2017). Accordingly, more research is required to determine how the infinite horizon MPC may handle the number of uncertainties associated with dam operation.

4. CURRENT REGULATORY DESIGN PRACTICES AND CONSIDERATIONS

In preparing this review, Canadian and US federal guidelines on dam safety, regulations, acts pertaining to water rights, and other public documentation concerning lake and river improvements, water resources management, and water security were consulted (BC, Office of Legislative Counsel, 2016) (Province of Alberta, 2022) (Ontario Government, 2020) (LegisQuebec, 2021) (Newfoundland and Labrador Environment and Climate Change, 2022) (Manitoba infrastructure, 2022) (International Watersheds Initiative, 2017) (Interagency Committee on Dam Safety; FEMA, 1979-2004) and its newer edition (FEMA, 2015) None explicitly considered or mentioned climate change. While this section of the review focuses on published work, it is important to note that the Canadian Standards Association (CSA) is currently developing the new standard CSA S910, "Climate Change Resiliency for Dams". The authors are aware of this standard and are working with the CSA as part of its development.

Unlike many Canadian and US regulations, several international dam organizations such as the International Commission on Large Dams (ICOLD), the International Joint Commission (IJC), and the International Organization for Standardization (ISO) have discussed climate change and its impact on dam safety and management. Although ICOLD's main publication on dam safety (Bulletin 167) (Committee on Dam Safety, ICOLD, 2017) does not contain any mention of a changing climate, ICOLD's Bulletin 169, titled Global Climate Change, Dams, Reservoirs and Related Water Resources (ICOLD Technical Committee "Y", 2016), discusses climate-induced impact on, and risk assessment of, dams, reservoirs and water resources systems. It then highlights climate as one of the drivers for change in the world's water resources. The bulletin further outlines the greenhouse gas emissions associated with reservoirs and water resources, presenting six case studies on adaptation strategies from around the world, and summarizes ICOLD's general recommendations[‡], which are as follows:

- Adjust the number and type of water control gates both for flood management and water release requirements.
- Increase the capacity of the spillway works and/or the provision of emergency spillways.
- Add controllable gates to free overflow spillways in order to provide greater regulation of flood peaks.
- Modify the dimension of canals or tunnels that are for water transfer.
- Create new upstream storage reservoirs and re-consider the multi-purpose potential of new reservoir projects.
- Modify the active storage capacity of reservoirs by increasing the height of the storage dam and/or raising the sill level of the overflow works.
- Increase the amount of freeboard above top water level in order to accommodate predicted increases in flood rise and wave surcharge values.
- Replace or reinforce upstream slope protection such as rip-rap to provide satisfactory erosion protection under increased dynamic loading from waves.

Bulletin 169 then states the following: 1- "Projected Impacts of climate change in water resources and floods and droughts are very uncertain, and cannot provide exact information of the rate of future changes to decision-makers, but they can offer very useful general information, and they could serve as preliminary and initial assessment." 2- "Adaptation to climate change will take more than a technological fix.", and 3- "Planned (and coordinated) adaptive management aims to replace ad hoc responses with long-term (policy) arrangements, which may include interim contingency measures. (This is particularly critical in the case of managing water supplies in times of extreme and prolonged drought.)"

These structural changes will be applicable to a wide range of dam and reservoir projects. Most water resource managers and engineers will be familiar with these types of physical intervention, including the expected costs, technical problems, and potential advantages. On the other hand, climate change-related uncertainties will augment the overall uncertainty that underlies these policies and actions. One thing is certain: in the future there will be a greater need to adapt, adjust and change. To solve these problems, future dams must be ready for structural interventions, such as the addition of spillways or other physical components that can be added to the infrastructure later if necessary (ICOLD Technical Committee "Y", 2016). Although these recommendations might impact operation, they are often too general and mainly focused on structural safety, rather than daily operation.

[‡]Note that these recommendations are intended for locations where higher frequencies of extreme events are expected.

5. RESEARCH GAPS

Dam operation has undergone significant advancement in the last few decades, in large part due to improvements in computation and artificial intelligence. Advances in operational models have helped dam operators better manage their resources. However, research gaps remain that can further aid dam operators, especially as the impacts of climate change become more prevalent. Below are three areas of research that could help dam operators better manage their water resources under future climate change scenarios.

1. Most research into the impacts of climate change on dam operation has focused on inflows to the reservoirs behind dams. However, just as important is better understanding how the impacts of climate change on downstream demands, such as agricultural use, municipal use, environmental stream flows, shifting electricity demands, etc., is expected to impact dam operation. Critical to this research is exploring how these shifting demands, due to climate change, are expected to impact dam operation on long and short-term operational schedules. This information would allow for more accurate and effective dam operation under future climate change scenarios.
2. Explore the impact of climate change on daily operational strategies. A significant amount of research has explored the impact of climate change on long-term dam scheduling. However, the impacts of climate change on daily operation have been less studied. To effectively do this, a combination model using long-term forecasts and short-term operational strategies will be required. Exploring and developing tools to assist with short-term dam operation under climate change will be critical to ensure effective management in the future.
3. Develop general, adaptable tools for dam operation – including inflow, outflow, and dam operation optimization. Significant advancements in inflow, outflow and dam operation optimization have occurred in the last couple of decades, as identified throughout this literature review. While some operators have developed their own tailored models based on these advances, many operators have been unable to benefit from these advances due to technological barriers or time constrains. General tools that can be calibrated to any dam using available specific data will enable operators to benefit from all the advances in computation and artificial intelligence.

6. CONCLUSION

This review has provided a comprehensive examination of the impacts of climate change on dam operations, focusing on inflows, outflows, storage, regulatory design practices, and dam operation models. Through the analysis of numerous studies, several key observations emerge.

Climate change is expected to significantly affect inflows due to changing precipitation patterns, snowmelt timing, and hydrological regimes. These changes vary regionally and can lead to both increases and decreases in water availability, thereby influencing operating strategies. Studies highlight the necessity for improved inflow prediction models that account for these climatic variations to ensure accurate and reliable water management.

Increasing temperatures and changing precipitation patterns also impact water demands for municipal, agricultural, and hydropower purposes. This requires dam operators to adapt their outflow strategies to meet these changing demands. Research indicates a growing need for operational models that integrate the impact of climate change on outflow requirements accurately.

Current regulatory frameworks in many regions do not adequately address the impacts of climate change on dam operation. However, international bodies like the International Commission on Large Dams (ICOLD) have started to incorporate climate change considerations into their guidelines. There is a critical need for national and regional regulatory bodies to update their standards to include climate resilience measures.

The impact of climate change on dam operations is a complex and multifaceted issue that requires a comprehensive and adaptive approach. By addressing the research gaps identified and incorporating climate change considerations into regulatory frameworks and operation models, dam operators can better prepare for and mitigate the effects of a changing climate. This literature review underscores the importance of continued research and collaboration among scientists, engineers, policymakers, and dam operators to ensure the resilience and sustainability of dam operations in the face of climate change.

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EXCAVATION AND FILLING TECHNOLOGY FOR DEFORMATION CONTROL IN HIGHLY WATER-BEARING MULTILAYER RESERVOIR BASINS (*)

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SUMMARY

The excavation and filling of the reservoir basin represents a pivotal aspect of the construction of pumped storage power station. The excavation process of the reservoir basin, undertaken in the context of challenging geological conditions, including the presence of high-water-bearing multi-layer strata, is characterised by uneven deformation of the reservoir slopes and the potential for significant destabilisation. The Israel Kokhav Hayarden pumped storage power station project involved the excavation of a reservoir through three layers of strata, each with varying thicknesses. These layers exhibited high water content, high plasticity, and were constructed using a cut-and-fill method, which exemplifies the challenges and

Technologie d'excavation et de remblaiement pour contrôler les déformations dans les réservoirs en présence de couches fortement aquifères

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techniques encountered in such projects. This paper presents a comprehensive overview of the design principles and primary influencing factors associated with the cut-and-fill construction of the reservoir basin at this pumped storage power station. It also outlines the cut-and-fill method and reservoir basin construction technology, which are applicable to a range of similar projects and serve as a valuable reference for practitioners. Numerical simulations of the excavation and filling process of the lower basin under different schemes is conducted using the finite element method. The proposed scheme is presented in conjunction with the deformation and safety factor. The synthesis of the findings is of significant value in the context of construction control for excavation and filling reservoir basin construction in the context of complex stratigraphy, as is the case with pumped storage power stations.

RÉSUMÉ

L'excavation et le remplissage d'un bassin de retenue constituent un élément central de la construction d'un aménagement de pompage-turbinage. Le processus d'excavation du bassin, dans le cas de conditions géologiques difficiles, y compris la présence de couches multicouches hautement aquifères, se caractérise par une déformation inégale des pentes du réservoir et un potentiel de déstabilisation significatif. Le projet de centrale de pompage-turbinage de Kokhav Hayarden en Israël a comporté l'excavation d'un réservoir à travers trois couches de couches, chacune ayant des épaisseurs différentes. Ces couches présentaient une teneur élevée en eau et une plasticité élevée, et ont été construites selon une méthode de coupe et de remplissage. Cela illustre les défis et les techniques rencontrés dans de tels projets. Le présent document présente un aperçu complet des principes de conception et des principaux facteurs d'influence associés à la construction du bassin et de son remplissage. Il décrit la méthode d'excavation et de remplissage, ainsi que la technologie de construction du bassin de réservoir, qui sont applicables à une gamme de projets similaires et qui servent de référence précieuse aux praticiens. Une simulation numérique du processus d'excavation et de remplissage du bassin inférieur selon différents schémas est réalisée en utilisant la méthode des éléments finis. Le schéma proposé est présenté en liaison avec la déformation et le facteur de sécurité. La synthèse des résultats est d'une grande valeur dans le contexte du contrôle de la construction pour la construction d'un bassin excavé et de son remplissage dans le contexte d'une stratigraphie complexe, comme c'est le cas pour les centrales de pompage-turbinage.

1. INTRODUCTION

The construction of pumped storage power station represents a significant step towards the development of a new power system based on renewable energy sources, a concept that is gaining increasing recognition among various countries. In general, the upper and lower reservoir basins of pumped storage power stations are relatively shallow, the height of the dam body is limited, and the overall slope is gradual. Domestic and foreign research on this topic is limited, with existingstudies primarily focusing on seepage issues in storage operations post-construction and the stability analysis of reservoir slopes under varying operational and climatic conditions[1,2]. Zeng and colleagues [3] investigated the seepage and stability of unsaturated complex soil bank slopes in the context of coupled rainfall and water level fluctuations. Shi et al [4] examined the impact of water level changes on the stability of dam slopes across three scenarios: water level drop, water level rise, and pit drainage in a reservoir in Baise.

Nevertheless, during the construction of pumped storage power station, the reservoir is often half-dug and half-filled [5], and a variety of challenging geologic conditions are frequently encountered. During the excavation phase, the stress field within the soil is redistributed, which can result in uneven deformation or even destabilisation of the reservoir slope [6]. Furthermore, the filling and loading of the reservoir dam will cause new settlement, which can affect the overall stability of the reservoir basin and the integrity of the seepage control facilities (panels or geomembranes) [7]. Huang et al [8] conducted a stability analysis and evaluation of slope excavation during the construction period on the rocky slope of the right bank of the lower reservoir of the Zhouning Pumped Storage Power Station. This was achieved through the utilisation of the discrete element numerical analysis method. Utilizing the FLAC3D software, Sun et al [9] conducted an investigation into the impact of slope rate and platform width on the deformation and stability of soil slope excavation. In conclusion, it can be stated that the deformation and crack development problems caused by the excavation process of the reservoir basin under complex geological conditions have not yet received sufficient attention and in-depth analysis. Furthermore, it can be observed that the deformation and other problems in the construction stage often exceed more than half of the overall deformation. The lower basin of the Kokhav Hayarden pumped storage power station (hereinafter referred to as KH pumped storage power station), which is constructed by our company, is located below the water table, with numerous strata and a complex lithology, which presents significant challenges for the development of the construction program and the management of the construction process are of equal importance. Furthermore, the project employs geomembrane seepage control of the entire basin, thereby ensuring that fluctuations in the water level within the reservoir do not impact the groundwater table line.

This paper, which is based on the actual lower reservoir basin of the KH pumping station, aims to provide a comprehensive analysis of the deformation law during the construction process of the reservoir basin excavation and dam filling. The objective is to ensure the stability and safety of the dam during the construction stage of the lower reservoir basin and to offer insights that can be applied to similar projects.

2. PROJECT OVERVIEW AND GEOLOGICAL PARAMETERS

The KH pumped storage power station has an installed capacity of 340 MW, comprising an upper reservoir, a water transmission system, an underground plant, a lower reservoir, a switching station, and other components. The reservoir is not subject to surface runoff recharge; instead, the water is supplied by a pipe from Lake Galilee in the north to the lower reservoir for initial storage and daily evaporation recharge. The lower reservoir of the KH pumping station is located in the Jordan Valley, with the ground elevation at -220m above sea level. The reservoir basin is constructed using a combination of excavation and reclamation, with the original ground elevation of the project area at approximately -220.00 m. The side slope has a slope ratio of 1:4. The slope ratio is 1:4, the slope height is 16.75 m, and the elevation of the bottom of the reservoir formed by excavation is -236.75 m. The slope ratio of the slope formed by upper filling is 1:1.6. The slope height is 6 m, the elevation of the top of the dam is -214.00 m, and the total elevation of the reservoir basin slope is 22.75 m. The reservoir basin is constructed using a half-excavation and half-filling method.

The ground geological survey and borehole investigation have revealed that the stratum within the lower reservoir is predominantly composed of lake-phase deposition, which can be subdivided into three distinct layers. The upper part is composed of gravel-bearing powdery clay (alluvial stratum), distributed at a depth of 2-3m below the ground surface. The middle part is characterised by gravel-bearing powdery clay (lake-phase sedimentary stratum), with a thickness of 3-8m. The soil layer is light brown or light grey in color, with a small amount of gravel present in localized areas. The lower part is composed of clay (marl), which constitutes the primary stratum of the lower reservoir basin and the bank slope. The soil layer is characterized by a dark grey or dark brown coloration, laminated to a thin, locally visible grain mud, with a clear distribution of the level. The inlet and outlet of the lower reservoir are located within this stratum. Please refer to Fig.1 below. Additionally, there is a layer of weak interlayer in the layer, soft plastic, with a standard penetration number of 8～13. Based on the aforementioned design parameters of the dam and the geologic conditions, a typical cross-section of the basin is presented in Fig. 2.

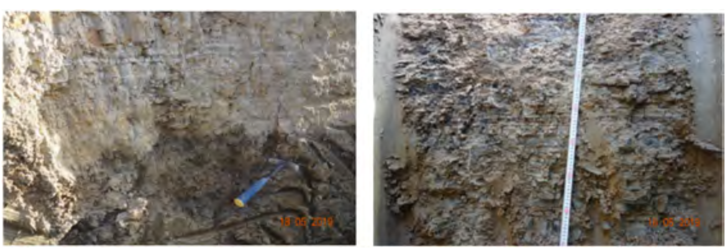

Fig. 1
The grayish-white layered structure of Marly Clay

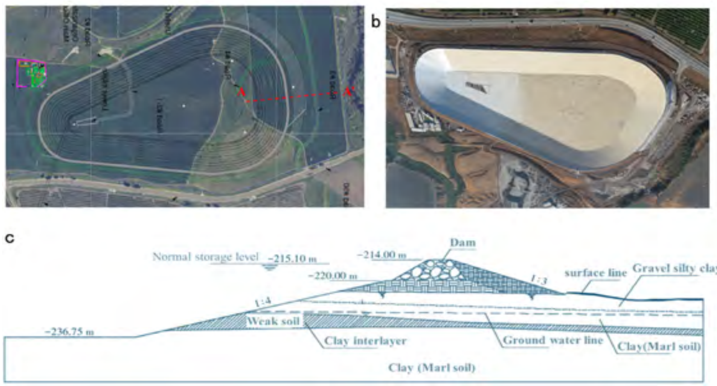

Fig. 2
Typical profile of lower reservoir of KH pumping and storage power station (a) Plane graph (b) Completion of the actual picture (c) A-A ‘profile

3. EXCAVATION AND FILLING DESIGN PRINCIPLES AND CONSTRUCTION INFLUENCING FACTORS

The reservoir design of a pumped storage power station should take into account the terrain, geology and environmental conditions, and balance the excavation and filling of the reservoir basin in order to achieve the optimal engineering volume and project investment. Accordingly, the overarching objective is to optimise the utilisation of excavated materials for dam construction or comprehensive utilisation, while minimising project waste, in accordance with the necessity of adjusting storage capacity and the variation of reservoir water level. It is important to consider ways of reducing the environmental impact of the project and the costs associated with transportation. In general, the quantities of excavation, abandoned slag and external material used in the reservoir are significant, while the quantities of filling are relatively minor. In general, the amount of excavation and filling works is from large to small in order to facilitate the construction of seepage prevention structures, including vertical seepage prevention stations, across the entire reservoir basin.

The current construction capacity and experience of the industry indicate that the excavation capacity is approximately $5\times10^4 m^3$/month, the filling and rolling strength of the earth dam is approximately $1\times10^4 m^3$/month, and the filling capacity of the core rockfill dam is approximately $100\times10^4 m^3$/month. The principal factors influencing the excavation and filling construction of a reservoir include geological conditions, the quality of survey results, water level conditions, climatic conditions, construction technology and equipment, construction organisation and management, and so forth. The factors and their effects on construction are illustrated in the following Table 1.

Table 1
Analysis table of construction factors for excavation and filling of reservoir basin of pumped storage power station

Influencing factor	**Description**	**Influence on excavation**	**Effect on filling**
Geological condition	Including rock type, strata distribution, geological structure and so on	Weak rock formations can make excavation difficult and slope instability	Poor geological conditions such as structure increase the difficulty of excavation and the stability of the project, and even require additional reinforcement measures, affecting the progress and cost
Hydrological condition	mainly includes water table and surface runoff	The presence of high groundwater levels will result in increased difficulty with regard to excavation, necessitating the implementation of measures to mitigate the impact of precipitation in advance, and will consequently affect the rate of construction progress. Furthermore, the influx of surface water into excavation and filling areas will have an adverse effect on the quality control of the construction, the adherence to the construction schedule, and the safety of the workforce.	
Climatic condition	Temperature, humidity, rainfall, etc	High humidity and rainfall will increase the difficulty of excavation and safety risks	Excessive moisture or dryness will affect the compaction effect of the filler
Equipment selection	Excavation machinery, transportation and rolling equipment	Efficient mechanical equipment can speed up construction progress, reduce labor costs, and ensure construction quality	
Construction technique	Methods and techniques of excavation and filling	Advanced technology can increase excavation speed and reduce safety risks	Efficient filling technology can ensure the stability of the filling body
Drainage system	Drainage facilities in the site	Poor drainage system will cause water accumulation on the working face and affect excavation	Water accumulation will affect the bearing capacity and stability of fill materials
Construction organization management	Mainly for construction planning and quality control	A scientific construction plan can allocate resources in an optimal manner, guarantee construction progress and efficiency, and prevent unnecessary delays. A rigorous quality control system can guarantee the quality of construction, prevent the necessity for subsequent rework and associated penalties and claims.	

The distribution of rock strata in this project is relatively flat, exhibiting minimal fluctuations. The geological structure exerts no discernible influence. The primary factors affecting the project are the water-rich and weak soil layer, groundwater, and climate conditions. During construction, it is essential to ensure effective drainage and precipitation within the formation, protect against rainfall erosion on the excavation and filling surfaces, and repair the gully.

4. BASIN EXCAVATION AND FILLING ZONING METHOD

The excavation and filling of the reservoir basin shall be conducted in accordance with the principle of “zoning, stratification construction, and parallel cross-flow construction of multiple working faces”. The specific zoning is divided according to the actual engineering conditions, including geological, transportation, and terrain conditions, among others. This is typically done according to the longitudinal section of the dam axis, the reservoir plane (including the original ground elevation and the dam top elevation). Each area is divided into a number of working faces. On each working surface, discharge paving, rolling, and quality inspection flow operations are carried out, respectively, and the horizontal filling method is constructed.

It is intended that the lower warehouse be subdivided into five sections, designated from Block 1 to Block 5, in accordance with the topography of the excavation for the inlet and outlet of the lower warehouse. The specific partition diagram is illustrated in Fig. 3. Given that Block 5 represents the inlet and outlet of the lower reservoir, this section will be the initial focus of the excavation process, followed by Block 1 through Block 4 in a sequential manner.

The relatively flat terrain of the area results in the ground elevation of the lower reservoir of the HK pumping and storage power station being situated between EL.226 and El.-218 m below sea level. The area is divided into two distinct working faces, each of which is engaged in discharge and rolling flow operations, respectively. The construction process is carried out using the flat filling method, as illustrated in Fig. 4.

Fig. 3
Excavation zoning diagram

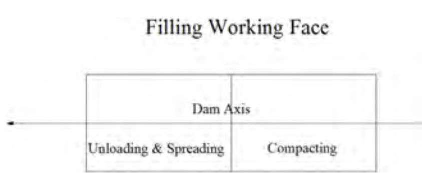

Fig. 4
Schematic diagram of dam filling

5. EXCAVATION METHOD OF RESERVOIR BASIN

5.1. Topsoil cleaning

The primary objective of site cleaning is the removal of topsoil. The surface humus soil is employed as a cultivation soil for agricultural land, which is gathered and stored in an appropriate manner for the restoration of agricultural land upon the completion of the project. During the cleaning of the topsoil, a hydraulic backhoe is utilized to peel along the opening line, with a peeling thickness of 50 cm. The 20t dump truck is then transported to the temporary storage yard for topsoil, which is located in the eastern area of the lower warehouse and is operated by the 6th construction organization.

The topsoil stripping area of this project encompasses both the excavation zone devoid of topsoil and the dam filling area. The lateral stripping of the dam filling area exceeds the edge line by 0.5m. Despite the upper and lower storage soil materials exhibiting characteristics of a high liquid limit and high water content, the lower storage soil materials display high shear strength, rendering the paving of a slag road prior to mining the soil materials unnecessary.

5.2. Water inlet/outlet excavation

Given that the floor elevation of the inlet and outlet of the lower reservoir is approximately 15 metres lower than the reservoir's own bottom, it is recommended that the excavation of the inlet and outlet area be carried out first when the reservoir is excavated.

The soil material within and outside of the water inlet must be excavated in layers, with the depth of each layer ranging from 3 to 4 meters. During the excavation of the water inlet area, a temporary road of 2-1# will be gradually formed to provide access to the bottom of the reservoir. The surface of the 2-1# road will be paved with 50 $\sim$ 80 cm-deep holes to facilitate the extraction of stone material. The road width is 9 m, the slope on both sides of the road is 1:1, and the longitudinal slope of the road is 1:10.

5.3. Excavation of storage basin

Prior to the commencement of excavation, it is recommended that the upper opening line of the excavation be marked with lime and wooden piles. Furthermore, the original longitudinal and cross-sectional drawings of the excavation should be mapped, the amount of excavation work checked, and the measurement results submitted to the supervision engineer for approval.

As a consequence of prolonged exposure to solar radiation, the moisture content of the soil material situated at a depth of between two and three metres on the surface of the lower reservoir is lower than or close to the optimal water content. Prior to mining, the direction of the soil material is determined in accordance with the water content. In the event that the water content is less than the specified fill water content, the soil material will be temporarily stored in the designated transfer yard following the excavation process. Alternatively, the water content of the excavation face may be adjusted prior to the dam being filled. Conversely, if the water content is within the range of the specified fill water content plus two percent, the soil material is directly filled onto the dam following the mining process.

In instances where the water content of the soil below a depth of 3m is in excess of the optimal water content, and the soil quality is poor, the soil excavation is conducted using a hydraulic excavator (backhoe) in a methodical top-to-bottom layer approach. The depth of excavation for each layer is approximately 3–4 metres, with the excavated soil transported to the ballast yard via a 20-tonne dump truck.

During the excavation of the lower reservoir, the formation of the excavation face of each layer creates a natural slope from the upstream to the downstream. The collection well is situated at the lowest point, and the necessary drainage equipment is in place to facilitate the pumping and discharge process. It is essential to protect the slope formed by excavation in a timely manner to prevent damage during the rainy season. The slope that has been excavated and formed without treatment should be protected by polyethylene film or colour strip cloth. It is imperative that excavation is completed before filling, and that excavation while filling is prohibited. All waste materials removed must be transported outside the dam base.

5.4. Excavation of storage basin

Prior to the commencement of excavation, it is recommended that the upper opening line of the excavation be marked with lime and wooden piles. Furthermore, the original longitudinal and cross-sectional drawings of the excavation should be mapped, the amount of excavation work checked, and the measurement results submitted to the supervision engineer for approval.

As a consequence of prolonged exposure to solar radiation, the moisture content of the soil material situated at a depth of between two and three metres on the surface of the lower reservoir is lower than or close to the optimal water content. Prior to mining, the direction of the soil material is determined in accordance with the

water content. In the event that the water content is less than the specified fill water content, the soil material will be temporarily stored in the designated transfer yard following the excavation process. Alternatively, the water content of the excavation face may be adjusted prior to the dam being filled. Conversely, if the water content is within the range of the specified fill water content plus two percent, the soil material is directly filled onto the dam following the mining process.

In instances where the water content of the soil below a depth of 3m is in excess of the optimal water content, and the soil quality is poor, the soil excavation is conducted using a hydraulic excavator (backhoe) in a methodical top-to-bottom layer approach. The depth of excavation for each layer is approximately 3–4 metres, with the excavated soil transported to the ballast yard via a 20-tonne dump truck.

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Excavation is conducted using a hydraulic backhoe with a capacity of $1.8m^3$ and a dump truck with a capacity of 20t. The excavation process is conducted in layers, from the top to the bottom. The thickness of each layer is determined according to the water content and soil property parameters. The initial excavation thickness is 3m. For further details regarding the earthwork excavation, please refer to Fig. 5.

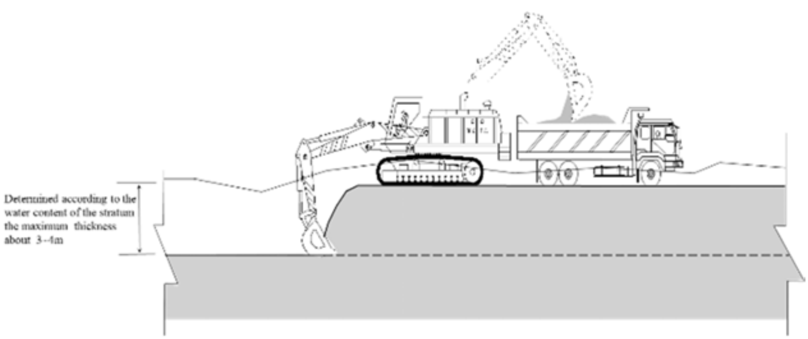

Fig. 5
Schematic diagram of earthwork excavation

6. FILLING METHOD OF RESERVOIR DAM

6.1. Filling process

The reservoir dam filling process commences at the lower elevation position. The construction steps and procedures include measurement, spreading, grading, compaction, testing and handling. As illustrated in the subsequent Fig. 6.

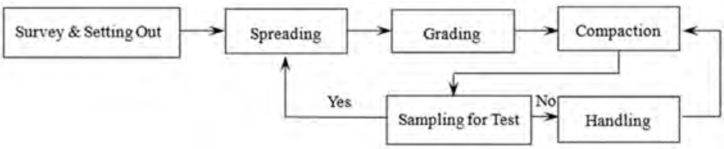

Fig. 6
Excavation procedure roadmap

6.2. Water content adjustment

The loss of water from soil materials during the processes of mixing, stockpiling, loading, transportation, laying, rolling, quality inspection, and other related activities necessitates the use of sprinklers to add water to the surface of the dam. In the event that the moisture content of the local soil material exceeds the upper limit of the construction control moisture content, prior to rolling, the filling surface is loosened and dried with a bulldozer equipped with a rake. The installation and mechanical soil material flipping equipment developed for use with excavators is illustrated in the accompanying Fig. 7. The soil water content of the lower reservoir dam should be maintained between 22% and 27%, and the gravel particle size should not exceed 15 cm.

Fig. 7
Soil drying and paving equipment

6.3. Paving and rolling

The upper and lower sides of the fill are initially treated with lime by the surveyor on the designated rolling surface, which has been deemed suitable for the purpose. The paving is conducted in accordance with the dam's longitudinal axis. The 20t dump truck is employed for the unloading process, while the grader is combined with the loader to facilitate the leveling of the material. In accordance with the prevailing technical specifications and industry standards pertaining to construction machinery and experience, the thickness of the finished product is typically controlled at 25 cm, with the thickness of the loose paving material ranging from 25 cm to 30 cm. The process involves layer filling from the bottom up, followed by layer rolling. The moisture content is 28% to 33%, the dry density is not less than 95%, and the allowable deviation for each layer thickness is ± 4 cm. A test is deemed to be successful if the proportion of samples that pass the requisite criteria reaches 80%.

The clay material is compacted by a 20T convex roller, with the rolling direction aligned with the dam axis. The rolling lap width is 0.3m, the segment lap length is 1.0m, and the rolling running speed is less than 3km/h.

6.4. Fill detection

Once the rolling process is complete, the compaction degree of the fill layer must be evaluated. The dry density must exceed 95% of the standard Platts maximum dry density, and the average dry density of the three consecutive layers must exceed 98% of the standard Platts maximum dry density. Upon successful completion of these criteria, the lower layer may then be filled.

6.5. Embedment of drainage flower pipe

The corrugated drainage flower pipe located in the lower warehouse has been slotted and wrapped in geotextile material at the processing plant. It has then been transported to the site, where it has been assisted by a crane during the artificial burial. It is imperative to ascertain whether the elevation and slope of the filling surface align with the prescribed design specifications prior to embedding. Once the flower tube has been positioned, the joint pipe is connected between the corrugated tubes, and the geotextile is wrapped around the joint. The drainage filter material should be filled within a radius of one metre around the drainage pipe, and the backhoe should be used to smooth and compact the surrounding area. The pipe exceeding one metre in length must be filled in accordance with the specifications set forth in the design drawing. The depth range of one to three metres must be compacted through the use of small vibration grinding and static pressing techniques. The pipe exceeding three metres in length must be compacted through the utilisation of conventional rolling equipment.

The horizontal drainage pipe at the base of the lower warehouse is drilled with a hydraulic crawler drill, with the drilling process monitored at all times to ensure that the hole is not offset. Once the drilling is complete, the PVC drainage pipe is inserted into the hole, and the pipe is then extracted using a pipe extractor once the required depth has been reached.

6.6. Surface treatment of fill surface

It is imperative that quality control (QC) personnel inspect the surface of each floor for cracks, regardless of the construction interval. Furthermore, they must coordinate with the quality assurance (QA) personnel of the owner to make corresponding decisions.

6.7. Dam slope trimming

Once the upper and lower storage soil has reached a designated height (1∼2m), the long arm backhoe or bulldozer is employed to trim the slope in accordance with the slope ratio specified in the design.

6.8. Filling of special parts

In this basin project, it is of the utmost importance to pay close attention to the concrete structure, particularly the water inlet. When the filling position is in close proximity to the concrete structure, it is essential to reduce the thickness of the filling layer. Furthermore, the use of a small vibration roller is recommended within a range of 30 to 50 centimetres from the concrete structure. Additionally, manual rolling should be employed within a distance of 30 centimetres from the concrete structure. The rolling thickness within 50 cm of the concrete structure is half of the allowable filling thickness of the dam body, which is 12.5 cm.

7. EXCAVATION AND FILLING SCHEME AND OPTIMIZATION CALCULATION

7.1. Calculation model and formation parameters

The typical section and stratigraphic lithology survey data were used to establish and calculate the excavation model of the reservoir slope. This was done with the GeoStudio software, which was used as the initial background for the excavation of the reservoir basin in a horizontal site. Fig. 8 illustrates the model diagram of the original formation and the completion of the excavation and filling process. The model is 230 metres in length and 35 metres in height, with an original ground elevation of -220 metres. The surface is subdivided into three distinct layers, comprising rock and soil bodies with varying properties. The superficial soil is characterised by low stiffness and comprises gravel, silty clay (alluvial strata), with a thickness of 3 metres. The intermediate soil layer is 7.5 metres thick, and the underlying soil is clay (marl soil) with high stiffness. The model is constrained in both the horizontal and vertical directions at the boundaries, with the exception of the left and right sides, where only horizontal displacement is permitted. The groundwater level, as determined from drilling data, is approximately -235m, which is comparable to the water level of the Jordan River. This indicates that the soil water content is relatively high. Following the excavation of the reservoir basin, the resulting elevation is -236.75m. The ground elevation above -220m comprises the fill body, with an elevation of -214m. The slope ratio of the reservoir is 1:3. The physical and mechanical parameters of each soil layer in the model are determined according to indoor and field tests, as detailed in Table 2.

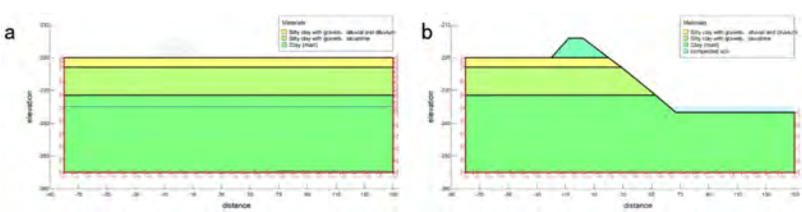

Fig. 8
Numerical calculation model
(a) Oringnal formation (b) After completing of excavation and filling

Table 2
Physical and mechanical parameters of different layers

Material	γ (kN/m^3)	effective stress		young's modulus	Poisson's ratio	permeability coefficient
		c\` (kPa)	φ\` (°)	E(kPa)		cm/s
①Silty clay with gravels, alluvial and diluvium	17.5	5	26	22500	0.34	1×10^{-6}
②Silty clay with gravels, lacustrine	17.5	6	31	22500	0.34	1×10^{-7}
③marly Clay	17.5	30	26	35000	0.43	1×10^{-8}
④compected soil	17.5	8.2	30.4	17500	0.38	1×10^{-8}

7.2. Excavation Scheme

In order to quantify the influence of the excavation method on reservoir slope displacement, determine the optimal excavation layer thickness and precipitation management, and ensure the construction safety and construction period, three excavation schemes are proposed for analysis and optimisation.

Scheme 1: The excavation process is divided into six phases, with the initial five layers excavated to a depth of three metres each and the final layer excavated to a depth of 1.75 metres, reaching the design elevation of -236.75 metres.

Scheme 2: The excavation is divided into four phases, with the initial three layers excavated to a depth of five metres each and the final layer excavated to a depth of 1.75 metres in accordance with the design elevation of -236.75 metres.

Scheme 3: The excavation is divided into three phases, with each layer excavated to the boundary of the soil layer. This results in the first layer being excavated to a depth of 3m, the second layer to a depth of 7.5m, and the third layer to a depth of 5.25m, reaching the design elevation of 236.75m. Following the completion of excavation under the three aforementioned schemes, the reservoir dam is to be filled to a depth of -214m.

7.3. Deformation analysis during excavation and filling construction

In accordance with the aforementioned model and parameters, the cumulative maximum horizontal displacement of each construction step reservoir under each scheme is presented in the following Table 3.

Table 3
Horizontal displacement of slopes under the different method of excavation

Working condition		**1st exca-vation**	**2nd exca-vation**	**3rd exca-vation**	**4th exca-vation**	**5th exca-vation**	**6th exca-vation**	**Filling**
Maximum horizontal displacement/m	Scheme 1	0.011	0.025	0.036	0.046	0.052	0.056	0.116
	Scheme 2	0.019	0.037	0.052	0.056			0.261
	Scheme 3	0.011	0.043	0.055				0.231

The deformation results demonstrate that the total deformation amount after the completion of excavation under each scheme is comparable. However, the deformation amount under each excavation step of Scheme 1 is the smallest, particularly under the first three excavation steps. Furthermore, the horizontal deformation generated is significantly less than that observed under the other two schemes. Upon completion of the filling process, the deformation observed in Scheme 1 is markedly less than that observed in the other two schemes. Therefore, it is recommended that excavation and fill construction be carried out in accordance with Scheme 1, with the excavation depth of a single layer not exceeding 3m.

7.4. Stability analysis of excavation and filling construction process

The limit balance method is employed to directly calculate the stability of the dam body and reservoir slope following each construction phase and the conclusion of excavation and filling operations, as illustrated in Fig. 9. The resulting calculations are presented in Table 4.

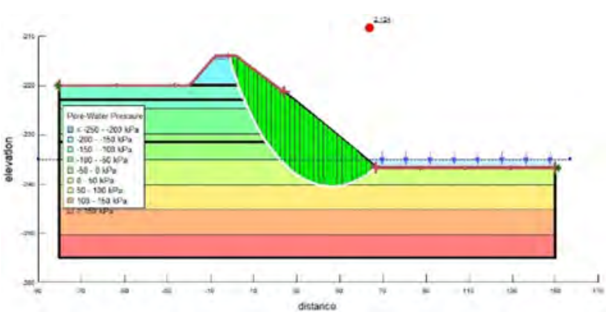

Fig. 9
Calculation diagram of the safety factor

Table 4
Changes of stability coefficient during excavation

Working condition		1st excavation	2nd excavation	3rd excavation	4th excavation	5th excavation	6th excavation	Filling
Stability coefficient	Scheme 1	2.391	2.242	2.241	2.166	2.381	2.174	1.406
	Scheme 2	2.441	2.121	2.388	2.165			1.105
	Scheme 3	2.391	2.178	2.215				1.142

The findings indicate that the stability coefficient is the lowest following the completion of filling construction, yet still reaches 2.124, signifying that the reservoir slope remains stable throughout the construction process and beyond.

8. DRAINAGE CONSTRUCTION

The geological exploration hole data of the lower reservoir indicates that the groundwater emerging elevation of the lower reservoir is between -230 and -240m, which is higher than the reservoir basin bottom elevation. In order to ensure the working face of the reservoir basin is dry during excavation, it is necessary to use an intercepting flume to reduce the groundwater level before excavation of the reservoir basin. Relief wells should be used to reduce groundwater pressure during normal operation of the dam body.

8.1. Construction of a cut-off water tank

A cut-over 1m wide and 10m deep is excavated along the dam body, filling the boundary line outside the reservoir (10m outside the reinforced stone cage dam filling boundary line, within the land requisition range). The cut-over adopts 12m deep steel sheet pile temporary support. Once the steel sheet pile has been driven into the pile bottom with a vibrating hammer, a 10-metre-deep trough is then excavated with a hydraulic backhoe with a long arm. During the excavation process, square logs measuring 10 cm by 10 cm are employed to provide support for the inner wall of the steel sheet pile at 5 m intervals. This is done to prevent the steel sheet pile from migrating inward due to the action of earth pressure.

Once the excavation of the trench is complete, the steel pipe, with a wall thickness of 5mm and a diameter of 800mm, is lowered into the trench. The steel pipe is buried in the bottom 2m (in the solid pipe section), and the pipe is more than 2m in the pipe section of 5m. The pipe is covered with a geotextile comprising 300 g/ m^2, and the surrounding area is filled with stone slag. The upper part of the pipe is a solid section, and the soil material excavated during the process is filled around it to the original ground elevation.

Once the stone slag and soil around the steel pipe have been filled, the steel sheet pile is extracted by the pipe drawing machine, allowing construction of the next sink to commence.

8.2. Relief Well Construction

The relief wells at the bottom of the reservoir and outside the reservoir are drilled using percussion drilling rigs. In order to prevent the orifice from collapsing, temporary locks comprising 3m-long steel pipes with a wall thickness of 5mm and an inner diameter of 1000mm are employed for the orifice.

In the construction of the relief well, a steel pipe with a wall thickness of 8mm and an inner diameter of 800mm is utilised as the arm and pipe to prevent borehole collapse. With the depth of the drilling hole, the pipe is gradually lowered into the hole, and water is injected into the hole to balance the earth pressure. The waste material resulting from the relief well excavation is then raised through the slag extraction bucket.

Once the relief well has been drilled to the designated elevation, the waste material within the hole should be cleaned, the well washed with clean water, and the washing pressure controlled to be less than 0.2 MPa until water is observed to be returning from the hole. Once the well has been cleaned, the PVC pipe, which has been covered with geotextile or geomesh in the processing plant, is installed in the hole in a sequential manner. The filter material is then placed between the PVC pipe and the steel pipe in a similar sequential manner. Finally, the steel pipe of the arm guard is extracted in a sequential manner.

Once the relief well has been approved, the deep well pump is installed at the base of the well, and the relief well begins to function.

8.3. Excavation of drainage trench and drainage blind trench

The excavation of the drainage trench is conducted through the utilisation of a hydraulic backhoe in conjunction with manual slope cutting techniques. The excavated soil material is deposited directly into the designated ballast dump area.

The drainage blind ditch is excavated with a small hydraulic backhoe, with an excavation depth of 2m, a bottom width of 1m, and slopes on both sides controlled at 1:0.5 to 1:1. The excavated soil materials are directly dumped in the ballast dump field when loaded into the truck. Following the excavation of the blind drainage ditch, the drainage material should be filled in a timely manner and compacted with a backhoe bucket.

9. CONCLUSIONS AND RECOMMENDATIONS

This paper presents a systematic summary of the design principles and main influencing factors of excavation and filling of storage power stations, based on the actual construction of the excavation and filling of the lower storage basin of the HK pumping and storage power station in Israel. It also expounds the zoning methods of excavation and filling of storage basins and provides a summary and exposition of the excavation and filling methods and construction technology of storage basins. The aforementioned summary and extraction are applicable and of value in a universal context. Numerical calculations were conducted to analyse the deformation and safety factor of the reservoir slope under different excavation and filling schemes. The results demonstrated that it is optimal to control the thickness of single-layer excavation below 3m. Excessive excavation thickness, due to precipitation and unloading, significantly impacts deformation and construction efficiency.

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LANDSCAPE SIGNAGE FOR PUMPED STORAGE DAMS (*)

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SUMMARY

This paper discusses the environmental landscape design of dams from the perspective of water conservancy project construction and the landscaping trend of pumped storage dams. In view of the existing problems, it puts forward the concept of integrated design of pumped storage dam signage and landscape environment. It carries out the initial exploration of the design in the three dimensions of “environment-objects-people”. Through the construction of the design concept, the maximum integration of the dam signage and the pumped storage landscape environment is realized, which highlights the characteristics that inherit the culture and realizes the harmonious unity of function, art and humanity. It will enhance the landscape benefits of the dam, open up new directions for development, and promote the national pumped storage business and spiritual civilization.

RÉSUMÉ

Ce rapport traite de la conception environnementale des barrages et de la tendance paysagère des barrages de pompage-turbinage. Au vu des problèmes existants, il propose le concept de conception paysagère intégrée du barrage de pompage-turbinage et de l’environnement paysager, en explorant les trois dimensions

**Conception paysagère des aménagements de pompage-turbinage*

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“environnement-objets-personnes”. Grâce à l’élaboration du concept de design, l’intégration maximale du barrage et de l’environnement paysager du pompage-turbinage est réallisée. Elle met en valeur les caractéristiques et le patrimoine culturel, et réalise l’unité harmonieuse de la fonction, de l’art et de l’humanité. Cela permettra d’améliorer les avantages paysagers des barrages, d’ouvrir de nouvelles voies de développement et de promouvoir les solutions à base de pompage-turbinage.

1. INTRODUCTION

Pumped storage dams not only have rich natural ecological resources but also carry a unique spatial environment. The landscape signage design promotes the harmonious coexistence of pumped storage construction and ecological environment, enhances the function and landscape quality of the dam area, and strengthens the dam’s cultural connotation and cultural heritage, functional efficiency and visual effect. Promote tourism and other related industries to drive the economy; at the same time, it is conducive to the popularization of the science of pumped storage and enhance its humanistic spirit. The landscape logo design of pumped storage dams has essential value and potential.

2. PROGRESS OF WATER ENGINEERING LANDSCAPE RESEARCH

2.1. Programme history

Foreign water conservancy project development time is early; many developed countries in the water conservancy landscape design continue to explore and practice, accumulated a wealth of design knowledge and experience in the field of “ecological water conservancy leisure tourism” has accumulated a lot of research experience. For example, Hoover Dam, known as the largest hydroelectric power plant in the United States, utilizes its advanced hydroelectric power plant technology and rich natural resources to create a water conservancy landscape tourism project successfully. The scenic tour flow with guided design provides a diversified viewing experience for tourists [1], which becomes a unique viewing point of regional attraction. Hammarby Eco-City in Sweden integrates the water conservancy project with the surrounding environment to create a livable, beautiful, and ecological urban space. Cheonggyecheon, South Korea, combines water conservancy engineering with landscape planning to achieve the dual goals of ecology and urban landscape optimization, creating a new urban landmark.

China is a vast country with abundant water resources such as rivers and lakes, so it is known as the “country of rivers” [2]. The initial water conservancy project is the management of rivers, and the pumped storage dam project belongs to a subcategory of water conservancy projects [3]. China started late in the programme of pumped storage dams, but under the great attention of the state, the development speed is relatively rapid, and it is expected that China will become one of the leading centres for the construction of pumped storage power plants in the future. The rapid development in the previous period is mainly reflected in the gradual increase in the number of dams constructed, the continuous improvement of construction technology and the gradual increase in construction scale. In recent years, China's pumped storage power plants have been in the planning and development of a more comprehensive, according to the form of society and positioning, landscape development is a vital direction; most of the power station has excellent natural landscape resources, power plant landscape construction to enhance the quality of the natural scenery, promote tourism and other related industries, driven by the economy; at the same time is conducive to the popularization of the science of pumped storage energy, and to enhance the power station of the humanistic spirit of the preachers: beautiful vision and a long history of the industry. There have been many famous water conservancy projects that are considered to be high-quality landscape resources with absolute value is actively developing their landscape function, such as the Minjiang River in the western part of the Chengdu Plain, known as "the originator of the world's water conservancy culture" Dujiangyan Water Conservancy Project, known as the "Artificial Heavenly River" Red Flag Canal water conservancy project, the South-to-North Water Diversion Project, Hubei Danjiangkou Hydropower Station on the upper reaches of the Han River in the middle line of the great South-to-North Water Diversion Project, and so on, the number of which is uncountable [4].

2.2. Development opportunities and directions

Traditional pumped storage landscape construction more focus on the construction itself, landscape environment that is the natural landscape environment, the humanities and the artistic value of the perspective of thinking little, but under the guidance of the concept of the construction of the project, the type of landscape is often too single, the lack of thematic and creative ideas, gradually lagging behind the higher ecological, environmental protection and aesthetic standards. In the country's "13th Five-Year Plan", the field of water conservancy has received particular attention, emphasizing the importance of water conservancy reform and proposing a planning and design methodology that integrates with the construction of ecological civilization. One of its goals is to solve the short board of the water conservancy project landscape, vigorously promote the environmental and ecological restoration and construction of the water conservancy project base, explore the direction of multifunctional planning, and enhance the landscape and ecological value of the water conservancy project [5].

Pumped storage dams have their unique nature; the achievement of this particular category of new landscape products, dam landscape marking and environmental landscape integration design emphasizes the close integration of pumped storage dams and environmental protection, balancing the integrated functions of power plant production and landscape tour, to ensure the harmonious symbiosis between man and nature, so that the construction of the dam to create unique landscape characteristics of the pumped storage as the overall development of the landscape of an Excellent direction.

3. EXPLORATION OF THE INTEGRATED DESIGN OF DAM SIGNAGE AND LANDSCAPE ENVIRONMENT

3.1. Landscape strategy

The pumped storage dam landscape signage design adapted to today's use of demand and environmental landscape expression of the integrated landscape design strategy for the dam area. The aim is to combine the pumped storage dam environmental landscape with the signage system to form a unified, coordinated and beautiful whole, integrating the power station as a whole to form a brand vision, symbolizing the environmental landscape, allowing the dam to go to the public and into the hearts of the people so that the spirit of the water conservancy and hydropower industry can be better propagated.

3.2. Theoretical inquiry

The landscape logo design of pumped storage dam should firstly clarify the design thinking, integrate the dam and landscape signage design from the spatial relationship, maintain the unity of style, and strengthen the sign function; then utilize the aesthetics to express the design, implement the ecological and environmental protection concept to protect the natural environment, and at the same time, integrate the cultural elements to embody the regional characteristics and history and culture; and finally enhance the sense of landscape use from the value point of view, and design the art derivatives according to the different timing. Finally, the landscape is designed to enhance the sense of use from the perspective of value, according to the different timing of the design of art derivatives, with particular consideration for the use needs of different groups of applicants and the addition of appropriate intelligent technology according to the actual situation, with a view to making it an integrated design with a high degree of acceptance by the public.

3.3. Purpose and significance

From the perspective of integrated design of dam environment and landscape signage, we explore new development ideas for spatial and functional integration of pumped storage dams. In this way, we not only expand the design form but also look for new development directions and planning and design strategies. The goal is to enable maximum synergy and integrated integration between the environmental landscape identity and the spatial construction system of the pumped storage power plant. At the same time, the interconnections and influences between the design systems, as well as the role ties between them, are emphasized in order to meet better the needs and spiritual pursuits of the spatial integration development of the dam. Through the coordinated integration of space systems and signs, a high degree of integration, artistry and humanization of the pumped storage dam space is realized.

Now, the pumped storage dam landscape is mainly based on water conservancy landscape; water conservancy landscape development stagnation over the years has not seen the development of uniqueness, making the pumped storage dam landscape more featureless, unable to highlight the majestic natural environment of our country also can not transmit China's advanced large-scale water conservancy function of the style. Under the guidance of the concept of integrated design, focusing on different disciplines across the boundaries of the organic integration of different professions so as to carry out a comprehensive innovation of spatial expression and display to enhance the experience of different groups of people, such as managers and visitors, to improve the quality of the space, enrich the cultural connotation, and to effectively solve the current problems of the dam space construction, such as improving safety, reducing environmental pollution, and enhancing the visual effect. It also effectively solves the existing problems of dam space construction, such as improving safety, reducing environmental pollution, improving visual effects, etc., thus significantly improving the service level of dam construction and landscape operation. The integrated design of dam signage and landscape environment not only meets the functional requirements of management but also demonstrates the unique charm of the dam, giving more people the opportunity and interest to understand the culture and spirit of water conservancy.

4. LANDSCAPE SIGNAGE DESIGN FOR PUMPED STORAGE DAMS

4.1. Conceptual analysis and formulation

A sign is a visual symbol that is clearly recognizable and communicates information [6]. Landscape signs of pumped storage dams are cultural symbols that can show the characteristics of the power station or enhance the visual effect of the environment in the pumped storage dam area, and the functional signs designed and installed in the slow-moving system for the purpose of clearly indicating the direction, explaining the function of the facilities, and warning of safety hazards, etc. They have specific shapes, materials, words, patterns or symbols integrated into the dam area. Signs with specific shapes, materials, words, patterns or symbols integrated into the landscape of the dam area are a set of visual information systems composed of several interrelated and complementary landscape signs.

By integrating natural and artificial elements, the landscape signage system creates a dam environment that meets the requirements of ecological protection and also has a sense of aesthetics and practicality. The system harmonizes and unifies the design of "environment-objects-people" and is a fully functional application of integrated design concepts, Fig. 1. The system is not only a physical structure that can effectively convey information and guide people's behaviour but also a visual branding super-symbol that can create a series of derivative applications to enhance the overall image of the power station and promote the spirit of water conservancy culture.

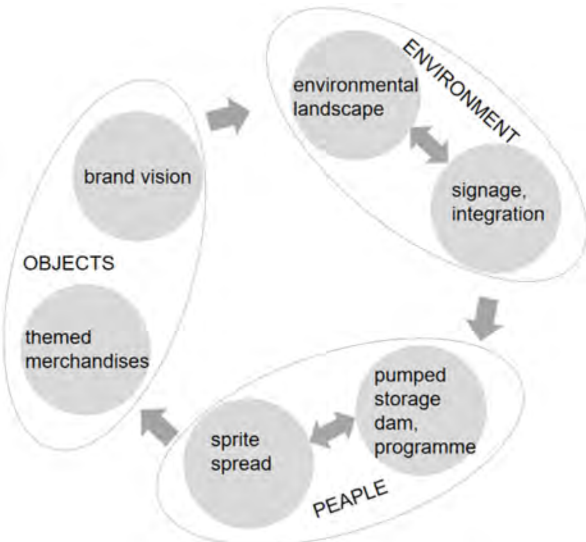

Fig. 1
Landscape Signage Integration Design Concept for Pumped Storage Dams

A series of legal, administrative and technical means are provided for the protection of signs with identifying, information transmission functions or specific values against unauthorized copying, imitation, misuse or damage so as to safeguard the lawful rights and interests of the sign designs and holders, and at the same time to promote the inheritance and development of culture, brand and environmental characteristics.

4.2. Design principles

The landscape signage design of the pumped storage dam should construct a signage system that is compatible with the scale of the power station and landscape features and conforms to the symbolic signage and slow-moving system functional signage in accordance with the conditions for the implementation of the dam project, and plan and layout for it. The construction realizes the protection of the ecological environment of the territory and the industrial safety of the power station, maintains the integrity of the spatial structure of the power station, and meets the functions of industrial propaganda, landscape recreation and safety protection.

4.2.1. *Principle of functionality*

Optimize the spatial structure of the power station, clarify the functional zoning of the power station, establish the office order to improve work efficiency, improve the excursion zoning, and connect the cultural landscape and ecological space of the dam. Make full use of the excellent natural ecological environment and the dam's industrial and humanistic structures and other characteristic spaces to meet the needs of convenient offices and public recreation.

4.2.2. *Principle of integration*

The integrated system of landscape signs should be configured in a hierarchical manner. Signs within the dam area should have a balanced layout, and the renovation area should be combined with the newly built area to add signs and optimize the layout; graded configuration of landscape signs should be differentiated between indoor signs and outdoor signs; reasonable configuration of symbolic signs and functional signs; and make full use of the traditional cultural spirit of the region and the power station to design and implement signs of different sizes.

4.2.3. *The principle of memorability*

Respecting the regional characteristics and the style of the power station, integrating nature and industry organically, protecting and presenting the natural landscape and industrial human resources, and promoting the corporate style. The cultural base of the region and the power station should be linked together and should promote the positive development of its cultural popularization and urban tourism.

4.3. Design methodology

4.3.1. *Symbol identification*

The zones of the pumped storage dam are marked with integrated landscape signage system symbols. The symbols and signs are divided into two categories: flat signs and physical signs. Interpretation of pumped storage dams as a cultural concept, presenting the dam born of water, inheritance of the red bloodline, continue the innovation gene, striding towards becoming a world-class green development field of the new journey of the heavy historical heritage. The graphic sign that can be promoted and used in online media, print media, printed materials, video exhibitions, publicity products, derivative souvenirs, and other carriers should be easy to extend and suitable for deepening the design. For the systematic expression of the graphic sign, Table 1. The physical sign shall be a combination of multiple elements that clearly express the design concept and are associated with the intent of the graphic logo.

Table 1
Systematic Representation of Graphic Identity

Graphic Signage Types	**Application Scenario**	**Application Requirements**
primary sign	They are used in most business scenarios. The sign should be used except in particular application scenarios.	Conforms to appropriate size requirements for different scenarios.
Loyalty sign	They are mainly used for political slogans, corporate slogans, and party scenes or the primary sign.	
EP sign	They are mainly used in eco-friendly field scenarios or using the primary sign.	
Public welfare sign	Mainly for CSR, holiday celebrations, etc., or when using the primary sign.	

4.3.2. *Functional identification*

Functional signage is the signage system used for the slow-moving system in each section of the dam area. Functional signage is an integrated design with symbolic sign as a whole. Functional signs are divided into two categories: multi-functional signs and specialized signs, Table 2.

Table 2
Synthesis of Functional Signage Systems for Slow-Moving Systems

Category	**Type**	**Identification Name**	**Content**	**Setting position**	**Characterization**
Multifunctional signs	Composite sign	Dam Overview sign	Panoramic photographs or pictures of the dam area, introduction to the dam, instructions for visiting the dam, information on services and management, and emergency telephone numbers.	The main entrances and exits of the slow-moving system in the dam area and important exhibition spaces must be installed, while others are installed as necessary.	Fixed location and a sign localized to set up a temporary display of the content area.
	Interpretation sign	area sign	Names, historical backgrounds, regional cultures, etc., of open sites in the dam area	Combined with open dams, regional cultural sites, industrial history sites, and others as needed.	It can be a non-fixed location; signage content can be set up in an irregularly updated area
specialized signs	lead sign	Guide sign	Directional guidance and location and distance information within the dam area, etc.	Slow-moving system entrances and exits, turnouts, and exhibition spaces in the dam area must be installed, as well as others as needed.	Fixed location and a sign localized to set up a temporary display of the content area.
		care sign	Elevation of the dam viewing area, time spent hiking, etc.	Set as needed	Fixed position, the content of the sign can not be adjusted arbitrarily
		Public welfare sign	Promotion of the spirit of dam industry, ecology, environmental protection, etc.	Set as needed	It can be a non-fixed location, and signage content can be set up in an irregularly updated area.
	warning sign	safety sign	Dam hazardous areas, prohibitions, etc.	It must be installed if there are hazardous areas and prohibitions in the dam area, and it must be installed as necessary for others.	Fixed position, the content of the sign can not be adjusted arbitrarily

5. CONCLUSIONS AND OUTLOOK

Based on the innovative concept of integrated design of dam signage and landscape environment, the pumped storage power station is no longer just a functional building providing energy, but a cultural carrier with story and temperature, dancing harmoniously with nature, becoming a part of the environment, and even a bright landscape. It is a design practice that subverts people's stereotypical impression of energy facilities in the past. While improving the functionality of the dam, it also emphasizes its integration with the surrounding natural environment, the injection of historical and cultural connotations, and a broader range of sustainable cultural dissemination through the application of artistic derivatives. Digging deeper into the intrinsic connection between the background of the dam and its location, we skillfully combine the dam with the signage elements in the spatial system to enhance the aesthetic value of the dam so that people can appreciate the beauty of the scenery and at the same time, feel the concept of green environmental protection and harmonious coexistence conveyed by the dam.

The future landscape signage design of pumped storage dams will become an essential force in the transmission of the spirit of water conservancy. A dam is a facility that provides clean energy, but it is also a platform that demonstrates human wisdom and conveys the concept of environmental protection. Through the innovative practice of integrated design of pumped storage dam signage and landscape environment, the brand image and value of the dam will be effectively conveyed, and a comprehensive landscape pumped storage dam with functionality, aesthetics, and culture will lead a new direction for the industry, and bring more beauty and surprises to people's lives.

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INNOVATIVE TECHNOLOGY AND APPLICATION RESEARCH ON ANTI-SEEPAGE OF PUMPED STORAGE POWER STATION RESERVOIR BASIN (*)

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SUMMARY

In recent years, with the rapid development and construction of pumped storage power stations in China, there have been more and more projects with complex geological conditions for dams and reservoirs at various stations, and breakthroughs have been made in key reservoir anti-seepage technologies. This article mainly introduces the application of anti-seepage schemes such as reinforced concrete panels, asphalt concrete panels, geomembranes, and clay coverings in practical engineering. By briefly describing the cutting-edge technologies and applications of two typical projects in reservoir anti-seepage, Jurong and K in Israel, the development trend of reservoir anti-seepage technology is predicted and forecasted, providing experience and reference for similar projects.

RÉSUMÉ

Ces dernières années, avec le développement rapide et la construction de centrales électriques à accumulation par pompage en Chine, il y a eu de plus en plus de projets avec des conditions géologiques complexes pour les barrages et les

**Technologie innovante et application sur l'étanchement du bassin de retenue d'une centrale de pompage-turbinage*

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réservoirs, et des progrès ont été réalisés dans les technologies de lutte contre les infiltrations dans les réservoirs. Ce rapport présente principalement l'application de panneaux de béton armé, de panneaux de béton bitumineux, de géomembranes, de revêtements en argile et d'autres méthodes d'imperméabilisation. Il fournit des leçons d'expérience pour des projets similaires en présentant brièvement les technologies de pointe et les applications dans l'imperméabilisation des bassins de stockage et deux projets typiques d'Israel K, en faisant des prévisions et des perspectives sur les tendances du développement de la technologie d'imperméabilisation des réservoirs.

1. INTRODUCTION

Since 1882, Switzerland has built the world's earliest pumped storage power station - the Zurich Netra pumped storage power station. The development of pumped storage power stations has a history of more than 140 years [1]. The development of pumped storage power stations in the 20th century was mainly concentrated in economically developed countries such as Europe, America, and Japan. As of the end of the 20th century, the total installed capacity worldwide was approximately 118000 MW [2].

The research and development of pumped storage power stations in China began in the 1960s. After entering the 1990s, with the completion of pumped storage power stations in Guangzhou, Shisanling, and Tianhuangping, it marked the peak of pumped storage power station construction in China.

In September 2020, General Secretary Xi Jinping proposed at the 75th United Nations General Assembly that China strives to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. Pumped storage power stations are the most technologically mature, economically optimal, and large-scale development conditions for green, low-carbon, clean, and flexible regulating power sources throughout the entire life cycle of the power system. Therefore, in order to implement renewable energy substitution and achieve carbon peak and carbon neutrality goals, China's pumped storage power stations have developed rapidly. As of the end of March 2024, the total installed capacity of built pumped storage power stations has reached 50940MW, ranking first in the world.

In the construction process of pumped storage power stations, countries attach great importance to the problem of reservoir leakage. Overall, various anti-seepage methods have been adopted based on engineering geological and hydrogeological conditions. These anti-seepage methods mainly include vertical anti-seepage, reinforced concrete panels, asphalt concrete panels, geomembranes, clay coverings, and comprehensive anti-seepage. At present, these anti-seepage methods have been successfully applied in multiple projects, accumulating rich experience in design, construction, and management, and the technology is relatively mature [3]

Abroad, such as the Latenton pumped storage power station in the United States, a comprehensive anti-seepage scheme for the entire reservoir basin is adopted, which combines a bottom clay blanket with asphalt concrete panels around the reservoir. The anti-seepage project of the upper reservoir of this power station is one of the earlier projects to adopt comprehensive anti-seepage. Although the bottom clay blanket has been repaired multiple times, its engineering construction has accumulated valuable experience for the design and construction of comprehensive anti-seepage in reservoirs. The upper reservoir of the Okinawa seawater storage power plant in Japan adopts a geotextile anti-seepage scheme. Since its construction and operation, the anti-seepage effect of the geotextile has been very good. The anti-seepage of seawater storage power station reservoirs faces a series of technical problems such as seawater corrosion, microbial adhesion, and building durability. The successful construction of Okinawa storage power station has made pioneering explorations for the anti-seepage of seawater storage power station reservoirs [4].

The Tianhuangping Pumped Storage Power Station, the first large-scale daily regulated pure pumped storage power station in East China Power Grid, has a total installed capacity of 1800MW and a maximum power generation head of 567m. The upper reservoir adopts a full basin asphalt concrete panel for anti-seepage, which is well adapted to complex engineering geological conditions. The upper reservoir of Tai'an Pumped Storage Power Station adopts a full basin anti-seepage type of reinforced concrete panel on the reservoir bank and geomembrane at the reservoir bottom, fully utilizing the strong adaptability of geomembrane to deformation, convenient and fast construction, and few joints. On the premise of ensuring project safety, good economic benefits have been achieved. The Baoquan pumped storage upper reservoir adopts a full basin anti-seepage type of reservoir bank asphalt concrete panel+reservoir bottom clay cover, which is the first domestic pumped storage power station anti-seepage project to use reservoir bottom clay cover.

2. OVERVIEW OF ANTI-SEEPAGE TECHNOLOGY FOR STORAGE BASINS

For multiple optional storage sites of pumped storage power stations, the construction conditions of different storage sites may vary greatly. When selecting the site for a pumped storage power station, in addition to engineering and technical conditions such as terrain and geology, construction conditions that need to be considered include: geographical location, water source, reservoir inundation, reservoir bank stability, type of water retaining structures and anti-seepage layout of the reservoir basin, environmental impact, and utilization of existing upper and lower reservoirs.

Given the terrain characteristics and runoff conditions of the upper reservoir, certain engineering measures need to be taken for anti-seepage treatment, and even some projects that rely on their natural conditions cannot form a reservoir require full basin anti-seepage treatment.

The types of anti-seepage measures for pumped storage power station reservoirs can be roughly divided into the following categories: full basin anti-seepage, half basin anti-seepage, and partial anti-seepage according to the anti-seepage range; According to the structural type of anti-seepage, it can be divided into surface anti-seepage and vertical anti-seepage; According to the diversity of anti-seepage types and materials, it can be divided into single structural anti-seepage and comprehensive anti-seepage. The upper reservoirs of the Thirteen Tombs, Tianhuangping, and Zhanghewan pumped storage power stations belong to typical full basin and surface single structure anti-seepage. The upper reservoirs of the Liyang, Baoquan, and Jurong (under construction) pumped storage power stations belong to typical full basin and surface composite structure anti-seepage. The upper reservoirs of the Tai'an, Langyashan, and Hongping pumped storage power stations belong to semi basin comprehensive anti-seepage. The upper reservoirs of the Tongbai, Xianyou, and Xianju pumped storage power stations belong to local vertical anti-seepage.

The main types of pumped storage power station dams are earth rock dams and concrete gravity dams, among which earth rock dams account for about 83% of the completed and under construction projects in China. And the earth rock dam is mainly composed of concrete face rockfill dam, accounting for about 60%. In the upper reservoir, asphalt concrete panel dams account for about 20%, mainly for the anti-seepage project of the entire reservoir basin. For most concrete face rockfill dams, only curtains need to be used for vertical anti-seepage.

2.1. Asphalt concrete panel

China's asphalt concrete panel anti-seepage has gone through three stages: from foreign monopoly and self exploration to domestic and international cooperation and independent innovation.

There are currently over 30 asphalt concrete panel anti-seepage projects completed in China. The pumped storage power station adopts asphalt concrete panels for anti-seepage. The Tianhuangping Project upper reservoir, which was completed in 1997, was the first to use asphalt concrete panels for anti-seepage in the entire reservoir basin. The Baoquan Project upper reservoir dam and bank, Zhanghewan upper reservoir, Xilongchi upper and lower reservoir dam and bottom, and Hohhot Project upper reservoir, which were completed in 2007, all use asphalt concrete panels for anti-seepage.

Asphalt concrete panels have been adopted by many pumped storage projects due to their good anti-seepage performance, strong adaptability to deformation, resistance to acid and alkali erosion, and no pollution to water quality [5].

There are two types of asphalt concrete panels: composite structure and simple structure (Fig. 1). The composite structure section consists of a surface sealing layer, a surface anti-seepage layer, an intermediate drainage layer, a bottom anti-seepage layer, and a leveling and bonding layer; The simplified structure section consists of a surface sealing layer, a surface anti-seepage layer, and a bottom leveling and bonding layer. In the absence of drainage capacity in the asphalt concrete underlying layer foundation, a drainage layer is also required. The structural type of the underlying layer is similar to that of reinforced concrete panels.

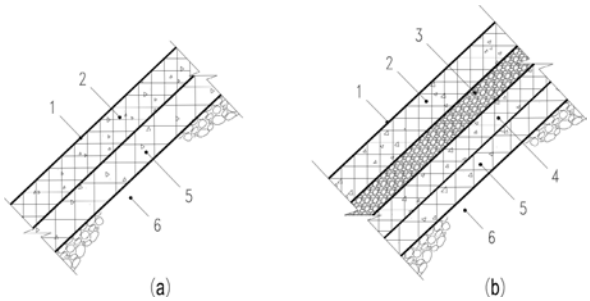


Fig. 1
Section type of asphalt concrete panel
(a) Simplified section (b) Composite section
1- Closed layer; 2- Anti seepage surface layer; 3- Drainage layer; 4- Anti seepage bottom layer; 5- Level the bonding layer; 6- Cushion layer

With the development of modern construction machinery, the equipment for mixing, paving, rolling, joint treatment, and testing of asphalt concrete has made significant progress. The mix design of asphalt concrete is also becoming increasingly mature. The previously feared anti-seepage effect of single-layer panels can now be solved through design and construction measures. Currently, most new construction projects use single-layer panels for anti-seepage.

In addition, asphalt concrete panels have achieved certain research results in high-temperature flow (extreme maximum temperature of 43 ℃ in Baoquan), low-temperature cracking (extreme minimum temperature of -41.8 ℃ in Hohhot), and joint safety (new materials such as SR and BGB), and have been applied in engineering.

2.2. Reinforced concrete panel

Reinforced concrete panel anti-seepage structure refers to a type of anti-seepage structure in which reinforced concrete panels are arranged on the surface of supporting structures such as rocks and piles to prevent water seepage. In practical engineering, it is often combined with toe boards, concrete retaining walls, connecting plates, anti-seepage curtains, anti-seepage walls, and joint waterproofing structures to form a closed anti-seepage system for reservoir dams or banks.

For dams, the anti-seepage structure of reinforced concrete panels usually consists of several parts: a reinforced concrete panel with a certain thickness on the surface, followed by a cushion layer, a transition layer, and a rock mass. The concrete panel anti-seepage structure of the reservoir bank includes concrete panels, crushed stone cushion layers, or sand free concrete, etc. The sand free concrete drainage cushion layer is mainly suitable for reservoir banks with rock foundations as the foundation surface (Fig. 2).

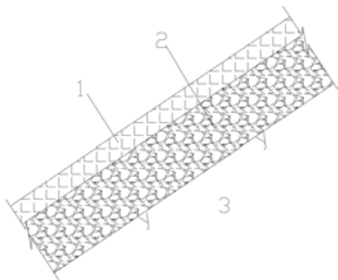


Fig. 2
Typical section of concrete anti-seepage panel on reservoir bank
1- Reinforced concrete panel; 2- Gravel cushion layer or sand free concrete (drainage layer); 3- Warehouse Bank

Reinforced concrete panels have many advantages, including the ability to adapt to steep slopes, mature construction technology, good impact resistance, high temperature resistance, and anti-seepage performance, fast construction speed, and strong adaptability to rainy and harsh weather conditions.

However, in the design and construction process, the following problems still need to be faced: relatively slow construction speed, multiple processes, and the need for a large amount of labor; The panel has multiple seams and there is a high risk of leakage due to inadequate waterproofing; Strict control of panel crack prevention. Therefore, although reinforced concrete face rockfill dams are commonly used in pumped storage power stations, there are relatively few projects that use full basin reinforced concrete face slabs.

Generally, cracks in panels can be avoided by adopting appropriate mix proportions, reasonable construction techniques, and strict control of construction quality. At the same time, many projects use polyurea coating to strengthen anti-seepage. The upper reservoirs of Yixing and Shisanling pumped storage power stations are all equipped with reinforced concrete panels for full basin protection [6].

2.3. Geomembrane

When the foundation of the anti-seepage structure is soil foundation, heavily deformed rock or slag filling, it is difficult to adapt to large deformations using rigid anti-seepage structures (such as concrete panels, etc.), which may cause cracks and damage to the anti-seepage structure. And geosynthetic membranes have good tensile properties, with relatively low technical requirements for the underlying layer, and can adapt well to foundation deformation. The permeability coefficient of anti-seepage geomembrane for hydraulic structures is generally 10-13cm/s. As long as the geomembrane is not damaged and its connection with the surrounding structure and welding quality are reliable, its anti-seepage effect can be guaranteed [7].

The commonly used geomembranes for anti-seepage in reservoirs mainly include PE, PVC, and TPO geomembranes. PE geomembranes have a higher hardness after exceeding a certain thickness, and it is difficult to bend during construction. The maximum yield elongation can reach over 12%; PVC and TPO geomembranes have relatively good flexibility, and the corners are easy to construct. The maximum yield elongation can reach over 20%, but their puncture resistance and wear resistance are relatively poor compared to PE geomembranes [8]. Therefore, when selecting geomembrane materials for anti-seepage, it is necessary to comprehensively consider the material's economic and mechanical properties.

At present, there is no pumped storage power station in China that adopts full reservoir geomembrane anti-seepage, and it is generally combined with other anti-seepage methods for anti-seepage. For example, Tai'an uses reinforced concrete panels around the warehouse and geomembranes at the bottom of the warehouse to prevent seepage, while Liyang uses reinforced concrete panels and geomembranes at the bottom of the warehouse to prevent seepage throughout the entire warehouse basin. However, there are many projects abroad that use full basin geomembranes for anti-seepage, such as the Imaichi pumped storage power station in Japan, the upper reservoir of the Okinawa seawater storage power station in Japan, the Waldeck I pumped storage power station in Germany, the La Coche pumped storage power station in France, and the Gilboa pumped storage power station in Israel.

2.4. Clay blanket

Due to the ability to fully utilize local materials, adapt to various terrain and geological conditions, and the rapid development of construction machinery, clay materials have been widely used as anti-seepage materials in the construction of earth and rock dams. Clay anti-seepage is also one of the anti-seepage methods for pumped storage power station reservoirs and basins.

Due to the low strength index of clay, the pore water pressure in the soil is not easy to dissipate and cannot adapt to the significant changes in water level in pumped storage power stations. Therefore, clay anti-seepage methods are rarely used for anti-seepage on the bank of pumped storage power stations, and are generally only used as auxiliary anti-seepage at the bottom of the reservoir. The clay anti-seepage structure used for the bottom of the reservoir mainly consists of the following parts: clay protective layer, anti-seepage clay, filter layer, transition layer, etc. (Fig. 3).

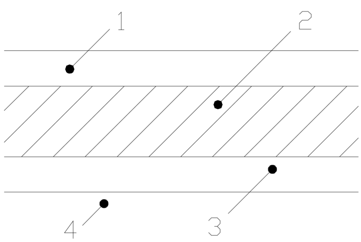


Fig. 3
Typical structural section of clay blanket anti-seepage
1- Clay protective layer; 2- Clay anti-seepage layer; 3- Anti filter layer;
4- Transition layer

2.5. Combination anti-seepage

For some pumped storage power station reservoirs, there are significant differences in the engineering geological conditions, hydrogeological conditions, or working conditions of anti-seepage structures in different parts. When a single anti-seepage treatment measure is difficult to meet the treatment requirements or requires a significant investment cost, it is necessary to adopt two or more anti-seepage measures based on engineering geological and hydrogeological conditions, permeability characteristics, permeability hazards, and working conditions. This anti-seepage treatment measure is called comprehensive anti-seepage. The selection of various anti-seepage measures in comprehensive anti-seepage is more targeted, so better economic results can be achieved on the basis of reasonable and feasible technology.

One of the key issues in the comprehensive anti-seepage plan is the connection between different anti-seepage structures. Due to the differences in materials, structural types, and operating conditions used in different anti-seepage structures, the connecting structures used need to adapt to these differences, meet the requirements of structural stress, deformation, and other aspects, and be safe and reliable. Therefore, the connection points of different anti-seepage structures are generally the weak points that are most prone to failure risks. According to different combinations of anti-seepage structures, there are mainly the following types of connection structures:

Reinforced concrete panel - geomembrane, reinforced concrete panel - clay overlay, asphalt concrete panel - geomembrane, asphalt concrete panel - clay overlay, reinforced concrete panel - asphalt concrete panel, etc. Table 1 shows the statistics of the connection methods between the comprehensive anti-seepage structures of some pumped storage power stations in China.

Table 1
Statistical table of connection methods between comprehensive anti-seepage structures of some pumped storage power stations in China

power station	**Type of anti-seepage for storage basin**	**Connection parts**	**Connection type**
Tai'an's upper reservoir	Reinforced concrete panels on the bank of the warehouse, geomembrane at the bottom of the warehouse	Reinforced concrete panel - geomembrane	Connection board, warehouse bottom corridor
Baoquan's upper reservoir	Asphalt concrete panel on the bank of the reservoir and clay blanket on the bottom of the reservoir	Asphalt concrete panel - clay overlay	Directly overlap
Liyang's upper reservoir	Reinforced concrete panels on the bank of the warehouse, geomembrane at the bottom of the warehouse	Reinforced concrete panel - geomembrane	Connection board
Jurong's upper reservoir	Asphalt concrete panel for reservoir bank and geomembrane for reservoir bottom	Asphalt concrete panel - geomembrane	Connection board, warehouse bottom corridor
Jurong's lower reservoir	Asphalt concrete panel on the bank of the reservoir and clay blanket on the bottom of the reservoir	Asphalt concrete panel - clay overlay	Directly overlap

3. INNOVATIVE TECHNOLOGY AND APPLICATION OF ANTI-SEEPAGE IN RESERVOIRS AND BASINS

In the process of constructing pumped storage power stations, various anti-seepage methods have been adopted, accumulating rich experience in design, construction, and operation management. This section takes Jurong and Israel's K pumped storage power stations as examples to briefly describe their innovative technologies and applications in reservoir anti-seepage.

3.1. The anti-seepage system of the upper reservoir of Jurong pumped storage power station

3.1.1. *Project introduction*

The Jurong Pumped Storage Power Station is located in Jurong City, Jiangsu Province. It is a daily regulated pure pumped storage power station with an installed capacity of 1350MW (6x225MW). The main buildings of the project consist of an upper reservoir, a water conveyance system, an underground powerhouse, a switch station, and a lower reservoir [9].

The karst within the engineering area is moderately developed, and the karst morphology is mainly composed of dissolution cracks, dissolution channels, dissolution troughs, and karst caves. The underground water level distribution and runoff regularity in the underground cave group area are poor, and there are problems such as karst water leakage, water inflow, and mud inflow [10]. The surface morphology of the upper and lower reservoir dams is shown in Fig. 4 and 5.

Fig. 4
Upper Reservoir dam foundation

Fig. 5
Lower reservoir dam foundation

The main dam of the upper reservoir adopts an asphalt concrete face rockfill dam, with a dam crest elevation of 272.40m and a maximum dam height of 182.30m. The reservoir basin is formed by a large platform at the bottom of the reservoir and an excavation slope of 1:1.7 around the reservoir. The bottom platform of the reservoir is half excavated and half filled, with a platform elevation of 237.00～236.50m. The filling materials for the reservoir basin are complex, mainly consisting of upper reservoir dolomite, diorite, and corner soil materials. The lower reservoir contains crushed stone soil materials, and the excavated dolomite in the lower reservoir basin is mixed with limestone, trachyte, andesite, and altered diorite. The maximum filling height is about 120m.

The main dam of the upper reservoir of Jurong Pumped Storage Power Station is the world’s tallest pumped storage power station dam (182.3m), the tallest asphalt concrete face rockfill dam, and the largest reservoir dam filling project (30 million m^3). The geological conditions of the reservoir dam foundation and the lithology of the filling material source are complex, and the control of dam deformation and reliable anti-seepage structure are key technical issues in the project. The excavation and filling site has a large height difference, small horizontal distance, high requirements for construction organization and dynamic balance of earthwork, and high technical difficulty in engineering construction.

The upper reservoir adopts a full basin anti-seepage scheme of asphalt concrete panels on the reservoir bank and geomembrane at the reservoir bottom, where the asphalt concrete panels are overlapped with the geomembrane through connecting plates. The layout plan of the upper reservoir is shown in Fig. 6.

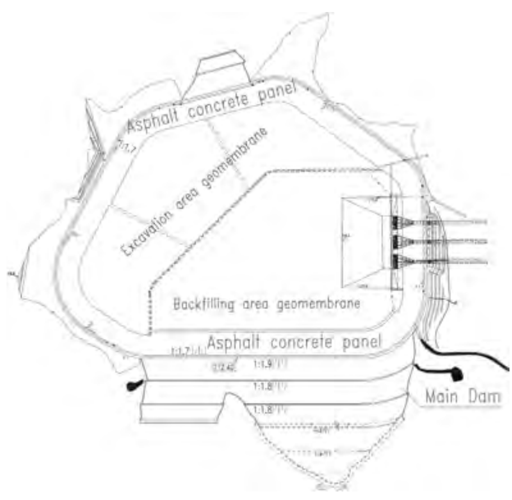


Fig. 6
Asphalt concrete panel on the bank of the upper reservoir+geomembrane anti-seepage scheme at the bottom of the reservoir

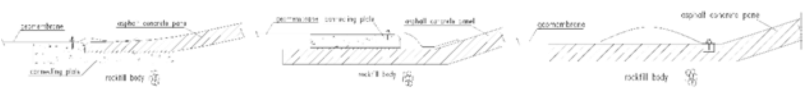
3.1.2. *Selection of anti-seepage joint scheme*

The maximum backfill depth of the connecting plate between the asphalt concrete panel and the geomembrane exceeds 100m. This area is crucial for the anti-seepage safety of the upper reservoir. If the joint is disconnected or cracks occur, it will lead to the formation of a concentrated leakage channel in the entire reservoir basin, seriously affecting the safety of the project.

To ensure the reliability of the anti-seepage joint, a large number of model tests were conducted before actual construction, mainly including:

1. The concrete connection plate of Scheme 1 is located below the asphalt concrete, and the water stop structure adopts a single anchor adhesive sealing fixed structure with SR flexible anti-seepage sealing;
2. The concrete connection plate of Scheme 2 is located above the asphalt concrete, and the water stop structure adopts a double anchored fixed structure with SR flexible anti-seepage sealing;
3. Scheme 3 adopts the elimination of concrete connection plates and the planting of screw anchoring anti-seepage structures;

The schematic diagrams of each scheme and the model testing process are shown in Fig. 7 and 8:



(a) (b) (c)

Fig. 7
Schematic diagram of each scheme
(a) Option 1 (b) Option 2 (c)Option 3

Fig. 8
Overall model indoor test

By making models of three connection plate joint schemes, refining each detailed structure, and conducting overall dynamic sliding verification tests, the final results show that all three scheme models have reliable anti-seepage performance under static water pressure conditions.

Considering the possibility of long-term stress relaxation in asphalt concrete, the 1 # scheme was ultimately adopted as the foundation, retaining the connecting plate for connection. The connecting plate only serves as an anchoring function and is not used as an anti-seepage structure. The surface layer of the geomembrane covers the connecting plate and then extends to bond with the asphalt concrete panel.

3.1.3. *Research on deformation adaptability*

According to the engineering application of the anti-seepage scheme using the basement geomembrane, the leakage of the basement geomembrane is mainly concentrated in areas with significant deformation differences such as excavation and filling boundaries, weak junctions, and anchoring. The lower part of the geomembrane in this project is the backfill material for the reservoir basin, which is different from the “softness” of the anchored gallery concrete, excavated bedrock surface, and upstream rockfill material of the main dam. After water storage, a large deformation gradient will inevitably occur at the anchoring parts of the geomembrane, inlet and outlet, and asphalt concrete panel. Therefore, the adaptability of the local geomembrane to large deformation gradients is the key to ensuring the reliability of the anti-seepage system.

Use finite element method to perform overall and sub model calculations on the anchoring parts of the main dam’s geomembrane and connecting plate. The calculation results show (Fig. 9) that the maximum strain of the local geomembrane at the anchorage of the submodel connecting plate reaches 3.75%. Considering that the unidirectional strain limit of the selected geomembrane under normal working conditions is 12%, and the bidirectional strain limit is about 3% to 4%. The geomembrane is already in a critical state of failure, and it is necessary to take measures to locally adapt to deformation to reduce the strain of the geomembrane [11].

For areas with prominent deformation, engineering measures such as setting up an additional mold area at the contact point, increasing rolling parameters, and reserving superelevation can effectively reduce the deformation of the geomembrane. Through finite element analysis and calculation, the maximum strain of the sub model can be reduced to within 1%.

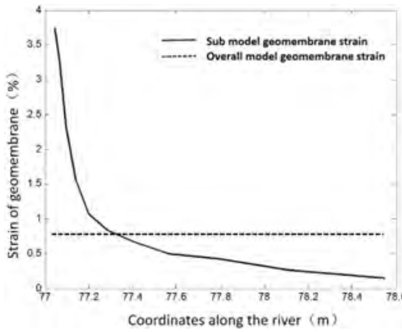


Fig. 9
Comparison of geomembrane strain between sub model and overall model at this location

3.1.4. *Material selection for geomembrane*

The filling height of the bottom of Jurong Upper Reservoir reaches 120m, and the filling materials mainly include crushed stone soil from the lower reservoir, corner materials from the upper reservoir, and weathered shale materials, with very complex material properties. By implementing corresponding measures, the local deformation of the geomembrane can be reduced. However, the local tensile strain of HDPE is still relatively large, with the maximum strain value of the geomembrane at the inlet and outlet exceeding 1%. The bi-directional yield elongation of HDPE geomembrane is only 3-4%, indicating a small safety margin. Therefore, it is important to seek a new type of material with better performance, adaptability to large-scale settlement deformation, and ease of construction.

(1) Material characteristics

The main geotextile materials used for anti-seepage engineering in China are PE and PVC geomembranes, with PE geomembranes being slightly more common. From the perspective of mechanical properties, the tensile strength of PE geomembrane and PVC geomembrane is not significantly different. When used only for anti-seepage and not as reinforcement material, tensile strength is not an important indicator for material selection. On the other hand, PVC geomembrane is flexible and easy to install due to the addition of plasticizers, and has strong adaptability to complex shapes. PE geomembrane is relatively hard, and it is difficult for thicker PE films to wrinkle.

Another commonly used waterproof material for roofs, thermoplastic polyolefin (TPO) geomembrane, is a polyolefin elastomer material that combines rubber and thermoplastic properties by using advanced polymerization technology to combine ethylene propylene rubber and polypropylene. It has the high elasticity of ternary ethylene propylene rubber at room temperature and the plasticization molding of polypropylene at high temperature. It does not contain plasticizers and has relatively good durability. At the same time, it has good multi-directional tensile properties, with strength and burst resistance superior to PVC. It is a rapidly developing polymer in recent years.

Based on the above characteristics and combined with the characteristics of this project, compare the performance testing of TPO and HDPE, and analyze the advantages and disadvantages of the two geomembranes.

(2) Comparative analysis of materials

Conduct comparative tests on the overall physical performance indicators of 1.5mm HDPE geomembrane and 1.5mm TPO geomembrane. The experimental comparison results are shown in Table 2.

Table 2
Comparison of physical performance indicators between HDPE and TPO

material name		**1.5mmTPO**	**1.5mmHDPE**
elongation at yield %	direction	32	13
	transverse	31	12
elongation at break %	direction	659	869
	transverse	766	894
Multi-directional ultimate strain %	direction	400	30
	transverse		
Elastic deformation variable %	direction	92	36
	transverse	94	28
Puncture displacement N		34	23.5
Puncture height mm		100	15
Thermal size change rate *,%		2.3	0.8
heat aging resistance（85°C, 90d）	Tensile strength retention rate	104%	86%
	Retention rate of elongation at break	106%	86%
	Retention rate of seam peeling performance	124%	63%
	Joint shear performance retention rate	108%	109%
The rate of change in the area of the sample when heated from 23°C to 80°C			

From the table, it can be seen that TPO material has significant advantages over HDPE in terms of tensile strength, puncture resistance, high temperature resistance, durability, and construction. It has better adaptability to uneven deformation in Jurong engineering.

According to the research on the deformation adaptability and material selection of geomembranes, HDPE geomembranes are selected for the excavation area of the upper reservoir basin, and TPO geomembranes are selected for the anti-seepage scheme of the filling area. At present, the upper reservoir of the project has been safely filled with water and the anti-seepage effect is good. The site appearance is shown in Fig. 10.

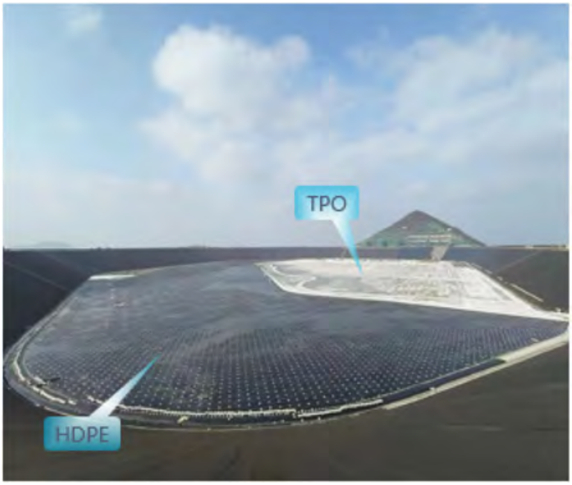


Fig. 10
Realistic view of the upper reservoir

3.2. Raeli K full reservoir geomembrane anti-seepage system

3.2.1. *Project introduction*

The Kokhav Hayarden pumped storage power station in Israel is located in northern Israel, near the lower reaches of the Jordan River. The access conditions for the power station are good, and it can be reached through Highway 90 on the West Bank of the Jordan River. The distance between the power station and the nearest cities, Beth Sh'ean and Tiberias, is 10km and 25km respectively. The project has been completed at present.

This project mainly consists of buildings such as an upper reservoir, a lower reservoir, a water conveyance system, an underground powerhouse, and a switch station The total installed capacity of the power station is 344MW, with two 172MW single-stage reversible generator units installed, and an effective storage capacity of 3.16 million m^3.

This project is located in the Middle East. Considering the scarcity of water resources, in order to minimize seepage and adapt to soil foundation deformation, both the upper and lower reservoirs use full basin geomembranes for anti-seepage. The foundation of both the upper and lower reservoirs is made of high liquid limit and high plasticity clay, and the dam is a homogeneous soil dam. Both the upper and lower reservoirs are filled with a full basin geomembrane for anti-seepage, using a 2mm thick composite PVC geomembrane for anti-seepage. The slope ratio of the upper reservoir is 1:3.5, and the slope ratio of the lower reservoir is 1:3.0. The total area of the geomembrane is 420 thousand square meters. The geomembrane of this project is designed to be exposed, with no protective layer on the upper part. The support layer at the lower part of the geomembrane is a geotextile mat, which serves as both a support layer and a drainage layer.

For the anti-seepage of the entire reservoir basin, the anchoring system and construction steps of the geomembrane, the leakage drainage system, and the monitoring layout are important components of the geomembrane anti-seepage design.

3.2.2. *Geotextile anchoring and construction steps*

The water level of the upper and lower reservoirs of pumped storage power stations often fluctuates between the dead water level and the normal storage level. The part of the geomembrane above the dead water level is often exposed outside the water level line. Due to the influence of wind load, directly laying the geomembrane on the slope is prone to sliding failure. Therefore, anchoring blocks or anchoring grooves need to be used to reinforce the geomembrane. Unlike the geomembrane on the bank of the reservoir, the geomembrane at the bottom of the reservoir is located below the dead water level for a long time and is always subjected to water loads, without the need for additional anchoring measures.

This project only requires anchoring of the geomembrane on the reservoir bank. The anchoring type adopts anchoring groove anchoring, and its main parameters include the material of the geomembrane, the layout and size of the anchoring groove, which should be selected based on local wind speed calculation. After verification and analysis, the main design parameters are determined as follows: excavate 70cm $\times$ 90cm sized anchor slots at equal intervals on the slope, with a top 1/3 anchor slot spacing of 8m and a bottom 2/3 anchor slot spacing of 16m [12]. The anchoring strip is buried at the bottom of the groove, and the other end extends along the excavation surface of the anchoring groove to the slope. After the strip is arranged, the groove is backfilled with dense soil material, as shown in Fig. 11 and 12.

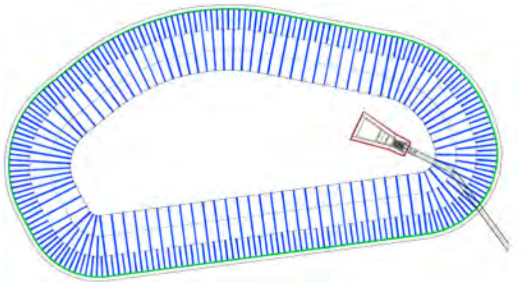


Fig. 11
Layout plan of slope noodle belt anchorage

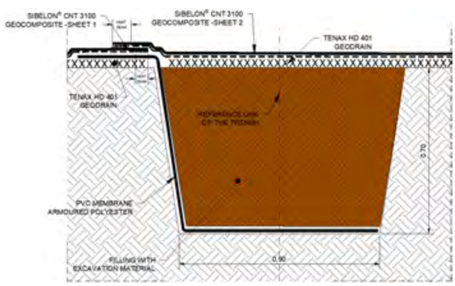


Fig. 12
Typical sectional view of anchorage groove

The construction steps for anchoring grooves on the construction site are shown in Fig. 13.

After the anchoring groove construction is completed, the slope geomembrane is welded and anchored as a whole. The specific construction steps are shown in Fig. 14.

a) b) (c)

(d) (e) (f)

Fig. 13
Construction steps of geomembrane anchoring groove
a) Slope excavation anchoring groove b) Cast in place mortar leveling layer along the groove edge (c) Lay geotextile pressure strip along the groove (d) Leveling the geotextile covering strip (e) Backfilling and compacting (f) Leveling and cleaning the slope surface

a) (b) (c)

Fig. 14
Construction steps of geomembrane
a) Geotextile cushion and geomembrane laying (b) geomembrane welding (c) anchoring with other concrete surfaces

3.2.3. *Partition seepage drainage and monitoring*

Geomembrane is an impermeable material, but there may be some defects such as welding leaks or puncture risks during production, manufacturing, or construction laying. The damaged points generated during the construction process should be comprehensively inspected and repaired before water storage. However, the occasional defects and holes that occur during the construction or operation of the reservoir cannot be completely avoided. Therefore, there is still a certain amount of leakage in the geomembrane reservoir after water storage.

To discharge the leakage water from the geomembrane and determine the location of the leakage, a partitioned drainage design was carried out on the reservoir bank and bottom, including 6 leakage drainage sub zones on the reservoir bank and 4 leakage drainage sub zones on the reservoir bottom. A layer of geotextile mat is laid under the geomembrane on the bank of the reservoir as a drainage cushion layer, and a layer of crushed stone drainage layer is laid under the geomembrane on the bottom of the reservoir [13]. The layout plan of the seepage drainage system in the lower reservoir is shown in Fig. 15.

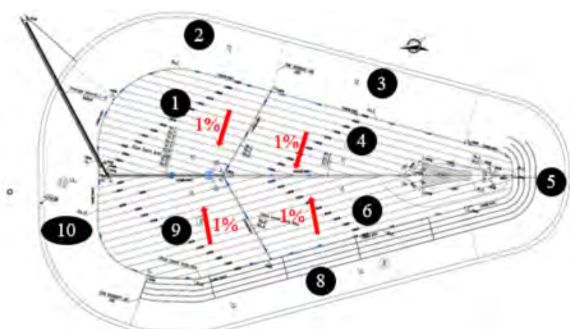


Fig. 15
Layout Plan of Lower Reservoir Leakage Drainage System

Leakage water can be collected into the water collection pipes in their respective zones through geotextile mats and gravel drainage layers. PVC drainage flower pipes are installed at the foot of each leakage zone to collect leakage water, which is then directed to the leakage collection well outside the reservoir. A triangular weir is installed in the collection well to monitor the leakage of each drainage channel in the reservoir in real-time. The leakage water in the collection well can ultimately be pumped back into the reservoir through a reverse pumping system to ensure the regulating capacity of the reservoir. The design and implementation of zoning monitoring for water measuring weir is shown in Fig. 16.

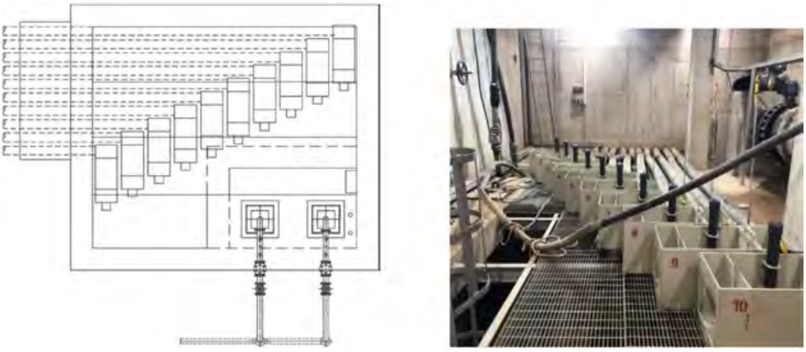


Fig. 16
Design and Implementation of Zoning Monitoring for Water Measuring Weir

4. CONCLUSIONS

After decades of development, China's pumped storage construction has developed the most critical reservoir anti-seepage technology. For different complex terrain and geological conditions, suitable engineering, advanced technology, reliable construction, and controllable quality schemes and construction processes can be developed. The anti-seepage technology has reached the international leading level.

From Tianhuangping pumped storage, which was the first to use asphalt concrete panels for anti-seepage in the entire reservoir, to Tai'an pumped storage, which used geomembranes for anti-seepage at the bottom of the reservoir for the first time, to Jurong pumped storage, which innovatively used asphalt concrete panels around the reservoir, geomembranes for anti-seepage at the bottom of the reservoir, and TPO new materials, as well as Israel K pumped storage, which uses geomembranes for anti-seepage in the entire reservoir, China's pumped storage workers have been continuously researching and innovating to provide more reliable anti-seepage solutions for different difficult projects.

For complex terrain and geological conditions, high dam height, and thick filling of the reservoir basin, using a geomembrane with better adaptability to deformation at the bottom of the reservoir for anti-seepage is more conducive to engineering safety. The anti-seepage scheme of asphalt concrete panels around the reservoir and geomembrane at the bottom of the reservoir can be selected.

In recent decades, the development of geomembrane materials has been rapid. Projects that use geomembranes for anti-seepage should choose geotechnical materials with better performance and more suitable for the project based on its characteristics. The geomembrane anti-seepage scheme for the entire reservoir basin has good adaptability to projects with poor foundation conditions and large uneven deformation. It is widely used in water conservancy and hydropower projects abroad, and can also be used as a reference for later domestic pumped storage projects.

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SAFETY RISK ASSESSMENT OF A HYDROPOWER DAM BASED ON RISK MATRIX METHOD (*)

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SUMMARY

This paper aims to identify safety risks associated with the operational period of a hydropower dam by employing the structured interview method within the framework of risk assessment techniques. The risk matrix method is utilized to analyze both the likelihood of occurrence and the severity of consequences for various potential risk sources, encompassing water-retaining structures, water release and energy dissipation structures, gates and hoists, reservoir banks and slopes, reservoir operation management, as well as natural disasters. A total of 17 potential risk sources have been identified through this comprehensive assessment. Based on expert experience, each risk source is rated, and targeted risk response and control measures are proposed. The findings and recommendations presented in this study can serve as a valuable reference for enhancing the safety management of dam operations.

**Évaluation des risques pour un barrage hydroélectrique par la méthode de la matrice des risques*

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RÉSUMÉ

Ce rapport vise à identifier les risques de sécurité associés à la période d'exploitation d'un barrage hydroélectrique en utilisant la méthode d'interviews structurés dans le cadre des techniques d'évaluation des risques. La méthode de la matrice des risques est utilisée pour analyser la probabilité d'occurrence et la gravité des conséquences pour diverses sources de risque potentielles, y compris les structures de retenue d'eau, les ouvrages annexes et les ouvrages de dissipation d'énergie, les barrières et les appareils de levage, les berges et les pentes des réservoirs, la gestion de l'exploitation des réservoirs, ainsi que les catastrophes naturelles. Au total, 17 sources de risques possibles ont été identifiées dans le cadre de cette évaluation exhaustive. Selon l'expérience des experts, chaque source de risque est cotée et des mesures de contrôle et d'intervention ciblées sont proposées. Les conclusions et les recommandations présentées dans cette étude peuvent servir de référence précieuse pour améliorer la gestion de la sécurité de l'exploitation des barrages.

1. INTRODUCTION

Hydropower dam systems constitute a complex infrastructure that encompasses not only water-retaining structures, water release facilities, and metallic structures but also the foundations of these structures, slope zones within the project area, and the near-dam reservoir banks. Each component plays a crucial role in ensuring the overall safety of the hydropower station, necessitating meticulous management and maintenance efforts [1–3].

To minimize the occurrence of dam failures and mitigate their potentially catastrophic consequences, the international community has conducted extensive research into the causes, mechanisms, failure modes, and resulting floods associated with hydropower dam breaches. This research has led to the development of a risk-based approach for dam safety analysis and management. At its core, this approach transcends the mere engineering safety of the dam itself, embracing the far-reaching impacts that a dam failure could inflict on downstream communities. Driven by this philosophy, a comprehensive and multi-layered safety system has emerged, integrating both engineering and non-engineering measures to safeguard the long-term operational safety of reservoirs and dams. This risk-based analysis and management paradigm has profoundly influenced China's approach to hydroelectric engineering safety, fostering a shift from an 'engineering safety' mindset to an 'engineering risk' mindset. This transformation permeates not only the routine maintenance and management of dams but also spans their entire lifecycle.

Dam safety risk analysis is a dynamic and ongoing process that encompasses risk identification, probability estimation, loss assessment, risk criterion setting, evaluation, decision-making, and risk mitigation. This framework integrates considerations of the dam's safety risk rate, potential consequences of a breach, societal and environmental impacts, and risk control standards. By doing so, it enables a more scientific assessment of the dam's safety status and breach likelihood, thereby facilitating more accurate predictions of potential life and property losses, as well as societal and environmental impacts. Ultimately, this approach guides the optimization of dam reinforcement efforts within limited human and financial resources.

Risk factors influencing dam safety can be broadly categorized into three domains: engineering risks, environmental risks, and human-induced risks [4,5].

(1) *Engineering Risk Factors*
Engineering risk identification focuses on uncovering inherent defects within the dam structure that could lead to failure. These include geological defects such as faults, structures, weak interlayers, and liquefiable soil layers in the dam foundation; engineering quality defects like inadequate impermeability treatment of buried culverts beneath the dam, insufficient compaction or steep slopes in the dam body that may cause landslides, and weak layers within the dam that could lead to seepage failure or landslides; insufficient dam crest height, which may result in overtopping; and gate failure or malfunctioning hoists, also contributing to overtopping risks.

(2) *Environmental Risk Factors*
Environmental risk identification centers on external forces that could precipitate dam failures, including extreme floods, severe droughts, earthquakes, temperature fluctuations, near-dam bank landslides, upstream dam breaches, and human-caused disruptions (e.g., war, and terrorist activities).

(3) *Human-Induced Risk Factors*
Huaizhi et al. study the fundamental principles of risk analysis, constructing a three-tier hierarchical structure for risk analysis and utilizing an improved analytic hierarchy process (AHP) to identify major factors influencing dam risks. Xu Qiang [4] integrates AHP, fuzzy theory, and genetic algorithms to develop a dam operation risk identification model.

The risk identification methods employed in this study include Step 1. an evidence-based approach, which involves reviewing historical acceptance, evaluation, appraisal, and inspection records to preliminarily assess the current safety status of the dam and propose potential risk sources; Step 2. a systematic expert team method, which organizes structured interviews with a team of experts using a set of prompts or questions to identify risks; and Step 3. the complementary use of other techniques, including brainstorming

2. METHODOLOGY

2.1. Structured interview

In structured interviews, the interviewer poses a series of predetermined questions to the interviewees based on a pre-designed outline, aiming to elicit their perspectives on a specific issue. The format allows for open dialogue to explore potential issues or nuances that may arise [6].

Step 1. Designing the Interview Outline: An interview outline is crafted to guide the interviewer throughout the session. The questions should be clear and concise, facilitating comprehension by the interviewees. Additionally, potential follow-up questions are prepared to clarify or elaborate on the initial inquiries. To ensure interview quality, questions should ideally focus on a single aspect at a time.

Step 2. Presenting Questions to Interviewees: When seeking responses, the questions are posed in an open-ended manner, avoiding leading the interviewees. Flexibility in considering answers is essential to allow interviewees the opportunity to express their genuine opinions as fully as possible.

Advantages and Limitations of Structured Interviews:

- They provide dedicated time for individuals to contemplate a particular issue.
- One-on-one communication fosters deeper contemplation on the matter by both parties.
- Compared to brainstorming sessions that often involve a limited number of participants, structured interviews engage a broader range of stakeholders.
- Gathering diverse viewpoints through this method can be time-consuming.
- Interviewees' opinions may be biased, as they are not subjected to the debiasing effect of group discussion.
- It lacks the imaginative spark characteristic of brainstorming sessions.

Structured interviews are particularly suited for the risk identification phase of risk assessment, as well as for consequence and likelihood analysis within risk analysis, and the risk evaluation stage. They are less impacted by resource and capability constraints, involving lower degrees of uncertainty and complexity. However, they do not offer quantitative outcomes.

2.2. Risk matrix method

The Risk Matrix Analysis (RMA) [7] is a structured approach to risk management that assesses the magnitude of risks by comprehensively considering their probability of occurrence and potential losses. The risk matrix categorizes risks into different levels, thereby facilitating risk prioritization and determination of the sequence in which risk treatment measures should be implemented.

The risk matrix typically comprises two dimensions: the probability (or likelihood) of risk occurrence and the degree of impact (or loss) should the risk materialize. By intersecting these two dimensions, a matrix is formed, with each cell representing a risk level. At its core, RMA constructs a comprehensive risk assessment framework that encompasses all potential risk sources and subjects them to quantitative evaluation. The outcomes of this assessment guide the formulation of risk response strategies.

In the context of hydroelectric dam safety, the application of RMA typically follows these steps:

Step 1. Data Collection: Gather historical data relevant to hydroelectric dam safety, including climatic, geological, and hydrological information, as well as records of dam design, construction, and maintenance.

Step 2. Risk Identification: Identify potential risk sources that may threaten dam safety through expert interviews, site investigations, and other methodologies. This step can be structured according to the Structured Interview Method.

Step 3. Risk Analysis: Evaluate the probability of occurrence and potential losses for each identified risk source. This assessment can be achieved through historical data analysis, expert judgment, or simulation modeling. The evaluation criteria for risk likelihood refer to the Chinese standards outlined in 'Risk Management - Risk Assessment Techniques', with corresponding score ranges presented in Table 1. The severity of risk consequences should consider factors such as casualties, economic losses, safety failure impacts, environmental impacts, and societal implications. It is advisable to model the outcomes of events and refer to the 'Specification for Risk Management of Large and Medium-sized Hydropower Engineering Operation' for guidance.

Step 4. Construction of Risk Matrix: Utilize the probability of risk occurrence and potential losses as axes to create a two-dimensional risk matrix. Each risk source is positioned in the matrix based on its assessment results, indicating its risk level. The construction of the risk matrix draws upon the 'Specification for Risk Management of Large and Medium-sized Hydropower Engineering Operation' and incorporates experiences from other engineering risk assessments, resulting in a risk rating scale presented in Table 2, classifying risks from highest to lowest as Levels I to IV

The RMA methodology offers several advantages, including its intuitiveness, flexibility, and ease of operation. It not only enables enterprises or organizations to gain a comprehensive understanding of their current risk landscape but also directs the development of effective risk response measures, thereby enhancing the efficiency and effectiveness of risk management.

Table 1
Evaluation Criteria for the Likelihood of Risk Occurrence

Serial Number	**1**	**2**	**3**	**4**	**5**
Likelihood	Very Low	Low	Medium	High	Very High
Score Range	(0，10]	(10，20]	(20，30]	(30，40]	(40，50]

Table 2
Risk Level Assessment

Likelihood	**Severity and Impact**				
	Minor	**Normal**	**Large**	**Significant**	**Extremely Significant**
Very Low	IV	IV	IV	III	III
Low	IV	IV	III	III	II
Medium	IV	III	III	II	I
High	IV	III	II	II	I
Very High	III	II	II	I	I

3. RISK ASSESSMENT

3.1. Project overview

The hydropower plant in question serves as a medium-sized pivotal project located in the mid-to-lower reaches of the Kashgar River, primarily focused on power generation while also accommodating irrigation and other comprehensive benefits. The plant is situated at the exit of the Mazhaer Gorge on the Kashgar River within the territory of Yining County, Xinjiang, approximately 51 km from Yining City and approximately 6 km downstream from the upstream Wenquan Hydropower Station. The reservoir boasts a total storage capacity of 17.5×10^6 m^3, functioning as a daily regulation reservoir. The installed capacity of the power station is 50 MW, with plans for an expansion to 60 MW through capacity enhancement and renovation. The normal water level of the reservoir stands at 865.00m, the design flood level at 857.00 m, the check flood level at 862.08 m, and the dead water level at 860.00 m. The key structures within the pivotal area encompass a concrete double-curvature arch dam, a concrete core-wall earth-rockfill auxiliary dam, a power water diversion system, a diversion and desanding tunnel, a surface powerhouse, and a switching station.

The concrete double-curvature arch dam boasts a maximum height of 54.5 m, a maximum base width of 14.38 m, a crest width of 3.5 m, a crest arc length of 179.24 m, and a crest elevation of 867.20 m. The dam is segmented into ten sections, with flood discharge outlets incorporated into sections 4 to 6. The inlet base plates are situated at elevations of 835.50 m and 839.50 m, respectively, utilizing ski-jump energy dissipation, and are equipped with plunge pools downstream of the dam.

The desanding tunnel (converted from the diversion tunnel) is positioned 30 m upstream of the power intake, with a baseplate elevation of 827.00 m. The tunnel extends 356 m in length, adopting a horseshoe-shaped cross-section with a width of 8m and a height of 8.5 m. The tunnel features a longitudinal slope of 2.92% and is fully lined with reinforced concrete. This tunnel serves a multi-faceted role during construction (for diversion), operation (for desanding), and reservoir emptying.

The river valley at the dam site exhibits a V-shaped profile. The entire reservoir basin comprises bedrock, characterized by relatively hard lithology and minimal faulting. No large tensile fractures traversing the river valley or inter-river areas have been identified, eliminating the risk of leakage towards adjacent valleys. The seismic design intensity for the dam is VII degrees.

3.2. Risk identification and analysis

3.2.1. *Water-Retaining Structures (WRS)*

Based on field investigations and historical dam safety inspections conducted at a certain hydropower plant, the following potential risk sources for water-retaining structures have been identified:

(1) *Significant Water Seepage in the Drainage Tunnel at an Elevation of 840 m on the Right Bank Downstream of the Dam (RS1)*

A water measurement weir has been installed within the drainage tunnel at an elevation of 840 m on the right abutment to monitor the seepage flow. During the initial dam safety inspection in 2000, it was observed that the seepage volume in this tunnel strongly correlated with the reservoir water level. When the reservoir level reached 860.0 m, the measured seepage flow rate was approximately 420 L/min. The seepage water within the tunnel was clear and transparent, with no fine sand or mud carried out. It was concluded that the seepage primarily originated from reservoir water bypassing the dam, likely due to insufficient depth and length of the curtain grouting on the right abutment.

In September 2001, reinforcement grouting was completed on the right bank curtain, extending the original curtain line with a hole spacing of 2 m and a bottom elevation reaching 830 m, 20 m deeper than the original curtain. Inspection holes confirmed that the reinforcement curtain met the design requirements, reducing the maximum seepage rate in the drainage tunnel at an elevation of 840 m from 8.53 L/s before treatment to 5.88 L/s after, indicating a decrease in seepage. In October 2005, Exploratory Tunnel

No. 2, located at an elevation of 850 m beneath the right abutment (discovered to be void during curtain reinforcement grouting), was sealed and backfilled with underwater non-dispersible fine aggregate concrete.

Between the third periodic inspection of dam safety in 2012 and the fourth periodic inspection in 2019, the maximum seepage rate in the drainage tunnel remained at 4.77 L/s, with clear water seepage. It was believed that the likelihood of seepage along the remote end of major fault zones within the ridged mountain range was high, but it did not pose an immediate threat to the safety of the abutment.

According to the Annual Detailed Inspection Reports on Dam Safety from 2020 to 2023, the maximum seepage around the right bank was recorded as 3.93 L/s, 3.93 L/s, 4.16 L/s, and 4.59 L/s, respectively. The process line of measured values is shown in Fig. 1. The maximum seepage flow rate around the dam showed minimal variation over the years. The significant seepage in the drainage tunnel on the right bank is attributed to three main factors: the geological conditions of the abutment, with fault fracture zones and steeply dipping joints facilitating seepage; the grouting design, as vertical hole grouting employed on the right bank platform curtain offered limited effectiveness against steeply dipping faults and fractures; and potential issues with construction quality, resulting in defects in the anti-seepage curtain. Consequently, the significant water seepage in the drainage tunnel at an elevation of 840 m on the right bank downstream of the dam constitutes a potential risk source.

Currently, the drainage tunnel at 840 m elevation on the right bank downstream of the dam experiences significant water seepage. Given that the seepage is clear and the volume remains stable, the water is likely infiltrating through the distal end of a major fault zone along the right bank, posing no immediate threat to the stability of the dam abutment. However, under extreme conditions such as strong earthquakes, the impervious curtain may be compromised, leading to the formation of a continuous seepage channel around the dam. This could result in a further increase in seepage volume, potentially affecting the stability of the dam abutment in severe cases. In such a scenario, the severity level of the consequences is classified as ‘significant.’

Fig. 1
Leakage of the drainage tunnel

(2) *Time-Dependent Deformation of Dam Section 10 Towards the Right Bank (RS2)*

During the third periodic inspection of dam safety in 2012, it was observed that Dam Section 10 on the right bank exhibited significant time-dependent deformation towards the right bank, with a displacement of 5.1mm recorded between 2008 and 2012.

The fourth periodic inspection of dam safety in 2019 revealed that the tangential time-dependent displacement at the right abutment persisted. Between 2013 and 2019, the tangential horizontal displacement at the right bank abutment ranged from -12.39mm to 0.02mm, with a maximum annual variation of 6.41 mm. Although the displacement tended to converge after 2015, it had not yet fully stabilized, accumulating to approximately 8mm of time-dependent displacement by 2019.

Reviewing the monitoring data from measurement points, from 2020 to February 2024, the tangential deformation of the right abutment pointed toward the riverbed, as shown in Fig. 2. This was analyzed to be a result of the manual calculation formula being defined with an opposite sign convention compared to the actual direction. However, from the variation pattern, it is evident that the tangential displacement measurements at the right bank abutment have stabilized and converged in recent years, without showing any notable trend changes.

Regarding the cause of the historical time-dependent displacement at the right abutment, based on the data from two boreholes revealed during the initial dam safety inspection in 2000, the rock mass joints and fractures at the right abutment exhibited good connectivity, which could have contributed to the continuous increase in tangential time-dependent displacement before 2019. As the reservoir dam operated, the rock joints and fractures gradually closed due to contact and compression, leading to the convergence of abutment deformation.

Given the historical occurrence of time-dependent displacement at the right abutment, despite the recent stabilization of observational data, there remains a risk of recurrence during future operations. Therefore, the time-dependent deformation of Section 10 towards the right bank constitutes a potential risk source.

Since 2020, no significant trend in tangential displacement has been observed at the right bank abutment. However, if the time-dependent displacement towards the right bank continues to increase during future operations, it may compromise the stability of the right bank abutment. In this case, the severity level of the consequences is also classified as ‘significant.’

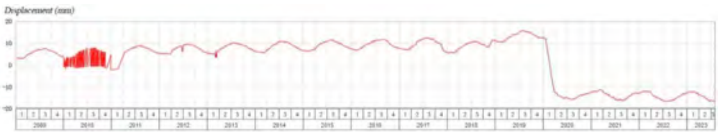

Fig. 2
Time-dependent deformation of Section 10

3.2.2. *Water release and energy dissipation structures (WRED)*

(1) Scour Pit at the Plunge Pool of the Spillway Trajectory Energy Dissipator (RS3)

According to the periodic dam safety inspection reports, the central spillway of the dam has historically caused scouring to the apron during flood discharges. Between 2001 and 2005, the scouring of the apron's baseplate, particularly at the plunge pool area, deepened progressively after each flood season. Since 2006, annual post-flood measurements of the scour pit downstream of the dam have revealed a maximum depth of 2.5 m, approximately 50 m from the dam site. To prevent further enlargement of the scour pit, a concrete tetrahedron with a side length of 1.2 m was used for backfilling the pit in 2010. During the fourth periodic inspection of dam safety in 2019, no structural defects such as cracks or abrasions were found in the spillway holes of the dam body. The downstream protection works on both banks operated normally, and the maximum depth of the scour pit at the downstream energy dissipation apron remained at 2.5 m, approximately 50 m from the dam toe, shown in Fig. 3.

In recent years, the water inflow in the Kashgar River basin has been relatively stable, with no major floods occurring. Additionally, due to the regulation and storage functions of the upstream Jilintai Level I Reservoir and Wenquan Reservoir, the inflow into the specific reservoir primarily originates from the outflow of the upstream Wenquan Reservoir. According to the Annual Detailed Inspection Report, the maximum inflow rates from 2020 to 2023 were 225.5 m^3/s, 298.5 m^3/s, 218.5 m^3/s, and 250.9 m^3/s, respectively, with return periods less than once every five years. The flood discharge structures have yet to be tested by major floods, and the spillway holes of the arch dam are primarily used for regulating the reservoir water level, with limited actual flood discharge events. It is analyzed that the project employs a trajectory energy dissipation method and has only been tested by floods with a return period of once every five years. In the event of major floods, the depth and extent of the scour pit downstream of the dam may further increase. Therefore, the scour pit at the plunge pool of the spillway trajectory energy dissipator constitutes a potential risk source.

The project employs a ski-jump energy dissipation method, which has only been tested under floods with a recurrence interval of less than five years. Currently, no deepening of the scour holes in the energy dissipation apron of the spillway has been observed, and the downstream protection works on both banks are functioning normally. During major flood discharge, the depth and extent of the scour holes behind the dam may increase further, potentially leading to the collapse of the protection works on both banks. In this scenario, the severity level of the consequences is classified as 'moderate.'

Fig. 3
Scour pit at the downstream

(2) *Cavitation Erosion Damage to the Service Gate Slot of the Dam Spillway Holes (RS4)*

According to the initial periodic dam safety inspection report in 2001, severe water leakage was observed in the middle outlet gate, prompting the urgent need for maintenance and repair. In 2003, the guide side rails and baseplate of spillway hole Gate No. 2 were addressed, significantly reducing the amount of water leakage through the gate.

In this risk assessment analysis, the service gates of the spillway holes are flat gates responsible for flood discharge tasks of the hydropower station, with requirements for partial opening operations. During frequent gate operations, the abrupt change in flow boundary conditions leads to cavitation erosion prone to occur near the gate slot due to the flow characteristics. During the initial stages of operation, pitted surfaces, frost-thaw damage, and cavitation erosion were observed on the downstream sidewall base adjacent to the service gate slot. In 2003, repairs were carried out, effectively mitigating the water leakage from the gate. Presently, localized cavitation erosion is present near the gate slot, and its extent is anticipated to expand over extended periods of operation. Consequently, cavitation erosion damage to the service gate slot of the dam spillway holes constitutes a potential risk source.

The working gates in the spillway are of the flat gate type, characterized by abrupt changes in the gate slot boundaries, which are prone to cavitating flow. Localized cavitation erosion occurs near the gate slots, and prolonged operation may lead to the expansion of defects, damaging the gate slot structure and affecting the normal opening and closing of the gates. In the event of this scenario, the severity level of the consequences is classified as ‘major.’

(3) *Erosion Defects in the Desilting Tunnel (RS5)*

Since its commissioning, the desilting tunnel has experienced multiple instances of erosion damage to its baseplate. In 2004, the tunnel underwent reconstruction with reinforcement of the baseplate. However, in 2005, inspections revealed renewed erosion and damage in the newly treated areas. Consequently, repairs were carried out in October of the same year to address the damaged sections of the baseplate. The reservoir was drained for inspection in 2006, revealing no abnormalities, yet subsequent inspections in 2008, 2010, and 2011 identified severe damage to the baseplate once again. In 2012, the wear-resistant layer of the baseplate within the first 50 m of the tunnel’s inlet section was repaired using steel fiber-reinforced concrete, while the layer from 50 m to 150 m was restored with silica fume concrete. The desilting tunnel remained inactive in 2013 and 2014, but since 2015, it has been utilized annually for desilting purposes to prevent sedimentation and consolidation upstream. During the fourth periodic inspection of dam safety in 2019, abrasion and exposed aggregate were still observed on the concrete baseplate of the desilting tunnel. Additionally, due to geological conditions, leakage was present in the tunnel body from 0+030 m to 0+105 m of the inlet section, though it did not compromise structural safety. In 2021, repairs were conducted to address the concrete defects in the baseplate of the desilting tunnel. To mitigate hydraulic scouring, concrete was backfilled at the right-angle plunge section behind the original desilting gate, connecting the upstream and downstream baseplates with a curved profile, effectively reducing the impact of sediment-laden flows on the baseplate. Post-flood inspections in 2021 indicated no significant scour pits compared to pre-repair conditions.

Upon analysis, the desilting tunnel was converted from a diversion tunnel, resulting in a suboptimal inlet section shape, turbulent flow patterns, and suboptimal operating conditions, which have contributed to repeated erosion damage to the baseplate. Although repairs have been made, with increasing operational time or during high-flow desilting operations, erosion defects in the baseplate of the desilting tunnel may recur and progress.

Therefore, erosion defects in the desilting tunnel constitute a potential risk source

The sand flushing tunnel was converted from a diversion tunnel, with a suboptimal inlet section shape resulting in turbulent flow patterns and suboptimal operating conditions. This has led to multiple instances of erosion damage to the tunnel floor. Although repairs have been made, further erosion defects in the tunnel floor may develop with increased operating time or during high-flow sand flushing operations. Structural damage to the sand-flushing tunnel could hinder its normal use, preventing sand flushing and reservoir drainage. In this case, the severity level of the consequences is classified as ‘significant.’

3.2.3. *Gates and Hoists (GH)*

Based on the field inspection findings and historical dam safety inspections conducted at a hydropower plant, the following potential risk sources related to gates and hoists have been identified:

(1) *Water Surge at the Top of the Service Gate for Dam Spillway Holes (RS6)*

According to the initial periodic inspection report on dam safety in 2001, during the initial operational phase, the flat service gate for the middle spillway hole experienced water surging directly onto the 852.43 m operating platform when the gate was lifted 15 cm to 20 cm above the lintel due to its low position. During winter, the operating platform was covered with ice, causing vibrations in the gate at openings ranging from 1.7 m to 2.0 m.

After modifying and raising the lintel, the water spraying issue was largely resolved, and gate vibrations ceased. However, due to the asynchrony between the two cylinders of the hoist, the top water stop rubber was frequently torn during frequent gate operations, resulting in water flipping during flood discharge. In 2000, technical modifications were made to the hoist, effectively addressing the asynchrony issue. Nevertheless, after raising the lintel, the gap between the new lintel and the top water stop was too small, and the clearance between it and the gate was not accurately adjusted.

This risk assessment analysis concludes that the service gate for dam spillway holes is responsible for regulating the reservoir water level through dynamic water opening and closing operations, including partial openings. After multiple operations, the top water seal is prone to tearing and damage due to friction forces, leading to recurrent water surging. Therefore, the water surge at the top of the service gate for dam spillway holes constitutes a potential risk source.

The clearance between the lintel and the top water seal is too small, causing the top water seal to be susceptible to tearing and damage due to friction during repeated gate operations. Water inrush through the top water seal can lead to gate vibrations and water seal freezing, potentially damaging the gate structure and hoist, and affecting the normal operation of the gate. Under these circumstances, the severity level of the consequences is classified as ‘moderate.’

(2) *Non-compaction of Second-Stage Concrete for the Support Base of Oil Cylinders in the Service Gate for Dam Spillway Holes (RS7)*

The service gate for dam spillway holes is operated by a hydraulic hoist, with the hydraulic oil cylinders supported at the top of the orifice openings on both ends of the gate slot. Upon on-site inspection, it was discovered that the support base for the oil cylinders had not been filled with second-stage concrete, as shown in Fig. 4. Instead, the support forces were borne solely by the anchor bolts and steel structure, which were not jointly stressed with the second-stage concrete. As a result, the absence of second-stage concrete in the support base for the oil cylinders of the service gate for dam spillway holes poses a potential risk source.

The foundation of the oil cylinder support does not have a secondary concrete filling, and the anchor bolts and I-beams are not integrated with the secondary concrete to share the load. Long-term operation may cause loosening and instability of the oil cylinder support base, leading to structural damage to the gate and affecting its normal operation. If this occurs, the severity level of the consequences is classified as ‘significant.’

Fig. 4
Support base for the oil cylinders

3.2.4. *Reservoir Bank and Slope Stability (RBSS)*

Based on the field inspection findings and historical dam safety inspections conducted at a hydropower plant, the following potential risk sources related to the reservoir bank and slope stability have been identified:

(1) *SL1 Landslide Mass (RS8)*

The SL1 landslide mass is located approximately 150 m above the normal water level of the reservoir. The average width of the landslide is approximately 100 m, with a downslope length of approximately 230 m. The landslide primarily comprises quaternary eolian and residual loess, with a thickness ranging from 3 m to 15 m, averaging approximately 10 m, and a total volume of approximately 23×10^4 m^3. The picture is shown in Fig. 5.

In 2005, tension cracks were observed at the trailing edge of the landslide. By March 2006, the sliding surface at the trailing edge had continued to descend by 0.5 m to 1.2 m, with cracks extending approximately 206 m in length. Subsequently, measures were taken to backfill the cracks and implement anti-seepage treatments. According to the fourth dam safety inspection report in 2019, a continuous ‘armchair-shaped’ boundary has formed at the trailing edge of the landslide, demarcated by L1. Within the landslide mass, 4 to 5 secondary cracks with widths ranging from 0.05 m to 0.1 m and lengths varying from 5 m to 20 m have been identified. The landslide mass primarily consists of blocky rubble and loess-like soil, exhibiting distinct settling and creeping characteristics in the middle and upper sections, with sporadic collapse signs observed on the steep front slope. Crack monitoring records from 2013 to 2019 indicate an annual deformation rate of approximately 10 mm to 13 mm, suggesting that the landslide is still in a state of slow movement. In 2022, a crack measuring 4 m in length, 1 m in width, and 0.3 m in depth at the lower part of the landslide was compacted.

During the field inspection, no significant signs of crack development were observed in the landslide mass. However, under conditions of heavy rainfall or strong earthquakes, there is a potential for localized instability. Therefore, the SL1 landslide mass is identified as a potential risk source.

The SL1 landslide mass is relatively small in volume, loosely structured, and riddled with cracks, making a catastrophic, single-event slide unlikely. Its deformation is closely related to atmospheric precipitation, with the potential for localized instability during heavy rainfall. However, once initiated, pore water pressures within the cracks dissipate rapidly, reducing the sliding velocity and causing the slide mass to disintegrate further, leading to reservoir sedimentation. This has minimal impact on hydraulic structures and reservoir operations. In the event of this scenario, the severity level of the consequences is classified as ‘minor.’

Fig. 5
SL1 Landslide

(2) *Rockfall Hazard on the Slope of the Power Intake Inlet (RS9)*

The slope of the power intake inlet and the sediment flushing tunnel entrance features a mountain gradient ranging from 30 to 40 degrees, comprising andesite and tuffaceous sandy gravel rock.

Upon field inspection, small-scale weathered and unloaded loose rock blocks were observed at the top of the slope of the power intake inlet, exhibiting frequent occurrences of collapse and rock shedding, as shown in Fig. 6. Although the slope remains stable under natural conditions, the potential for large-scale rockfalls arises under scenarios such as heavy rainfall, strong earthquakes, or animal activity. These factors can destabilize the slope, leading to the release of larger rock fragments. Consequently, rockfall from the slope of the power intake inlet is identified as a potential risk source.

The top of the power intake slope hosts small-scale weathered and loosely packed rock blocks. Under conditions of heavy rainfall, strong earthquakes, or animal activity, these blocks may detach, leading to large-scale rockfalls that could jeopardize the safety of personnel and structures below. The severity level of consequences in such a scenario is classified as ‘moderate.’

Fig. 6
Slope of the Power Intake Inlet

3.2.5. *Reservoir Bank and Slope Stability (RBSS)*

Based on the field inspection findings and historical dam safety inspections conducted at a hydropower plant, the following potential risk sources related to reservoir operation and management have been identified:

(1) *Inadequate Reservoir Dispatching Regulations (RS10)*

During this risk assessment, it was noted that according to the 'Preliminary Design of the Yili Hydropower Station on the Kashi River in Xinjiang' report, the reservoir dispatching of a particular power station encompasses various aspects such as power generation, flood control, sediment flushing, irrigation, and ice prevention. However, the 'Reservoir Dispatching Regulations' issued by the hydropower plant in 2022 contain simplified content regarding irrigation and ice prevention, and lack provisions for sediment flushing. The compilation of these regulations did not adhere to the 'Guidelines for the Compilation of Operation and Dispatching Regulations for Hydropower Projects'. In cases of extreme adverse weather conditions in the reservoir basin, improper ice prevention dispatching may occur. Consequently, inadequate reservoir dispatching regulations constitute a potential risk source.

In cases of extremely cold weather, improper ice control operations may result in ice jams blocking downstream channels, causing ice floods that may overflow the dam. The severity level of consequences in this situation is deemed ‘moderate.’

(2) *Inaccurate Hydrological Measurement and Forecasting (RS11)*

The design flood for a particular reservoir is based on the regulated flood outflow from an upstream reservoir after flood routing calculations. This power station does not have a dedicated hydrological measurement and forecasting system, and during the main flood season, hydrological information is primarily obtained from the Jilintai Level I Hydropower Station built in 2004, and the Wenquan Hydropower Station built in 2010.

Although the incoming water volume in the Kashi River basin has remained relatively stable over the past five years without major floods, the Wenquan Hydropower Station has only weekly regulation capabilities and is located relatively close to the power station, with a flood propagation time of approximately 40 minutes. The flood measurement and forecasting for the reservoir rely on the outflow from the Jilintai Level I Hydropower Station combined with the runoff generated in the intervening area. Due to the absence of a dedicated hydrological measurement and forecasting system at the power station, any delays in maintenance and calibration of hydrological equipment such as water level gauges and rain gauges in the Jilintai Level I to the power station section or the Jilintai Level I to Wenquan section could lead to significant errors in flood measurement and forecasting. Therefore, inaccurate hydrological measurement and forecasting represent a potential risk source.

Failure to promptly maintain and calibrate hydrological equipment such as water level gauges and rain gauges in the Jilintai I - Certain Section or Jilintai I - Wenquan Section may lead to misreported water level and rainfall data. Significant errors in flood forecasting can underestimate predicted water levels during major floods or high water stages, potentially delaying response times and allowing reservoir levels to rise rapidly. The severity level of consequences under these circumstances is assessed as ‘moderate.’

(3) *Non-Standard Flood Warning Procedures (RS12)*

Furthermore, there are instances of non-standard flood warning procedures at the hydropower plant. The distance from the dam to the dewatered river section leading to the powerhouse is approximately 1.2 km. Currently, during flood discharge, only an alarm is sounded on the dam crest, without the installation of a flood warning broadcast system in the downstream river section or the specification of a warning period. Consequently, non-standard flood warning procedures constitute a potential risk source.

The river section between the dam and the powerhouse, approximately 1.2 km long, lacks a dedicated flood warning broadcast system downstream. Currently, flood warnings are only sounded on the dam crest, without specifying a warning period. During flood release periods, villagers in the affected river segment may not evacuate in time, posing a risk of fatalities. The severity level of consequences in this scenario is rated as ‘moderate.’

(4) *Reservoir Sedimentation (RS13)*

The total storage capacity of a certain reservoir is 17.5×10^6 m^3, with a dead storage of 1,280 m^3 and a regulated storage capacity of 470 m^3. In 2005, the measured total storage capacity was $9.6\times10^6 m^3$, with a regulated storage capacity of 4.137×10^6 m^3, indicating a loss of 45.1% in total storage capacity and 12% in regulated storage capacity. The central part of the reservoir experiences significant sedimentation, with the sedimentation level reaching 862.7 m. Following the impoundment of the upstream Jilintai Level I Hydropower Station and Wenquan Hydropower Station in 2004 and 2010, respectively, the sedimentation in this reservoir has generally stabilized.

A re-measurement of the reservoir capacity in 2011 revealed a total storage capacity of 9.94×10^6 m^3 and a regulated storage capacity of 4.48×10^6 m^3, translating into a loss of 43.2% in total storage capacity and 5% in regulated storage capacity. Compared to the 2005 measurements, there were no significant changes, suggesting a roughly balanced condition between scouring and sedimentation in the reservoir.

During the reservoir emptying inspection in 2019, the sedimentation level at the dam toe was found to be 830 m. The inlet bottom elevations of the three flood discharge holes at Dam Sections 4 to 6 were 835.50 m and 839.50 m, respectively, while the bottom elevation of the sediment flushing tunnel was 827.00 m. The sedimentation in the reservoir has already reached the inlet bottom elevation of the sediment flushing tunnel and is approaching that of the flood discharge holes. Should sedimentation, landslides, debris flows, or other similar events occur in the reservoir area, they could potentially cause blockage at the inlet of the sediment flushing tunnel. Therefore, sedimentation at the inlet of the sediment flushing tunnel is identified as a potential risk source.

The 2019 reservoir draining inspection revealed that the reservoir had already silted up to the elevation of the sand-flushing tunnel inlet. Further sedimentation could block the tunnel inlet, impairing its sand-flushing and reservoir-draining capabilities. The severity level of consequences in this case is classified as ‘moderate.’

3.2.6. *Natural Disasters (ND)*

The primary natural disaster risks associated with a given engineering project encompass meteorological hazards, floods, and earthquakes. Upon analysis and identification, the following potential risk sources have been pinpointed:

(1) *Beyond-standard Floods and Upstream Cascade Dam Failure Floods (RS14)*

The initial design criteria for the dam flood at a hydropower station stipulated a 100-year return period with an added safety margin (corresponding flow rate of 1310 m^3/s) for design and a 500-year return period with an added safety margin (corresponding flow rate of 1580 m^3/s) for checking. In 2000, during the first periodic safety inspection, the revised 100-year and 1000-year flood flow rates were calculated as 1204 m^3/s and 1548 m^3/s, respectively, both slightly lower than the original design values. In 2012, during the third periodic safety inspection, considering the completion of upstream Jilintai Level I and Wenquan hydropower stations, the flood flow rates were reassessed, resulting in natural design flood levels of 1226 m^3/s for the 100-year event and 1559 m^3/s for the 1000-year event at the dam site. After considering upstream reservoir regulation, the inflow flood flow rates for the 100-year and 1000-year events were reduced to 1153 m^3/s and 1419 m^3/s, respectively, with the design flood for the dam site adopting the outflow from the Wenquan hydropower station.

In 2016, a flood close to the 100-year recurrence interval occurred in the basin, yet after joint regulation by the upstream Jilintai Level I and Wenquan reservoirs, the inflow to the target reservoir was merely 533 m^3/s, indicating a recurrence interval of less than 5 years. According to the Annual Detailed Inspection Reports, the maximum inflow rates for 2020 to 2023 were 225.5 m^3/s, 298.5 m^3/s, 218.5 m^3/s, and 250.9 m^3/s, all with recurrence intervals less than 5 years. In recent years, the water inflow to the Kashgar River basin has remained relatively stable, with no major floods recorded.

The hydropower station is equipped with a concrete double-curvature arch dam featuring three spillway outlets, each with a dimension of 5.0m$\times$5.5m. At the normal water level of 865 m, the total spillway discharge capacity of these three outlets is 1580 m^3/s, sufficient to meet the flood discharge requirements.

However, since the upstream Wenquan hydropower station (with a total storage capacity of 207×10^6 m^3 and located approximately 7.8 km upstream, covering an area of 52 km^2) possesses only weekly regulation capability, in the event of beyond-standard floods or dam failures at the upstream Jilintai Level I and Wenquan hydropower stations, a series of structural safety issues could arise. Consequently, beyond-standard floods and upstream cascade dam failure floods constitute a potential risk source.

Beyond-standard floods or dam failures of upstream Jilintai I or Wenquan hydropower stations would raise the reservoir water level above the check flood level, posing significant threats to the water-retaining structures due to extreme hydraulic pressures. The immense force of the floodwaters could damage structural integrity, causing cracks, seepage, or even collapse. Floating debris and sediment could also erode the structures. If the flood discharge exceeds the capacity of the outlet structures, gates and spillways may be overloaded, resulting in overtopping, dam failure, and catastrophic consequences. The severity level of consequences in this event is categorized as ‘extremely severe.’

(2) *Locally Severe Rainstorms in the Project Area (RS15)*

The project area, situated at the northern foot of the Middle Tianshan Mountains and far from the ocean, experiences a temperate continental climate. Due to the westward-opening terrain of the Ili River Valley, which facilitates the influx of warm and moist Atlantic air currents, the region is known as the ‘Jiangnan Beyond the Great Wall’ and the ‘Wet Island of Central Asia,’ being the most humid area in Xinjiang.

According to Ili Meteorological Station data, the multi-year average temperature in the Ili area is 8.4°C, with the highest recorded temperature being 37.9°C and the lowest being -40.4°C. The multi-year average precipitation is 257.2 mm, while the multi-year average precipitation recorded by a hydrological station in the vicinity is 347.8 mm. The highest annual rainfall measured at the dam site was 418 mm (in 2016), and the highest daily rainfall was 79 mm (on June 26, 2015). Locally severe rainstorms in the project area pose a risk of equipment failure and geological disasters. Therefore, locally severe rainstorms in the project area are identified as a potential risk source.

Localized severe rainstorms in the hydro project area could damage dam equipment, reduce the reliability of power supplies, and trigger secondary small-scale geological disasters that could disrupt transportation and impede emergency response. The severity level of consequences in this scenario is rated as ‘moderate.’

(3) *Extreme Low-Temperature and Severe Cold Weather (RS16)*

According to the Second Regular Inspection Report on Dam Safety in 2006, frost-thaw damage was observed on the upstream face of the dam within the water level fluctuation zone. Notably, severe frost-thaw deterioration was identified on the upstream side of the bulkhead gate chamber section on the right flank of the dam, as well as the vortex-proof beams of the three flood discharge outlets. The frost-thaw damage at the vortex-proof beams had been addressed in 2002, achieving satisfactory results without further deterioration. Subsequently, the frost-thaw damage on the upstream face of the bulkhead gate chamber section was repaired using 903 polymer cement mortar from 2006 to 2007. During the Third Regular Inspection of Dam Safety in 2012, partial erosion was still detected in the bulkhead gate chamber area, which was then re-treated with high-grade mortar for surface protection in 2014, resulting in effective remediation. The Fourth Inspection Report on Dam Safety in 2019 indicated that during colder years, the maximum ice thickness in front of the dam reached approximately 0.4m, tapering to 0.1m towards the center of the reservoir.

In the event of extreme low-temperature and severe cold weather, the water surface in front of the dam freezes, rendering the previously frost-thaw-damaged areas on the upstream face of the dam vulnerable to recurrent frost-thaw damage. Additionally, even areas without prior frost-thaw damage may experience new frost-thaw deterioration under historically low temperatures. Consequently, extreme low temperatures and severe cold weather constitute a potential risk source.

During extremely cold weather, ice formation on the upstream face of the dam, particularly in areas with a history of freeze-thaw damage, could weaken the structure further. Even undamaged areas may experience new freeze-thaw cycles at historically low temperatures. Extensive freeze-thaw damage could compromise the structural integrity and seepage control of the dam, affecting the safety of gate slots and normal gate operation. The severity level of consequences in this case is deemed ‘significant.’

(4) *Beyond-Standard Earthquake (RS17)*

During the initial design phase, the Xinjiang Earthquake Administration concluded that the probability of an earthquake exceeding magnitude VII within the next century in the dam site area was low, but the possibility of a magnitude VII earthquake existed. Furthermore, the basic seismic intensity influenced by peripheral earthquakes on the reservoir and dam area was less than magnitude VII, thus setting the basic seismic intensity for the dam site at magnitude VII.

Following the ‘Seismic Ground Motion Parameters Zonation Map of China’ the basic peak ground acceleration in the dam site area is 0.20 g, corresponding to an upgraded basic seismic intensity of VIII. The Fourth

Regular Inspection and Seismic Reassessment Analysis of Dam Safety in 2019 found that when the basic peak ground acceleration increased from 0.15 g to 0.20 g, the maximum tensile stress on the downstream face of the arch crown beam base reached 1.87 MPa. However, this localized exceeding of tensile stress did not significantly impact the overall safety of the dam.

Nonetheless, in the case of an earthquake exceeding magnitude VIII, the dam may encounter issues such as abutment instability, excessive tensile stress leading to cracking in the dam body, and malfunctioning of gates. Therefore, a beyond-standard earthquake represents another potential risk source.

Earthquakes exceeding Magnitude VIII on the Richter scale could impair the dam's shoulder stability, exceed tensile stress limits, and prevent proper gate operation. Structural damage to the dam body could lead to dam failure. The collapse of flood discharge structures and the inability to open gates would hinder flood discharge, leading to dam overtopping and failure. Secondary small-scale geological disasters could damage power supply equipment, disrupt transportation, and hinder flood discharge and emergency response efforts. The severity level of consequences in these extreme circumstances is classified as 'extremely severe'.

To assess the likelihood of various risks associated with the operation of a hydroelectric dam, a panel of experienced experts from diverse fields, including hydraulics, hydrology, geology, metallurgical engineering, and operational management, was convened. This comprehensive expertise ensures a thorough evaluation of all potential risks [8]. To achieve a scientific, objective, and comprehensive outcome, a blinded scoring system was employed, wherein each expert individually rated the identified potential risk sources according to the evaluation criteria outlined in Table 1, about the probability of risk occurrence. The final scores indicate that there are three risk sources categorized as 'extremely low' probability, seven as 'low' probability, and seven as 'medium' probability. Notably, no risk sources were deemed to have a 'high' or 'extremely high' probability of occurrence.

One risk source was identified with a severity level of 'minor'; eight risk sources were categorized as 'general' severity; five risk sources fell into the 'major' severity level; one risk source was rated as 'significant' severity; and two risk sources were deemed as 'extremely significant' severity. Ultimately, the risk classification for each risk source was determined and is presented in Table 3. The risk matrix method was employed to identify, analyze, and evaluate 17 operational safety risk sources categorized into six major groups for a certain reservoir. Among them, there were no risk sources classified as Level I or Level II; 13 risk sources were identified as Level III, accounting for approximately 76%; and 4 risk sources were classified as Level IV, comprising roughly 24% of the total.

Table 3
List of risks

Number	Project	risk sources	Likelihood	Risk Consequences and Severity	Classification
1	WRS	RS1	Low	Major	III
2	WRS	RS2	Very Low	Major	IV
3	WRED	RS3	Medium	General	III
4	WRED	RS4	Low	Significant	III
5	WRED	RS5	Medium	Major	III
6	GH	RS6	Medium	General	III
7	GH	RS7	Low	Major	III
8	RBSS	RS8	Low	Minor	IV
9	RBSS	RS9	Medium	General	III
10	ROM	RS10	Low	General	IV
11	ROM	RS11	Medium	General	III
12	ROM	RS12	Medium	General	III
13	ROM	RS13	Medium	General	III
14	ND	RS14	Very Low	Extremely Significant	III
15	ND	RS15	Low	General	IV
16	ND	RS16	Low	Major	III
17	ND	RS17	Very Low	Extremely Significant	III

3.3. Risk response measures

After risk identification, analysis, and evaluation, further research into risk response is necessary. Following the principles of feasibility, applicability, effectiveness, as well as proactivity, timeliness, and full-process coverage, operable and easily implementable risk management and control measures are formulated. For risks of different levels, risk management and control measures are primarily developed from four aspects: routine management and control, prediction and early warning, risk reduction, and emergency response [9,10].

(1) Routine management and control measures primarily involve strengthening routine inspections and monitoring of dam cracks, dam foundation seepage, water release structures, reservoir bank slopes, gate metal structures, hoists, etc., as well as routine rainfall and water level forecasting, and flood prevention measures for water release.

(2) Prediction and early warning measures focus on monitoring and early warning of landslides near and far from the dam bank, enhancing hydrological forecasting to address issues such as inadequate water release and untimely flood notification, and strengthening communication with local governments and cascade hydropower stations to obtain real-time rainfall, water level, and engineering condition information to prepare for localized heavy rainfalls and exceedance floods.

(3) Risk reduction measures primarily involve adopting engineering measures to mitigate the impact of further dam cracks, dam foundation seepage, and concrete damage to water release structures. If further abnormal deformation or sliding is observed in near and far dam bank slopes, dam abutment slopes, or downstream bank slopes, measures should be taken to reduce risks. For metal structure components, maintenance and repairs should be conducted if further damage occurs. When anticipating the arrival of dam failure or landslide dam breach floods, measures should be taken to release water and prepare the reservoir for flood storage.

(4) Emergency response measures primarily involve formulating or activating corresponding emergency plans based on investigation results or under relevant circumstances to address risks such as damage to flood discharge and sediment flushing facilities, impact on outlet gate working gates, debris boom rupture, and overtopping, dam breach floods, earthquakes, heavy rainfalls, and exceedance floods. If large-scale instability occurs near or far from the dam bank, potentially causing reservoir water to overtop the dam and cause rapid river water level rises, the government should be notified to organize the evacuation of downstream residents.

High-risk sources of dam operational safety should be prioritized in response. On the one hand, real-time and comprehensive monitoring and control of the dam's operational status should be conducted through technical means to ensure timely early warning and handling of abnormal situations, especially for risks with high consequences but low probabilities that may lead to complacency among managers. On the other hand, the intensity and frequency of routine audits and inspections should be strengthened, with regular and detailed inspections of all critical dam components. Upon discovering abnormalities, corresponding risk reduction or emergency response measures should be promptly proposed to ensure the safe and stable operation of the dam.

4. CONCLUSIONS

(1) Based on the collection of various data, including operation records, management systems, inspection reports, and emergency response plans of a

hydropower station project, an industry expert team was organized to conduct a systematic and structured risk source identification process through the integration of historical evidence and the application of brainstorming methods. This process resulted in a comprehensive risk source list comprising 17 items categorized into six major areas: water-retaining structures, water release and energy dissipation structures, gates and hoists, reservoir banks and slopes, reservoir operation management, and natural disasters. Using the risk matrix analysis framework, the risk levels of each source were determined based on their likelihood of occurrence and severity of consequences. No risks were classified as Level I or II; 13 were categorized as Level III, accounting for approximately 76%; and 4 were identified as Level IV, accounting for approximately 24%.

(2) Guided by the principles of feasibility, applicability, effectiveness, as well as proactivity, timeliness, and full-process coverage, operable and readily implementable risk management and control measures were formulated based on the in-depth identification, comprehensive analysis, and objective evaluation of risk sources. Tailored to risks of different levels, specific risk response strategies were proposed encompassing routine management and control, prediction and early warning, risk reduction, and emergency response.

(3) It is recommended that future issues identified through regular dam safety inspections, daily safety patrols, and special inspections be promptly addressed in a closed-loop manner to mitigate safety risks. The risk response and improvement measures proposed in this risk assessment should be integrated into daily management practices, with dynamic adjustments made to these measures to reduce dam safety risks and enhance the service life of the hydropower station. Additionally, training programs should be strengthened for daily management personnel in risk awareness, assessment, and control.

(4) The matrix risk analysis method employed in this study is primarily suitable for evaluating individual risks, with the probability of risk occurrence primarily based on qualitative analysis. To enhance the comprehensiveness of risk assessment, future work could explore the adoption of multi-risk coupling analysis methods, considering the chain effects of various risks and accurately calculating risk probabilities.

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INTRODUCTION TO THE WORLD'S FIRST 100-METER-DEEP FLOATING PHOTOVOLTAIC PROJECT IN SOUTHEAST ASIA (*)

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SUMMARY

Located in a hydropower reservoir, Cirata 145MW project was the largest floating photovoltaic project in Southeast Asia, with a water depth of 100 meters. The geotechnical condition was complex with bottom slopes larger than 20 degrees. A new type of gravity anchors with shear-keys was used to address the high-slope problem. More than 2000 anchors were installed during construction period. The "Ultra Short Baseline" system was adopted to ensure the accuracy of anchor installation. A multi-mode fusion system combined with the Operation and

**Présentation du premier projet photovoltaïque flottant ancré à 100 mètres de profondeur en Asue du Sud-Est*

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Maintenance system was used to monitor both array displacement and mooring line tension. The "Full life cycle" and "integrated" safety design concepts were adopted, to meet the requirements of dam safety. This successful project showcases the use of innovative technologies and serves as an example for similar FPV projects.

RÉSUMÉ

Le projet Cirata de 145MW est le plus grand projet photovoltaïque flottant d'Asie du Sud-Est. La profondeur de l'eau est de 100 mètres. Les conditions géotechniques sont complexes avec des pentes de fond supérieures à 20 degrés. Un nouveau type d'ancrages gravitaires avec des clés de cisaillement a été utilisé pour résoudre le problème de ces pentes élevées. Plus de 2000 ancrages ont été installés. Le système "Ultra Short Baseline" a été adopté pour assurer la précision de l'installation des ancrages. La centrale flottante est située dans un réservoir de barrage hydroélectrique. Un système de fusion multi-mode combiné avec le système d'exploitation et de maintenance a été utilisé pour surveiller à la fois le déplacement et la tension des lignes d'amarrage. Les concepts de conception de sécurité "cycle de vie complet" et "intégrée" ont été adoptés pour répondre aux exigences de sécurité du barrage. Ce projet a été très réussi avec l'utilisation de toutes les nouvelles technologies et peut servir d'exemple pour des projets d'ingénierie similaires.

1. INTRODUCTION

The Cirata project is located in the reservoir area of a hydro-power station, with the water depth of 100 meters and a water level variation of 20 meters. The geotechnical conditions at the bottom of the water were complex, with steep slopes. Due to the lack of reservoir clearing work during development period, there were submerged obstacles such as tree debris and abandoned structures. After 30 years of operation, sedimentation resulted in thick layers of sludge on the reservoir bed, with the thickest areas exceeding 5 meters in depth and some areas having slopes of over 20 degrees. Ordinary concrete anchor blocks would not meet the project's requirements, necessitating the design of new anchor block products. Due to the large installed capacity of the project and the extensive area of the floating array, a sufficient number of anchor blocks were required to ensure the mooring and positioning of the floating array. The total number of anchor blocks used in the project exceeded 2000 pieces, with narrow spacing between them, making anchor rope interference a significant challenge during installation.

The total capacity was 192 MW on the DC side, and 145 MW on the AC side. The FPV area included totally 13 floating arrays. Each floating array has a DC side capacity of approximately 15.7 MW. On the AC side, one 6.874 MVA container-type transformer and two 3437 kVA centralized inverters were utilized to convert the DC electricity generated by the photovoltaic panels into AC and boost it to 22 kV for transmission to the booster station. The project involves extremely long lengths of AC and DC cables with numerous intermediate joints, posing significant challenges in cable laying to ensure zero fault rates, which is crucial for construction.

In addition, the project faces significant challenges in assembling floating components due to the large variation in water levels. During high water level periods, the water level rises and the shoreline advances, potentially submerging assembly platforms. During low water periods, the water level recedes and completed floating components may run aground, severely affecting assembly efficiency. Addressing the design and construction challenges of large water depth and significant water level fluctuations, innovative solutions were implemented in the project.

2. “FULL LIFE CYCLE” AND “INTEGRATED” SAFETY DESIGN CONCEPTS

Due to the project’s location in the reservoir area of a hydroelectric power station, the floating photovoltaic power station is situated near facilities such as the dam intake and spillways. In the event of an accident at the photovoltaic power station, there is a potential risk to the safety of the dam. Given Indonesia’s geographical characteristics, where various water bodies are interconnected, this project’s water area is upstream from the capital Jakarta. Therefore, the local dam safety committee places a high emphasis on the project’s safety and maintains stringent control over all risks involved.

The “full life cycle” safety design concept ensures that safety considerations are integrated into every phase of the project, from planning and construction to operation and decommissioning. This approach aims to mitigate risks effectively and ensure the long-term safety and sustainability of the project.

In the Cirata project, GPS positioning technology is used to provide real-time monitoring of the position and status of floating pontoons. This technology is a global first and has been developed entirely independently by our institute. Multiple-mode fusion positioning devices are installed on the floating systems to receive satellite positioning signals and determine their locations. The signals are transmitted to the data center via wireless networks. The data center processes and analyzes the data to determine real-time positions, drift speeds, and other relevant parameters of the floating systems.

Emphasizing integration with dam safety throughout the project lifecycle, from planning and development to design, construction, and operations management, involves close collaboration with the local dam safety committee. During the planning and development stage, there was extensive sharing of photovoltaic plant area and hydroelectric station design data. The project design team collaborated with the dam committee to conduct multiple rounds of risk assessments aimed at minimizing the impact of the photovoltaic power station on dam safety. Throughout the design and construction phases, the dam safety committee supervised the design documents and construction acceptance materials. All design drawings, calculations, and completion inspection reports underwent review by the dam safety committee. These innovative design approaches not only ensured the reliability and efficiency of the project but also enhanced its environmental compatibility and performance under challenging environmental conditions.

The project is located in the reservoir area of a hydroelectric power station, where some water bodies serve both aquaculture and drinking water purposes, necessitating stringent environmental requirements. All materials and equipment used in the project adhere strictly to international standards and undergo testing by internationally renowned third-party inspection agencies to ensure environmental friendliness. The project adopts a green and environmentally-friendly design concept. To ensure that the materials used for the floating bodies do not contaminate the reservoir, all raw materials and samples were sent to the internationally renowned testing organization TUV (TÜV Rheinland) for testing. These tests simulated conditions such as high temperature and UV exposure that occur at the project site. The testing confirmed that the materials possess adequate properties such as aging resistance and fire resistance. Importantly, the materials are non-toxic and do not produce toxic substances when burned or melted in fire accidents. This comprehensive testing ensures that the materials used in the project meet stringent environmental standards and pose minimal risk to the ecosystem of the reservoir.

3. DESIGN AND CONSTRUCTION CHANLLENGES

3.1. Anchor block product design

A novel product design was adopted using metal shear keys and rapid assembly concrete anchor blocks. To validate the reliability and safety of this design, a two-month continuous pull-out test was conducted prior to installation, generating substantial experimental data for validation.

Fig. 1
Concrete anchors vs shear key anchors

Shear key anchors were shown in Fig. 1 (a). This product design effectively reduces anchor block slippage, ensures precise installation, and accommodates underwater slopes of up to 24 degrees.

Due to the large water depth and close spacing between anchor blocks, measures were taken to prevent entanglement of anchor ropes underwater. Symmetrical anchoring of adjacent photovoltaic arrays was implemented to enhance coordination between two installation platforms and minimize mutual interference. Following these improvements, the installation speed of anchor blocks increased significantly from single digits per day to 30-40 blocks per day, peaking at 43 blocks per day. Over 2000 anchor blocks were installed in just three months, significantly reducing the installation period.

3.2. Electrical design

To achieve a zero-fault rate for cable joints, extensive optimization was carried out. The design team collaborated closely with cable manufacturers to determine optimal positions for intermediate joints and select the most suitable cable reel lengths. This meticulous planning ensured the safe and reliable laying of medium-voltage cables, meeting the scheduled deployment targets.

Considering the project's location on the reservoir surface, where it is exposed to high humidity and corrosive conditions year-round, the selection of electrical equipment was optimized accordingly. The project opted for N-type monocrystalline double-sided dual-glass modules. These modules offer superior temperature performance with low annual degradation rates, making them suitable for long-term operation on water surfaces. Additionally, to mitigate temperature rise in combiner boxes exposed to prolonged sunlight radiation compared to land-based photovoltaics, sunshades were installed to reduce equipment temperature, ensuring stable long-term operation. This choice not only enhanced electricity generation efficiency but also reduced carbon emissions per unit energy produced, thereby enhancing environmental sustainability throughout the project's lifecycle.

Addressing shading issues caused by surrounding terrain, numerical simulations were conducted using PVSYST software in compliance with IEC standards. Three-dimensional modeling of the surrounding terrain was performed to optimize layout arrangements, minimizing the impact of mountain shading and effectively increasing electricity generation efficiency.

3.3. Innovative floating assembly platforms

The project has designed a high water level floating assembly platform, establishing an effective and comprehensive assembly plan for floaters/components, significantly enhancing the efficiency of assembling floating photovoltaic systems. In response to identifying 9 critical factors, the QC team developed a root cause identification plan. They assessed the impact of each factor to determine if it was a primary issue: (1) Insufficient cleanliness of work surfaces; (2) Shortage of electrical and other resources at work sites; (3) Low utilization rate of floating component assembly platforms; (4) Low utilization rate of floating component assembly platforms; (5) Delayed supply of cables and auxiliary materials; (6) Delayed supply of floats/components and unreasonable site utilization; (7) Shortage of unloading and transportation vehicles; (8) Inadequate deployment of construction tools; (9) Inexperienced workers.

The team conducted a detailed analysis and confirmed three root causes: delayed supply of floats/components and unreasonable site utilization, low utilization rate of floating component assembly platforms, and low utilization rate of floating component assembly platforms. Based on these three main factors, they improved the design of the floating component assembly platform, focusing on accommodating the impact of high water levels to meet operational requirements effectively.

Additionally, they optimized the assembly process to minimize waiting and idle time, thereby enhancing operational efficiency. After optimization, the workflow was streamlined, workers' skills and experience levels were significantly improved, and the assembly platform remained robust and reliable despite fluctuations in water levels. As a result, the efficiency of floating component assembly increased by 30%.

3.4. Digital construction method using the "Ultra-Short Baseline" system

Throughout the design and construction phases, the dam safety committee supervised the design documents and construction acceptance materials. All design drawings, calculations, and completion inspection reports underwent review by the dam safety committee.The project employs concrete gravity-based anchor foundations with numerous anchor blocks, each requiring precise installation coordinates and angles. During anchor installation, the depth of water is significant, compounded by complex underwater conditions, making precise positioning of the anchor blocks challenging. The introduction of "Ultra-Short Baseline" (USBL) equipment has effectively facilitated digital construction methods in this regard.

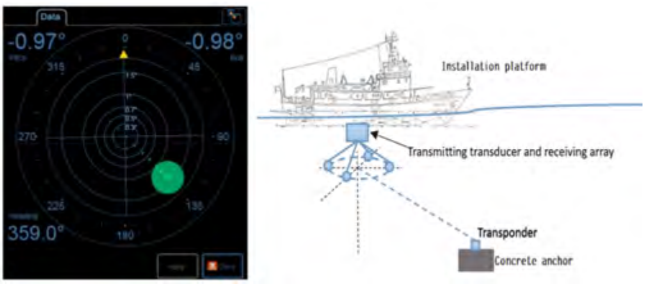

Fig. 2
The "Ultra-Short Baseline" system

During the project construction process, there were challenges with a large number of anchor blocks and the difficulty of anchor installation. To ensure that each anchor block meets the requirements for installation coordinates and angles, a "Real-Time Kinematic (RTK)" equipment was introduced. This equipment utilizes underwater ultrasonic positioning technology to measure the installation position and angle of anchor blocks in real time, enabling digital construction implementation.

3.5. Substations

The volume of backfill soil poses significant construction challenges. Indonesia experiences an extended rainy season with abundant rainfall and frequent heavy downpours, leading to potential soil landslides. This presents a considerable challenge for slope stabilization measures. To address the challenges posed by steep slopes and high precipitation in the booster station area, a hybrid approach for soil backfill slope protection has been proposed. Four different methods of slope support are employed: gabion retaining walls, soil nail walls, reinforced earth retaining walls, and counterfort retaining walls. These methods are chosen flexibly based on the characteristics of different slope areas to optimize cost-effectiveness and enhance construction efficiency. The booster station is located on an existing steep slope adjacent to the reservoir, necessitating a design that combines earthwork with high slope protection to maintain road gradients below 10%. Given Indonesia's high rainfall, the design addresses the significant challenge of reduced shear strength in saturated soil. The site employs four types of slope protection: gabion retaining walls, soil nail walls, reinforced earth walls, and counterfort retaining walls.

(1) Entrance Road and Internal Roads on the West Side (Height $<$ 8 meters): Gabion retaining walls are used to support slopes, aiming to reduce costs and enhance efficiency. (2) North Side High Slope (Height 20 meters) and West Side Entrance Road Slope (Height 12 meters): Soil nail walls are employed due to the presence of original soil in these areas, allowing for minimal soil disturbance, effective drainage on slopes, and faster construction. (3) Southwest and Southeast Fill Slopes (Maximum Height 28 meters): Counterfort retaining walls (up to 11 meters high) combined with reinforced earth walls (17 meters high) are used. These choices are optimal for high fill slopes where conventional gravity walls are impractical. The design includes pile foundations for the counterfort walls and one-way geogrid layers every meter vertically to stabilize the slopes effectively.

This comprehensive approach ensures stability while meeting stringent land use regulations, reflecting a cost-effective solution tailored to the challenging terrain and climatic conditions of the project site.

4. OPERATION AND MAINTENANCE

In the operations and management phase, recommendations from the dam safety committee were implemented. This included the introduction of a GPS detection system into the operational framework to establish a real-time alert mechanism based on monitoring data. This system was complemented with risk management and response measures, ensuring dual security safeguards for both the photovoltaic plant area and the hydroelectric dam. By integrating the expertise and oversight of the local dam safety committee throughout the project lifecycle, comprehensive measures were taken to enhance safety and minimize risks associated with the operation of the photovoltaic power station near the hydroelectric dam.

Due to the significant fluctuation in water levels at the project site, the photovoltaic arrays and floating inverter platforms may drift during low water levels, making real-time monitoring of these floating facilities crucial. This project utilizes advanced GPS positioning technology to ensure the safe and efficient operation of the floating photovoltaic system, promptly identifying and addressing potential issues and risks. Multi-mode fusion positioning devices are installed on various components of the photovoltaic arrays and floating inverter platforms. These devices accurately receive satellite signals from the GPS system to determine the precise location of the floating photovoltaic system. Each photovoltaic array is equipped with 2 dual-mode fusion positioning terminals, placed in between two longitudinal corridors. Each floating inverter platform is also equipped with 1 dual-mode fusion positioning terminal.

The dual-mode fusion positioning terminals transmit collected location data to the data center using multiple wireless communication technologies (including RDSS communication, 4G communication modules, and LoRa communication modules), ensuring stable and real-time data transmission. At the data center, received location data is immediately processed and analyzed to accurately determine the real-time position, drift speed, and other relevant parameters of the floating photovoltaic system. The monitoring system continuously monitors the position status of the floating photovoltaic system. If the system's position exceeds predetermined limits or exhibits abnormal behavior, the monitoring system triggers immediate alarms. Detailed reports are generated to provide specific location information and descriptions of abnormal conditions to operators, enabling them to take prompt corrective actions.

This monitoring solution is widely applicable not only to floating photovoltaic systems but also to environments such as marine and inland river vessels. Through real-time monitoring and management, the system effectively addresses issues related to anchor rope slack and drift caused by water level fluctuations, thereby mitigating potential risks and preventing damage or efficiency loss. It also provides scientific and timely decision-making support to operators, significantly reducing operational maintenance costs. The implementation of this monitoring and management system enhances the safety, reliability, and operational efficiency of the floating photovoltaic system, providing robust technical support and assurance for long-term project operation and maintenance.

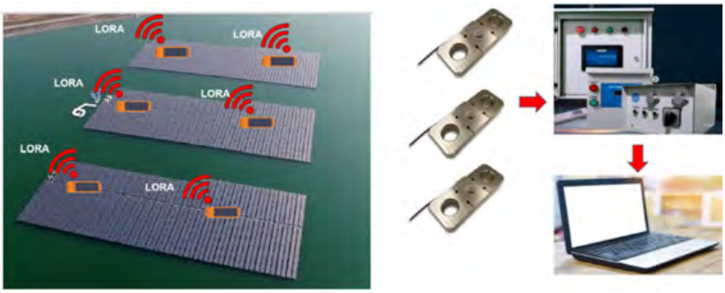

Fig. 3
Monitoring system for array displacement and mooring line tension

5. CONCLUSIONS

From the results of this study, it can be concluded that a floating photovoltaic energy farm will be applicable in a hydropower station reservoir with a large water level variation. On one hand, the design of the floating photovoltaic arrays plays a role in the dam safety, and on the other hand, the operation of the hydropower station has a big influence on the design and construction of the floating photovoltaic farm. The successful Indonesia 192 MW project provided a good design method for similar joint projects of solar energy and hydropower.

To ensure the safety of the hydroelectric project, it is important to facilitate the sharing of relevant data, such as hydrological data, environmental impact assessments, and safety regulations, among all stakeholders. Additionally, conducting comprehensive pre-construction geological surveys can provide valuable information on the site's geological conditions, which can help identify potential risks and hazards. By involving contractors in the early stages of the project, they can provide their expertise and insights on construction techniques, feasibility, and safety, which can help ensure the project's success and safety.

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DAMS FOR ENERGY TRANSITION AND NEED FOR PUMPED STORAGE AND HYDROELECTRIC PROJECTS IN INDIA (*)

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INDIA

SUMMARY

From fewer than 300 large dams in India at the time of independence in 1947, today the number has risen to more than 6200. Hydroelectric generation in India has traversed a long journey from the time of independence with only 508 MW of installed capacity to 52,004 MW including small hydro ending September 2024 and unit size of 22 MW at that time, now going up to 250 MW. Globally, unit sizes have gone upto 800 to 1000 MW.

For achieving net zero emission target by 2070, renewable energies have to power growth of India. As per Paris Agreement, 2015 the goal is to limit the temperature rise to within 1.5°C of pre-industrial level by the end of the century. It requires complete transformation for production and consumption of energy. Almost 100% of electricity generation by 2050 has to come from non-fossil fuel sources.

India's commitment for energy at COP26 held at Glasgow in 2021 was for creation of 500 GW non-fossil power generating capacity, to meet 50% of its energy requirements from renewable energy by 2030 and to achieve net-zero emission by 2070. These targets to clean energy transition are very much feasible though challenging. To achieve these targets, it is important to ensure grid stability, security

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**Les barrages pour la transition énergétique et la nécessité de projets de pompage-turbinage et d'hydroélectricité en Inde*

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and to provide peak power as well as ancillary services. These targets require complete transformation of energy production and consumption.

As on 30th September, 2024, India's total electricity installed capacity is 452.69 GW, out of which non-fossil fuel capacity is 209.65 GW, which is 46% of the total capacity which comprises 201.47 GW of renewable (solar, wind and bio-mass) and 8.18 GW of nuclear power. Fossil fuel installed capacity is 243.06 GW which is 54 % of the total capacity. The target of having 40% of non-fossil fuel power capacity by 2030 committed during Paris Agreement has been achieved much in advance in 2019, about 11 years before 2030.

Dams for producing hydropower through over the year/seasonal water storage, diurnal pondage/storage to cater to the peak requirements and for pumped storage plants, will need to step in to take over the role of 'guardians of the electricity grid' for energy transition.

Pace of progress of addition of hydroelectric power in the country has been slow and significant acceleration is required to meet the future challenges. Momentum of marathon to develop sustainable hydropower has to be triple in comparison to the existing pace.

India needs to add around 5,000 MW of hydropower per year in coming years till 2030 and till 2047 on an average around 2100 MW each year for ensuring energy transition. It is achievable, as India has already added this capacity in a year in the past. There remains a vast amount of economically viable potential across the country, which is sufficient to achieve the essential role of hydropower in the energy transition. India has planned to have around 19 GW of pumped storage plants by 2030. To achieve this target, off the river pumped storage plants can be widely developed on fast track basis. However, with the present set of rules and regulation it may be difficult to achieve the target of addition of new pumped storage plants.

This paper deals in detail with the role of dams and pumped storage plants for energy transition and the policy interventions required in order to achieve the net zero emission target commitments made during different Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC).

RÉSUMÉ

De moins de 300 grands barrages en Inde au moment de l'indépendance en 1947, leur nombre est aujourd'hui passé à plus de 6200. La production hydroélectrique en Inde a parcouru un long chemin depuis l'indépendance, avec seulement 508 MW de capacité installée, jusqu'à 52 004 MW, y compris les petites centrales hydroélectriques en septembre 2024 et la taille des unités de 22 MW à

l'époque, passant maintenant à 250 MW. À l'échelle mondiale, la taille des unités est passée de 800 à 1000 MW.

Pour atteindre l'objectif de zéro émission nette d'ici 2070, les énergies renouvelables doivent alimenter la croissance de l'Inde. Conformément à l'Accord de Paris de 2015, l'objectif est de limiter l'augmentation de la température à 1,5°C par rapport au niveau préindustriel d'ici la fin du siècle. Elle nécessite une transformation complète pour la production et la consommation d'énergie. D'ici 2050, près de 100 % de la production d'électricité devra provenir de sources non fossiles.

L'engagement de l'Inde en matière d'énergie lors de la COP26 était de créer une capacité de production d'énergie non fossile de 500 GW, de répondre à 50 % de ses besoins énergétiques à partir d'énergies renouvelables d'ici 2030 et d'atteindre des émissions nettes nulles d'ici 2070. Pour atteindre ces objectifs, il est important d'assurer la stabilité et la sécurité du réseau et de fournir une puissance de pointe ainsi que des services auxiliaires. Ces objectifs nécessitent une transformation complète de la production et de la consommation d'énergie.

Au 30 septembre 2024, la capacité installée totale d'électricité de l'Inde est de 452,69 GW, dont 209,65 GW de combustibles non fossiles, soit 46 % de la capacité totale qui comprend 201,47 GW d'énergie renouvelable (solaire, éolienne et biomasse) et 8,18 GW d'énergie nucléaire. La capacité installée de combustibles fossiles est de 243,06 GW, soit 54 % de la capacité totale. L'objectif de 40 % de capacité d'énergie non fossile d'ici 2030 engagé lors de l'Accord de Paris a été atteint bien en avance en 2019, soit environ 11 ans avant 2030.

Les barrages pour la production d'hydroélectricité grâce au stockage d'eau sur l'année/saisonnier, les bassins/stockages diurnes pour répondre aux besoins de pointe et pour les centrales de pompage-charge, devront intervenir pour assumer le rôle de « gardiens du réseau électrique » pour la transition énergétique.

Le rythme des progrès de l'ajout de l'énergie hydroélectrique dans le pays a été lent et une accélération significative est nécessaire pour relever les défis futurs. Le rythme de développement d'une hydroélectricité durable doit être trois fois plus élevé que le rythme actuel.

L'Inde doit ajouter environ 5 000 MW d'hydroélectricité par an dans les années à venir soit une moyenne d'environ 2100 MW par an pour assurer la transition énergétique. C'est réalisable, car l'Inde a déjà ajouté cette capacité au cours de l'année écoulée. Il reste encore un grand potentiel économiquement viable à travers le pays, ce qui est suffisant pour atteindre le rôle essentiel de l'hydroélectricité dans la transition énergétique. L'Inde prévoit d'avoir environ 19 GW de centrales de pompage-turbinage d'ici 2030. Pour atteindre cet objectif, les centrales de pompage-turbinage hors de la rivière peuvent être largement développées sur une base accélérée. Cependant, avec l'ensemble actuel de règles et de réglementations, il peut être difficile d'atteindre l'objectif d'ajouter de nouvelles centrales de pompage-turbinage.

Ce document traite en détail du rôle des barrages et des centrales de pompage-turbinage dans la transition énergétique et des interventions politiques nécessaires pour atteindre les engagements pris lors de la Conférence des Parties (COP) à la Convention-cadre des Nations Unies sur les changements climatiques (CCNUCC).

1. INTRODUCTION

Human activities, principally through emissions of Green House Gases (GHG), have caused global warming, with global surface temperature increase reaching 1.1^{0}C. The range of future temperature increase is large and depends on our actions to reduce GHG emissions. Human influence has increased the frequency and intensity of extreme events, heatwaves, droughts and floods.

For achieving net zero emission target by 2070, renewable energies have to power growth of India. As per Paris Agreement, 2015 the goal is to limit the temperature rise to within 1.5^{0}C of pre-industrial level by the end of the century. It requires complete transformation for production and consumption of energy. Almost 100% of electricity generation by 2050 has to come from non-fossil fuel sources. As per International Energy Analysis (IEA) to reach net zero emissions by 2050, annual clean energy investment worldwide will need to more than triple by 2030 to around $4 trillion.

At COP26 in Glasgow, India announced the following 'Panchamrit' (five principles) targets to be achieved by 2030.

i) India will reach its non-fossil energy capacity to 500 GW by 2030.
ii) India will meet 50% of its energy requirements from renewable energy by 2030.
iii) India will reduce the total projected carbon emissions by one billion tonnes from now onwards till 2030.
iv) By 2030, India will reduce the carbon intensity of its economy by less than 45%.
v) The fifth target announced at COP26 is India's commitment to net-zero emission by 2070.

India's commitment at COP26 held at Glasgow in 2021 was for creation of 500 GW non-fossil power generating capacity by 2030. This target to clean energy transition is very much feasible though challenging. However, to achieve this target of addition of 500 GW of non-fossil fuel, we simultaneously need to ensure grid resilience and security as well.

2. EXISTING ENERGY GENERATION SCENARIO

As on 30th September, 2024, India's total electricity installed capacity is 452.69 GW, out of which fossil fuel capacity is 243.06 GW, which is 54 % of the total capacity. Non-fossil fuel installed capacity is 209. 65 (46%) which comprises 154.53 GW (34%) of renewable (small hydro, wind, bio-mass, waste to energy and solar), 46.93 GW (10%) of large hydro and 8.18 GW (2%) of generation from nuclear power. Thus, the target of having 40% of non-fossil fuel power capacity by 2030 has been achieved much in advance in 2019 about 11 years before 2030. Distribution of installed capacity through different modes of generation as on 30.09.2024 is given below in Fig. 1.

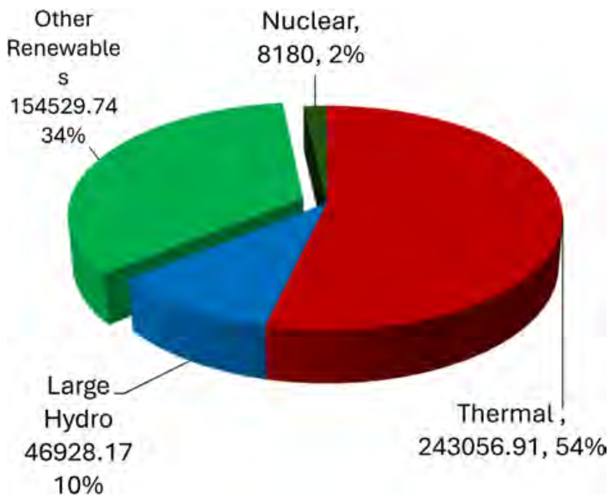

Fig. 1
Total Electricity Installed Capacity as on 39.09.2024* (Total 452.69 GW)
*Figures given in pie-chart are in MW

Though, non-fossil fuel installed capacity is 46% of the total capacity, yet the energy generation from non-fossil fuel during the year 2023-24 is 24% of the total. 76% of the total energy generation has been from thermal power (fossil fuel). Sector wise break up is given in Fig. 2 below.

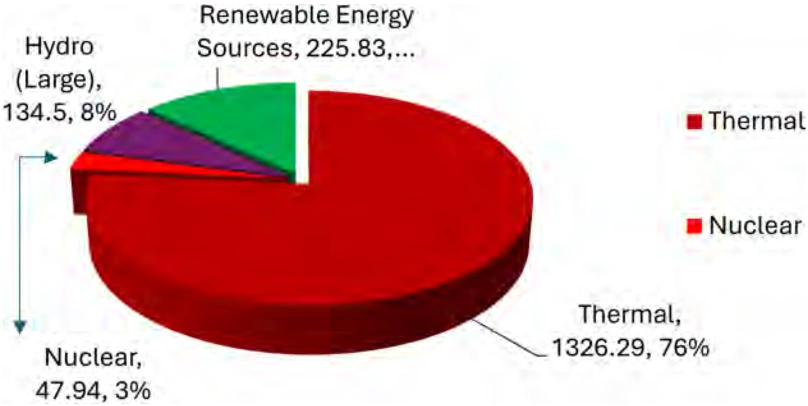

Fig. 2
Sector-wise energy generation during the Year 2023-24* (Total 1649.9 BU)
*Figures written in pie-chart are in BU.

Pace of progress of addition of hydro in the country has been slow and significant acceleration is required. During the last nine years from 2015-16 to 2022-24, only 5593 MW hydropower capacity has been added against target power generation of 11799 MW. Thus, achievement of capacity addition of hydropower has been 47.4% of the target.

3. ENERGY GENERATION SCENARIO BY 2030

It is well known that renewable energy in form of solar and wind is site specific and intermittent in nature. In order to cater to balancing solar and wind energy, storage in form of water (in reservoirs) or battery, is essential for grid stability and security.

India's peak power demand is surging up gradually from 221.684 GW during March, 2024, it has gone to 260 GW during day time and 240 GW during evening so far during the year 2024-25. Energy deficit at present (September, 2024) is 0.3% and peak power deficit is 1.4%.

As per 'Report on Optimal Generation Mix 2030 Ver 2.0' by Central Electricity Authority, Ministry of Power, GoI, installed capacity by the end of 2029-30 is projected to increase to 777.14 GW comprising of hydro 53.9 GW (excluding hydro imports 5856 MW), Pumped Storage Projects 19 GW, small hydro 5.35 GW, Coal 251.7 GW, Gas 24.8 GW, Nuclear 15.5 GW, Solar 292.57 GW, wind 99.9 GW and Biomass 14.5 GW along with a battery storage of 41.7 GW (208.25 GWh). This shows that thermal power addition from now till 2030 will be around 33.45 GW. Pumped storage capacity addition will be about 14.3 GW. By 2032, total pumped storage capacity is likely to grow to 27 GW. By 2030, 500 GW of generation capacity will be from non-fossil fuel sources.

Considering life of equipment in thermal power plant as 25 years, new thermal power plants being added now, on completion of their initial life span of 25 years, need to be phased out completely before 2070. Most of the countries in the world as well as in South Asia have planned that 100% of electricity generation by 2050 has to come from non-fossil fuel sources.

3.1. Pumped storage plants

Pumped storage plants by pumping water from lower to an upper reservoir, allow displacement of energy from off-peak to peak hours. Off-river, pumped storage plants do not depend on hydrology of the site and are versatile in terms of their location. These plants are becoming more and more popular in India. In certain cases, existing reservoirs and transmission infrastructure are being used in reversible pumped storage plants, to minimize environmental impact. Such reversible pumped storage plants using existing infrastructure, being non-consumptive in nature, synergize well with other consumptive uses such as irrigation, industrial and domestic water supply, recreational uses etc. thereby minimizing generation as well as operation and maintenance (O&M) costs of these pumped storage plants.

India at present has installed capacity of 4.1 GW pumped storage power plants. Total identified pumped storage capacity in the country is 181 GW. Another 4.1 GW is under construction. Around 66 GW of pumped storage capacity is under survey and investigation and detailed project report preparation.

To meet commitments made during United Nations Climate Change Conference, also known as the Conference of the Parties (COP), clean energy transition is the top priority, since energy is the main source of carbon emissions. India has planned to add about 23 GW of pumped storage plants by 2032. Total pumped storage capacity by 2047 is likely to increase to 116 GW. Fig. 3 shows the projected planned growth of pumped storage plants in the country.

Other renewables i.e. solar and wind are projected to be 1200 GW and 436 GW respectively by 2047. Similarly, battery energy storage system (BESS) is projected to be 47 GW and 364 GW by the year 2030 and 2047 respectively.

Capacity of large hydroelectric projects excluding pumped storage is planned to be 55 GW by 2030 and 87 GW in 2047. Bundling of hydropower having storage and pumped storage with renewable energy is also being carried out in many certain cases.

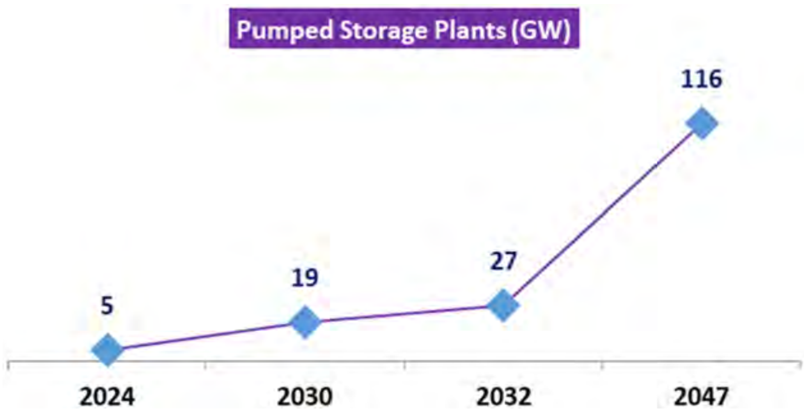

Fig. 3
Future projections of pumped storage systems in India

4. GRID SUPPORT BENEFITS OF HYDROELECTRIC PROJECTS

Broad breakup of total tariff structure of hydropower projects comprises basic tariff of (45%), social infrastructure cost (11%), taxes (general sales tax, GST) (10%), catchment area treatment plant and local area development funds (3%), free energy to be given to the state/province where the project is located (11%), payment security mechanism (5%) and interest risk rate (5%). Thus, out of total tariff, basic tariff cost component is only 45% and other costs mentioned above get added by about 55%. This makes tariff of hydropower during the initial years much higher, till repayment of loan is over.

For accelerating development of hydropower projects, Government of India provides subsidy for infrastructure cost at the rate of Indian Rupees (INR) 20 million per MW for projects upto 100 MW and INR 15 million per MW for projects beyond 100 MW capacity. Even this incentive, so far, has not helped to fast track construction of hydroelectric projects.

Pumped storage and hydroelectric projects are reliable, versatile and scalable resources for planning of the grid. These projects are backbone of the grid stability and security. They provide back up and spinning reserves; flexibility services for peak, diurnal and seasonal variations; part-load operations and fast ramping up and down to meet system imbalances; storage solutions for energy arbitrage, peak shaving and firming up renewable energy capacity, primary frequency response support, reactive power support, ramping up and down, black start support, help in avoiding curtailment of wind and solar renewables, and emission reduction. Pumped storage absorbs excess renewable energy (RE) during periods of low demand and release energy during the peak and lean periods of RE generation. These projects provide long duration energy storage from hours to days to weeks thus helping in smoothening load curves in anticipated and unanticipated solutions.

By monetising, all these benefits amount to INR 2.9 per Kwh (3.5 cents per Kwh), thereby aggregating to almost 53% of the total cost of generation of hydro-electric energy. Thus, effective tariff of hydroelectric projects gets reduced and remains only 47% of the total generation cost. In addition, by quantifying the positive environmental impacts of dam and reservoir projects contributing to water needs, energy transition and adaptation to climate change total per Kwh tariff from hydro-electric projects will be much less. Thus, the positive impacts of dams for water storage in hydroelectric and pumped storage projects for grid stability would out-weigh other negative impacts.

5. NET ZERO EMISSION TARGETS BY 2070 IN INDIA

In order to meet India’s global commitment to become net zero by the year 2070, it is important to have a clear sector wise way forward to achieve this target of 2070 rather than pursuing target till 2047. Detailed studies considering energy mix in generation upto 2070 are yet to be conducted. Preliminary studies carried out by USAID, SAREP shows that by 2070 size of Indian power sector will be around 7500 GW. Projections carried out in this study are shown below in Figure 4.

From Figure 4, it is clear that reliance has to be placed on no fossil fuel energy generation. In order to reach net zero emissions targets, renewable energy will have to power the growth of India.

India need to provide thrust to construct sustainable hydroelectric projects (including pumped storage) for absorbing intermittent power from solar and wind for grid stability and security and also nuclear power stations for providing base load in order to power sustainable growth. We have to shift away from coal to the immense untapped hydropower potential that exists in India.

There will not be any energy transition without action. More action is required to deliver affordable energy access, clean air and high-quality jobs. Financial resources have to be re-directed to renewable hydropower including pumped storage projects. Country needs to focus on volume and urgency for hydropower including pumped storage and nuclear power for providing the base load rather than adding dirty thermal power.

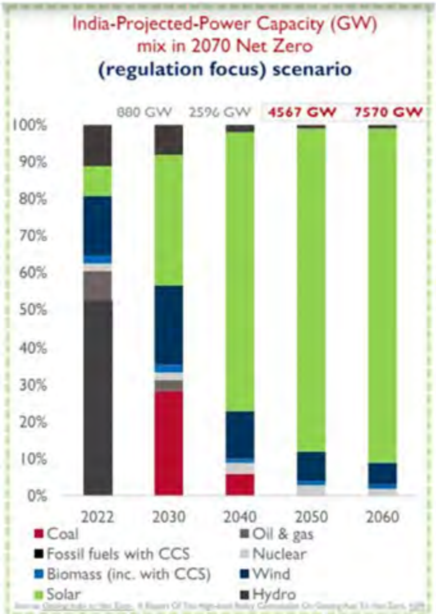

Fig. 4
Decade wise Broad Projections of India Power Sector
(Source: USAID, SAREP)

Momentum of marathon to develop sustainable hydropower has to be triple in comparison to the existing pace. International Energy Agency (IEA) and International Renewable Energy Agency have estimated that the most cost effective, achievable global net zero energy system will require around twice as much hydropower by 2050 as it is today, that is between 2,500 GW and 3,000 GW including pumped storage.

Looking at the Global hydropower scenario as shown in Fig. 5, total installed capacity globally during 2023 was 1416 GW. Out of this, six countries, viz, China (421 GW), Brazil (110 GW), United States (102 GW), Russia (56 GW), India (52 GW) and Japan (50 GW) constitute more than 50% of the global installed capacity. This is worry some, as most of other countries need to accelerate development/ construction of their hydroelectric resources and pumped storage plants in order to achieve global net zero carbon emission targets.

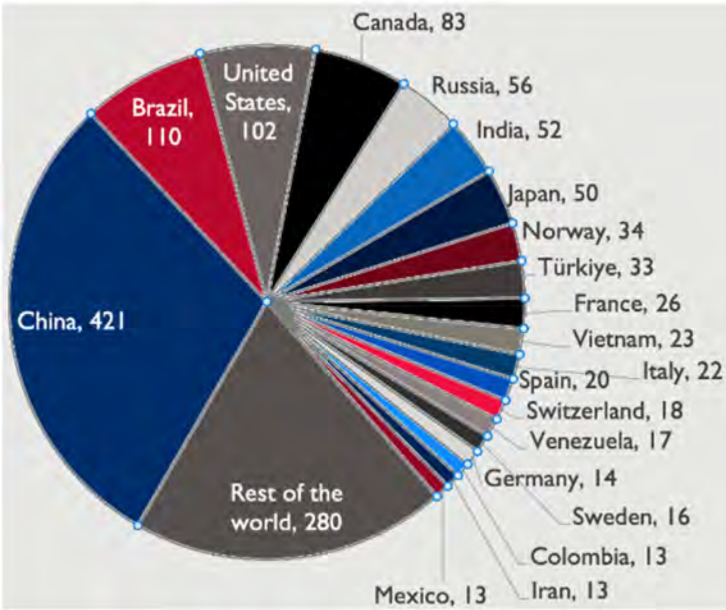

Fig. 5
Global Hydropower Scenario in GW (Source: World Hydropower Outlook by IHA)

6. DAMS FOR PUMPED STORAGE PLANTS AND TO COMBAT EXTREME EVENTS

The Climate change study in India depicts a warmer temperature by 1.5° to 3°C in near future by the year 2060 and 2.5° to 4°C rise in far future by 2100 [11]. Based on the analysis of climate change studies, there is a high chance of occurrence of concurrent and repeated climate hazards over many States of India which exacerbate the water security problem as well as lead to risks to health, ecosystems, infrastructure, livelihoods and food. The results from this study highlights that the water security of India needs to be evaluated under changing climate so that proper adaptation and mitigation of the vulnerabilities of water resources in India arising out of weather extremes can be addressed. To provide water and food security, water storage is required at the State /Provincial, District and village level. This will need construction of large number of dams throughout the country.

Adapting to the changing climate inherently depends on the degree of vulnerability of the ecosystem and humans towards the changes. Thus, the long and short term adaptation measures/interventions against flood hazards, heat waves, reduced agricultural yield, optimum water use etc., are required to be taken to ensure the National Water Security under the changing climate scenarios.

Similarly, for addition of pumped storage projects and almost doubling total installed capacity of large hydroelectric projects number of dams required to be constructed are going to be very large, in order to meet challenge of water storage as well as that of energy transition.

In order to add 22 GW of pumped storage capacity by the year 2032 and 111 GW by 2047 and addition of 35 GW of hydroelectric power projects by 2047, India needs to construct around 1000 dams. Apart from meeting requirement of energy transition, these high dams with water storage will provide resilience and address environment vulnerability against droughts, mitigate the risk of flooding and reduce the frequency and extent of inundations and development of artificial wetlands. These dams will also help to adapt to climate-resilient water supply for irrigation and food security, safe drinking water, energy generation, flood regulation, droughts mitigation, and other uses. Increased Dams with reservoir storage capacity will help to tackle hydrologic variability and heightened risk and uncertainty due to climate change.

7. MEASURES TAKEN TO FAST TRACT HYDROELECTRIC INCLUDING PUMPED STORAGE PROJECTS

i) Expediting Grant of Concession: In order to provide thrust to development of hydropower, Central Electricity Authority (CEA) has reduced timeline for survey and investigations of hydroelectric projects from 900 days to 690 days and for concurrence of detailed project reports from 150 days to 50 days. There is need to further reduce the timeline for concurrence of such PSPs from 50 days to less than a month. Though CEA has expedited the process by granting clearances on fast tract basis, however, in certain cases inspite of reduced timelines, in practice it is taking long time. Time period of preparation of Detailed Project Report and obtaining other statutory clearances of the projects from Centre and State Governments authorities which at present takes somewhere 3 to 5 years need to be reduced to around one and a half year in order to meet our energy transition targets.

ii) On line submission of Detailed Project Report (DPR): Detailed project reports are being submitted online with completion of first 12 basic design chapters. Some of the chapters in DPR have been dispensed with without compromising the dam safety aspects. In addition, PSPs have been exempted from examination of cost estimation.

iii) Undertaking from Developer of PSPs: Developers of PSPs are made to give an undertaking that the Detailed Project Report has been prepared in line with pre-DPR clearances required by the appraising authorities. This obviates requirement for re-examination of DPR and saves time in concurrence process.

iv) Waiver of charges for Inter-State Transmission System (ISTS) and other transmission charges has been provided in order to encourage IPPs to install PSPs.

v) Simplified environmental clearance procedure: Ministry of Environment, Forest and Climate Change (MoEFCC) has simplified Terms of reference for pumped storage projects though much more is required to be done on this account.

8. CONCLUSION AND POLICY INTERVENTION

From the above background, it is clear that there is no energy transition without sustainable hydropower and construction of dams for water storage. For energy transition immediate action is required to accelerate development of hydropower and pumped storage projects with designated timelines. Pace of development of hydropower in India and in most of the developing countries has to be at least three times more than the existing rate of addition of projects. The following policy interventions are required to be carried out immediately. It is pertinent to mention that most of these policy interventions will also be equally applicable to Global South and other developing countries.

i) Exempt closed loop Pumped Storage Hydro Projects from environmental clearance. Simplifying the concept, these off the river closed loop Pumped Storage Plants create two water bodies or rather large ponds at different elevations on upstream and downstream of the power house for energy conversion. These water bodies help in our fight against the climate change. Thus, clearance from environmental angle from Ministry of Environment & Forest and Climate Change which is time consuming need to be waived off for these off the river closed loop pumped storage projects.

ii) Expedite licensing pathway for non-powered dams (NPDs) controlling water supply and inland navigation and closed-loop PSPs on the lines of the Community and Hydropower Improvement Act in United States .

iii) Possibility be explored for provision of small hydroelectric projects in Non Powered Dams.

iv) For Govt.-identified PSP sites, formulate a Special Purpose Vehicle (SPV) to carry out survey and investigation, prepare a detailed Project Report to obtain clearances/concession. After obtaining concession and necessary clearances, tariff based competitive bidding be carried out for expeditious execution of these projects. Permission or clearances/concession obtained by SPV be allowed to be transferred to affiliate/group company.

v) Simplify, procedure for obtaining permission from the Forest Department to carry out survey and investigation. At present, it takes 6-12 months to obtain these permissions. Grant these permissions on the State/Provincial level almost on the lines of National Development and Reform Commission (NDRC) of China.

vi) In case of upgradation and refurbishment of existing hydropower facilities (including PSPs) provide incentives for improving efficiency by or more than 3%.

vii) Provide Investment Tax Credit for investments in hydroelectric and pumped storage projects to improve power production and to provide environmental benefits. Taxes on PSP equipment be reduced and made at par with other renewable generation assets. This will enhance the viability of PSPs and will improve the investment environment.

viii) Financial support for infrastructure provided for hydropower projects be made applicable for the self-identified PSPs as well.

ix) Development of pumped storage projects identified in coal mines need to be expedited. Detailed guidelines are required to be prepared for such projects.

x) In order to provide certainty for purchase of energy from PSPs create renewable purchase obligations (RPOs) or obligate distribution companies for buying energy from PSPs. This will isolate these projects from competition with battery energy storage, which gradually is becoming cheaper.

xi) Establish stable regulatory mechanism to incentivize PSPs for ramping up and down, providing peak power during non-solar hours and for grid flexibility services.

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COMMISSION INTERNATIONALE DES
GRANDS BARRAGES

VINGT-HUITIEME CONGRES DES
GRANDS BARRAGES
CHENGDU, MAI 2025

CONNECTION OF THE LIBOUŠ SURFACE QUARRY WITH THE NECHRANICE RESERVOIR (*)

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CZECH REPUBLIC

SUMMARY

Currently, the Libouš brown coal quarry is one of the largest active quarries in the Czech Republic. Based on government resolutions, the end of mining and the start of the final phases of reclamation of the area is expected between 2030 and 2041. In addressing the water management issues of the Sub-Erzgebirge lignite basin after the end of lignite mining and the reclamation of the area, the alternative of a direct connection of the Nechranice reservoir with the Libouš quarry is also currently being considered.

The water management solution for the connection of the Nechranice reservoir - Libouš reservoir was used to evaluate the strengthening of the reservoir storage and retention space for the Nechranice reservoir and the benefits in the area of the downstream Ohře River. The assessment has shown that the connection of the Nechranice Reservoir and the Libouš Reservoir will significantly increase the

*Connexion de la carrière de surface de Libouš avec le réservoir de Nechranice

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enhancement effect in the Ohře River downstream of the Nechranice Reservoir by up to 24 % compared to the current situation. At the same time, the connection will ensure the current enhancement effect on the downstream Ohře River even for the furthest horizon of climate change (year 2100). Since implementing new reservoirs on the Lower Ohře is not currently feasible, this is an excellent opportunity to adapt the water resources in this heavily agricultural area to climate change.

RÉSUMÉ

Actuellement, la carrière de lignite Libouš compte parmi les grandes carrières actives les plus importantes en République tchèque. Sur la base des décisions du gouvernement, la fin de l'extraction et le début des phases finales de remise en état du territoire sont attendus entre 2030 et 2041. L'alternative d'un raccordement direct de l'ouvrage hydraulique de Nechranice à la fosse résiduelle de Libouš est également traitée dans le cadre de la gestion de la problématique d'aménagement des eaux du bassin lignitifère sous les monts Métallifères après la fin de l'extraction du lignite et la remise en état de ce territoire.

Le concept d'aménagement du raccordement des ouvrages hydrauliques Nechranice et Libouš a permis de valoriser le renforcement de la zone de stockage et de rétention du réservoir pour les besoins de l'ouvrage hydraulique de Nechranice, ainsi que les apports dans le territoire de l'Ohře inférieure. L'évaluation réalisée a démontré que le raccordement du réservoir de Nechranice au lac de Libouš accroîtra considérablement l'effet positif sur la rivière Ohře en aval de l'ouvrage hydraulique Nechranice, et ce de jusqu'à 24 % par rapport à la situation actuelle. Le raccordement permettra dans le même temps de garantir un effet positif simultané sur l'Ohře inférieure également pour l'horizon le plus lointain du changement climatique (année 2100). Étant donné que la réalisation de nouveaux réservoirs de stockage sur l'Ohře inférieure ne semble pas réaliste à l'heure actuelle, il s'agit d'une excellente opportunité pour que les sources aquatiques situées dans ce territoire fortement sollicité d'un point de vue agricole s'adaptent au changement climatique.

1. INTRODUCTION

The Nechranice Dam is located approximately halfway downstream of the Ohře River between the towns of Chomutov, Kada and Žatec. It is the largest reservoir in the Ohře basin with a total storage of 287.6 million m^3 and a flooded area of 13.38 sq. km. One of the largest surface quarries of the Most coal basin is located near this reservoir. (Fig. 1)

The possibility of connecting the Nechranice Reservoir and the adjacent residual quarry of the Libouš lignite quarry was dealt with in a techno-economic study prepared in January 2022 [1]. The study focused on finding technically and economically optimal variants of this connection, including the connection to the surrounding reclaimed areas. At the same time, the issue of bypassing the resulting reservoir was addressed, to ensure a minimum residual flow in the Hutná watercourse, from the industrial water intake and from the Erzgebirge watercourses of the area.

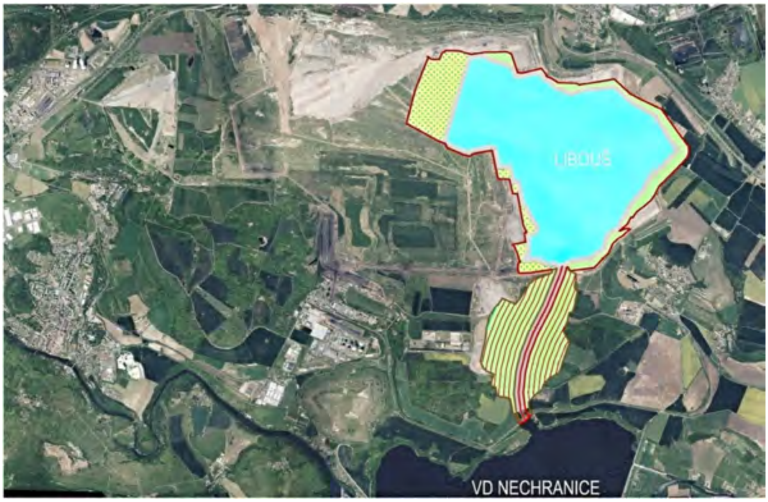

Fig. 1
The situation of the connection between the Nechranice Reservoir (near bottom) and the Libouš surface quarry (blue) - open channel option.
Situation de la connexion entre le réservoir de Nechranice et la carrière de surface de Libouš - option canal ouvert.

2. TECHNICAL SOLUTION

Technically, three methods of connection were designed – an open channel (canal), a pressurized tunnel and a combination of a tunnel and a channel. It was shown by hydraulic calculations that any water body connection combining an open channel and a pressurized tunnel or tunnels has practically no water management effect, therefore only the two remaining variants of open channel and sole pressurized tunnel or tunnels were developed.

The basic data for the individual conceptual designs were the current digital terrain model of the area of interest with the mining termination in 2041, variant water management solutions for the storage and flood protection functions of the connected water bodies, hydraulic calculations and calculations of the stability of the slopes of the connecting channel and the banks of the future reservoir.

2.1. Open channel variant

The open channel was designed with a total length of 3.2 km, trapezoidal in shape with a bottom width of 15 m and slopes of 1:8 (Fig. 2). The bottom is horizontal and unconsolidated, the slopes are reinforced with rockfill up to the level of the berm. On the Nechranice Reservoir side of the canal, an inlet/outlet structure is proposed, combined with a second-class road bridge. The canal will allow navigation in the recreational Class I waterway. The design of the route of the canal connecting the Nechranice Reservoir with the future Libouš Reservoir takes into account the requirement to minimise disruption of the original landscape. The entire canal encroaches exclusively on the landscape transformed by the disposal of scraped materials (spoil heaps) and coal combustion products (storage of fly ash and fly ash mixtures).

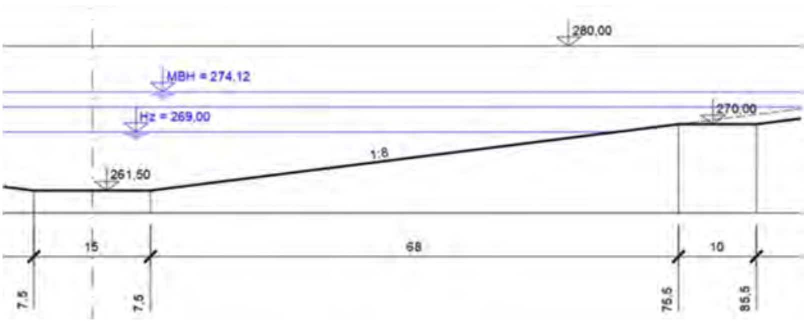

Fig. 2
Resulting cross-section of the connecting channel (symmetrically second bank).
Note: MBH ... limit safe water level for Nechranice reservoir, Hz... the upper limit of the active storage area of the Nechranice reservoir.
Coupe transversale du canal de liaison (deuxième rive symétrique). Note : MBH ... niveau limite de sécurité pour le réservoir de Nechranice, Hz ... limite supérieure de la zone de stockage du réservoir de Nechranice.

2.2. Variant of the pressurized tunnel

The tunnel would have a zero longitudinal slope similar to the open channel and would be fitted with a gated shaft at each end. The 5 m diameter tunnel would be carried out with a TBM (tunnel boring machine). The length of the mined section of the tunnel is 2.7 km.

During its construction, only a fraction of the soil material would be excavated compared to the excavation of the channel (canal). However, compared to an open canal, it cannot fulfil all the required water management functions and complications related to the complex geology of the subsoil can be expected during construction and operation. A major question is how the operational control and maintenance would be carried out.

2.3. Libouš surface quarry

An important element of the technical design of the reservoir is the stabilization of the steep slopes of the Libouš residual quarry. It will be constructed with an embankment berm made of soil excavated during the excavation of the connecting channel. Excess material will be deposited on the reservoir/former quarry bed. In the case of tunnelling, the material for stabilising the reservoir slopes would have to be extracted from the spoil heaps in the mine area. Heavy mining equipment - excavators and conveyor belts - are planned for the heavy earthworks. As part of the reclamation works, it is proposed to fortify the entire perimeter of Libouš reservoir with a riprap within the range of water level fluctuation in the reservoir.

3. WATER MANAGEMENT SOLUTIONS

The aim of the water management solution for the connection of the Nechranice Reservoir - Libouš Reservoir was to evaluate this enhanced reservoir storage and retention volume for the purposes of the Nechranice Reservoir and the benefits in the area of the downstream Ohře River.

3.1. Flood retention function

The retention function of the Nechranice Dam will be strengthened by transferring part of the flood wave volume to the Libouš reservoir, which will reduce the peak discharge downstream of the dam and increase flood protection on the lower Ohře River and further on the lower Elbe River. Currently, the Nechranice Reservoir provides flood protection to the downstream areas up to less than a theoretical 20-years flood.

The assessment of the flood retention function was carried out by transforming a winter theoretical flood wave with a return period of 100 years. For the open channel connection option, the analysis results in the finding that the level in the Libouš Reservoir corresponds with only a very small time lag with the water level in the Nechranice Reservoir. The maximum water level in the Nechranice Reservoir is only 0.14 m above the maximum water level in Libouš Reservoir. The maximum flow through the connecting channel is about 300 $m^3.s^{-1}$ and the corresponding mean profile velocity is 0.32 $m.s^{-1}$.

The capacity of the channel has fully demonstrated the ability to use the flood retention space of the Libouš reservoir as efficiently as possible for the transformation of flood waves. In the case of the pressurized tunnel connection option, the result of the analysis is that the tunnel with a diameter of D = 3.0 m has almost no beneficial effect on the retention potential of the Nechranice reservoir. This is due to the fact that the connection or more precisely the hydraulic parameters of the pressurized tunnel between the Libouš Reservoir and the Nechranice Reservoir are not sufficient during flood flows due to the limited capacity of the tunnel. Even the connection through the two D = 5.0 m diameter tunnels would not be perfect in terms of the utilised retention function of the Libouš reservoir (Table 1).

Table 1
Comparison of the retention effect by Theoretical Flood Wave (TFW) transformations
Comparaison de l'effet de rétention par les transformations de l'onde de crue théorique (TFW)

Level of controllable flood retention storage (after modernisation of the Nechranice Dam spillway) 272.20 m above sea level.						
TFW (return period – years and season)			100 winter	50 winter	20 winter	10 winter
Initial level	H0	[m above sea level]	269.00	269.00	269.00	269.00
Inflow peak discharge	Pmax	[$m^3.s^{-1}$]	753	648	509	415
Flood wave volume above non-damaging discharge (200 $m^3.s^{-1}$)	W	[mil. m^3]	104.3	81.7	48.7	29.4
Peak discharge outflow						
Current status	O_{max}	[$m^3.s^{-1}$]	380	312	221	200
Tunnel 1 x D = 3.0 m	O_{max}	[$m^3.s^{-1}$]	376	307	216	200
Tunnels 2 x D = 5.0 m	O_{max}	[$m^3.s^{-1}$]	333	259	200	200
Open channel = perfect connection	O_{max}	[$m^3.s^{-1}$]	268	220	200	200

Legend: O_{max} ... peak discharge from Nechranice reservoir

3.2. Storage functions

The assessment has shown (Table 2) that the connection of Nechranice reservoir and Libouš reservoir by all considered variants will significantly increase the enhancement effect in the Ohře River below Nechranice dam, up to 24% compared to the current situation. At the same time, the connection will ensure the current level of enhancement on the lower Ohře River even for the most distant climate change horizon (year 2100). Given the fact that the implementation of new storage reservoirs on the Lower Ohře is not currently feasible, this is an excellent opportunity to adapt the water resources in this heavily agricultural area to climate change.

Table 2
Results of water management solution of the storage function
Résultats de la solution de gestion de l'eau de la fonction de stockage

	Overall enhancement		**Increase in enhancements due to connection**	
	Nechranice Reservoir	**Nechranice Reservoir and Libouš Reservoir**		
Climate variant	**[$m^3.s^{-1}$]**	**[$m^3.s^{-1}$]**	**[$m^3.s^{-1}$]**	**[%]**
Current climate	12.3	15.2	2.9	23.6
Time horizon 2050	11.5	14.1	2.6	22.6
Time horizon 2100	10.0	12.4	2.4	24.0

3.3. First filling

Part of the water management solution for the connection of the water areas was also the determination of the schedule for the first filling of Libouš Reservoir. The size of the filling flow was considered to be a maximum of 2 $m^3.s^{-1}$, which is the flow that can be ensured in both cases of the connection of Libouš reservoir and Nechranice Dam. The first filling analysis was prepared for hydrological conditions under the current climate (2020) and for two future time horizons of climate change: 2050 and 2100. For the assessment of the first filling period, three options for the transfer of water from Nechranice Reservoir were selected.

Option 1 is based on the requirement that the total period of the first filling of Libouš Reservoir should be 10 years, in line with previously developed documents. This recommended fill time corresponds to a required average transfer from the Nechranice reservoir of 0.79 $m^3.s^{-1}$. Options 2 and 3 are used to assess the sensitivity of the delivery schedule to the size of the transfer and consider a transfer of 1.0 $m^3.s^{-1}$ and 2.0 $m^3.s^{-1}$. Given that inflows from the catchment of the Libouš Reservoir and inflows from deep aquifers account for only a small fraction of the transfer from Nechranice Reservoir, the calculations performed have shown that the scheduling of the first filling of Libouš Reservoir is very reliable (Table 3).

Table 3
Average time to fill (Tavg) and time to fill with 95% reliability (T95)
Temps moyen de remplissage (Tavg) et temps de remplissage avec une fiabilité de 95% (T95)

	Q transfer	climate 2020		climate 2050		climate 2100	
		Tavg	T95	Tavg	T95	Tavg	T95
	$[m^3.s^{-1}]$	[years]	[years]	[years]	[years]	[years]	[years]
Option 1	0.79	9.8	9.9	10.1	10.2	10.6	10.8
Option 2	1.00	7.7	7.8	7.9	8.0	8.2	8.3
Option 3	2.00	3.8	3.8	3.9	3.9	3.9	4.0

4. EVALUATION OF CONNECTION OPTIONS

The comparison of the two alternatives was carried out by means of a multi-criteria evaluation, and criteria such as the fulfilment of the required water management functions, ecological aspects, investment and operating costs, economic benefits in the area downstream of the Nechranice Dam, safety and operational reliability, and durability and maintenance were selected for the assessment.

In the final evaluation, the tunnel option outperforms in only two criteria - investment costs and operating costs. However, the higher costs of building an open channel might in the future be outweighed by the economic benefits associated with increased flood protection of the areas downstream of the dam. In three criteria the two methods of connection achieve identical results (filling, discharge enhancement and durability), in the others open channel connection dominates. The most significant differences are in the criteria of flood wave transformation and maintenance requirements. The results of the evaluation clearly show a preference for the option of connecting the Nechranice Reservoir and the Libouš residual quarry by an open channel before the pressurized tunnel.

5. EVALUATION OF THE EFFECTIVENESS OF THE RECOMMENDED TECHNICAL SOLUTION

The financial analysis compared the estimated investment costs for the construction of the planned dams in the Czech Republic with the costs of building the Libouš Reservoir by connecting with the Nechranice Reservoir through an open channel. The comparison criterion was the cost of creating 1 m^3 of available storage determined by the sum of the storage and retention volume. For the planned reservoirs in the Czech Republic, the price of 1 m^3 of available reservoir volume varies ranges from 287 to 785 CZK (i.e. 11–34 EUR). The ratio of the estimated investment costs for the implementation of the connection of the Nechranice Reservoir with the Libouš Reservoir in the form of an open channel is 20,886 million CZK (i.e. 835.44 million EUR) and the sum of the storage and retention volume of the reservoir of 106.565 million m^3 results in the price of 1 m^3 of the available volume of 196 CZK (i.e. 8 EUR). The comparison shows that the connection of the reservoirs via an open channel is efficient.

6. CONCLUSION

The technical-economic assessment of the proposed connection of the Nechranice Reservoir with the Libouš residual quarry evaluated the implementation of a trapezoidal open channel with a bottom width of 15 m and slope gradients of 1:8 with a total length of 3.2 km as the optimal option. The analysis of the water management solution demonstrated the considerable potential of connecting the water areas through an open channel to strengthen the storage and retention function of the Nechranice Reservoir with significant water management benefits for the downstream part of the Ohře River.

REFERENCE

[1] VODNÍ DÍLA – TBD, JSCo in cooperation with Assoc. Prof. Pavel Fošumpaur. Connecting the Libouš residual quarry with the Nechranice reservoir, technical and economic study

Q.108 - R.22

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ADAPTATION OF THE RESERVOIR OPERATION RULES IN THE CONTEXT OF CLIMATE CHANGE (*)

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SUMMARY

The alternating periods of rising average temperatures on the Earth's surface, changes in the intensity of ocean movements and their levels, as well as the increasing frequency of extreme events (floods and droughts), are visible signs of the growing effects of climate change.

Climate change and environmental degradation are constant threats to the planet, and their negative effects are felt both economically and socially. To assist member states, the European Commission has taken steps to adopt strategies aimed at mitigating the global effects of climate change. Romania like other European countries faces the effects of climate change.

Adaptation des règles de fonctionnement des réservoirs dans le contexte du changement climatique

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Climate change affecting water resources will most likely influence the achievement and maintenance of the environmental objectives set by the Water Framework Directive 2000/60/EC. To meet and maintain the environmental objectives of the Water Framework Directive, Romania defined the ecological flow in the Water Law 107/1996, with subsequent amendments and completions. The determination of the ecological flow downstream of a water intake/barrier is carried out following Government Decision No. 148 of February 20, 2020, approving the methodology for determining and calculating the ecological flow.

Currently, there are concerns regarding the optimization of water resource allocation and the operation of multi-purpose reservoirs (flood mitigation, electricity generation, water supply) in the context of climate change and the introduction of ecological flow as a water usage requirement.

In this paper, an approach for coping with climate change and environmental requirements according to the Water Framework Directive in the case of a reservoir is shown. To highlight it a case study is done, namely Paltinu reservoir located in Romania.

Additionally, an estimation was made of how the operation rules of a reservoir (Stânca-Costești) should be changed due to repeated extraordinary events occurring within a short period.

RÉSUMÉ

Les périodes alternées de températures moyennes croissantes à la surface de la terre, les changements d'intensité des mouvements océaniques et de leurs niveaux, ainsi que la fréquence croissante des événements extrêmes (inondations et sécheresses), sont des signes visibles des effets croissants du changement climatique.

Le changement climatique et la dégradation de l'environnement représentent des menaces constantes pour la planète, et leurs effets négatifs se font sentir tant sur le plan économique que social. Afin d'aider les États membres, la Commission européenne a pris des mesures pour adopter des stratégies visant à atténuer les effets mondiaux du changement climatique. La Roumanie, comme d'autres pays européens, fait face aux effets du changement climatique.

Le changement climatique affectant les ressources en eau influencera probablement la réalisation et le maintien des objectifs environnementaux fixés par la Directive-cadre sur l'eau 2000/60/CE. Pour atteindre et maintenir les objectifs environnementaux de la Directive-cadre sur l'eau, la Roumanie a défini le débit écologique dans la loi sur l'eau 107/1996, avec ses modifications et compléments successifs. La détermination du débit écologique en aval d'une prise d'eau/barrière est effectuée conformément à la décision du Gouvernement n° 148 du 20 février 2020, approuvant la méthodologie de détermination et de calcul du débit écologique.

Actuellement, il existe des préoccupations concernant l'optimisation de l'allocation des ressources en eau et l'exploitation des réservoirs multi-usages (atténuation des inondations, production d'électricité, approvisionnement en eau) dans le contexte du changement climatique et de l'introduction du débit écologique comme exigence d'utilisation de l'eau.

Dans ce rapport, une approche pour faire face au changement climatique et aux exigences environnementales selon la Directive-cadre sur l'eau dans le cas d'un réservoir est présentée. Pour le mettre en évidence, une étude de cas est réalisée, à savoir le réservoir de Paltinu situé en Roumanie.

De plus, une estimation a été réalisée sur la manière dont les règles de fonctionnement d'un réservoir (Stânca-Costești) devraient être modifiées en raison de la survenue répétée d'événements extraordinaires dans un court laps de temps.

1. INTRODUCTION

One of the findings of the World Economic Forum held in Japan, in January 2024 was that in the longer term, climate-related threats dominate the top 10 risks global populations will face. The 2021 European Union Climate Law places, for the first time, a legal obligation on the European Union and its Member States regarding adaptation to climate change. In addition, it also requires the Commission to assess the consistency of relevant national measures to ensure progress towards continuous progress in enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change. Measures for adaptation to climate change and coping with environmental issues and other constraints are a challenge for the scientific community and water authorities.

For the Romanian area, over 90% of climate models forecast serious droughts during the summer, especially in the South and Southeast of Romania (with negative deviations compared to the 1980-1990 period higher than 20%). Other studies indicate an increase in winter precipitation in the Western and North-Western parts of Romania. Additionally, an increase of 50–60% in the frequency and duration of heat waves from 2021 to 2050, particularly in southern Romania, is a realistic scenario (www.climatechangepost.com, 2023). Due to the expected climate change, the frequency and intensity of natural disasters will most likely increase.

Based on the analysis done within the National Institute of Hydrology and Water Management, Bucharest, Romania, for the monthly mean multiannual discharge, for 275 gauging stations selected from the 20 river basins (representing 71.6% of the Romania's surface) a significant discharges increase in January and February and a significant decrease in April, May and August to November was obtained, indicating a decrease in the probability of occurrence of extreme events in these months.

The effect of climate change manifests itself amongst others in an increase in flooding and drought. Many measures can be taken to tackle these effects, amongst others reforestation, longer retention of precipitation, and an increase of water buffer capacity. Besides the more technical approach, improvement of water management is key, especially in reservoir management. Reservoir management measures are meant to regulate water supplies to prevent both surplus and shortage.

The current paper focuses on approaches for water management considering climate change: case study 1 - a water management model considering environmental issues and case study 2 - flood mitigation.

2. CASE STUDY 1

From climate change to adaption measure, there are 3 main pillars: meteorological model, hydrological model, and water management model. The meteorological model has as outputs precipitation and temperature series in new climatic conditions which are inputs for the hydrological model. The hydrological model has as outputs the estimated discharges in new climatic conditions which are inputs for water management models. The current paper is focusing on the water management model.

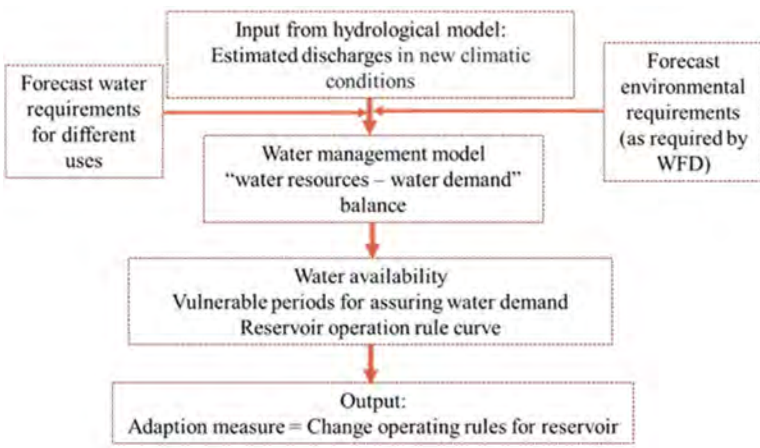

Fig. 1
Approach for a reservoir considering climate change and environmental requirements according to the Water Framework Directive.
Approche pour un réservoir en tenant compte du changement climatique et des exigences environnementales selon la Directive-cadre sur l'eau.

The Paltinu Dam was chosen as a case study for applying the above-mentioned approach considering climate change and environmental requirements according to the Water Framework Directive because it is located in the southeast of Romania, an area potentially deficient in terms of water resources.

The Paltinu Dam is a gravity arch dam and provides water necessary for multiple uses (supplying drinking water to the cities of Câmpina and Ploiești, electricity production, and flood protection). In terms of importance, the Paltinu Dam is under the second class and category B, of special importance, with an associated risk coefficient of RB=0.38. The design flow for the dam is Q=435 m^3/s, while the verification flow is Q=718 m^3/s + 20% safety margin.

2.1. The estimation of monthly mean multiannual discharges in climate change conditions inputs within the Paltinu reservoir

In Romania, the estimation of the impact of climate changes and variability on the hydrological regime of the hydrographic basin of the reservoir was based on the long-term simulations carried out with the help of the WATBAL (Water Balance Model) hydrological model, using as input data the precipitation series and temperatures resulting from climate evolution simulations made with the regional meteorological model REMO. The output of the hydrological model is monthly mean multiannual discharges.

Based on the climate evolution simulations (RCP 8.5 Scenario) and the precipitation and temperature series, the average monthly flows entering the Paltinu reservoir, under the assumption of climate change for the period 2021–2050 was done within the National Institute of Hydrology and Water Management, Bucharest, Romania.

The average monthly flows determined for the time horizon 2021-2050, under the assumption of climate change, are used to determine the environmental requirements (ecological flow) and further create the “water resource–water demand” balance.

2.2. Forecast water requirements for different uses including environmental flow

The share of the population served by drinking water from the Paltinu reservoir, relative to the total population of Romania, is 2.56%. This percentage remains constant throughout the entire forecast period and across all forecast scenarios and is applied to the population evolution forecast for Romania.

By knowing the annual growth rate of urbanization and the level of urbanization in the study area, the annual increase in the urbanization rate was determined. Based on the level of urbanization and the population forecast for the study area, the distribution of the projected population across living environments was determined for the three forecast scenarios.

Using the population forecast for the urban environment in the study area, as well as the water usage rate for the population in urban areas (95 m^3/person), the projected water demand for the urban population was calculated. Similarly, using the forecast of the rural population evolution for the study area, the connection rate forecast, and the water usage rate for the rural population (128 m^3/person), the projected water demand for the rural population was calculated.

Table 1
Projected water requirements for the population (urban and rural living averages), for 2050, for the study area (mil.m^3)

Study area	**Scenario**	**Year 2050**
Paltinu reservoir	Minimal scenario	39,421
	Baseline scenario	42,865
	Maximal scenario	46,408

Knowing the projected water requirements for the population, Table 2 presents the average flow rate required for the water supply to the population, for the study area, for the time horizon 2021–2050, under the assumption of the three forecast scenarios.

Table 2
Average flow rate for water supply to the population, for the study area, for the time horizon 2021–2050 (m^3/s)

		Year (forecast horizon)			
Study area	**Scenario**	**2021**	**2030**	**2040**	**2050**
Paltinu reservoir	Minimal scenario	1,517	1,490	1,379	1,250
	Baseline scenario	1,517	1,517	1,447	1,359
	Maximal scenario	1,520	1,545	1,516	1,472

Based on the average flow rates for water supply to the population for the time horizon 2021–2050 and the monthly variation coefficient of the water supply flow rate (k, j), for the study area, the projected average monthly flow rates required for the water demand of the population the 3 forecast scenarios) were calculated for the time horizon 2021–2050.

For the forecast of water requirements for industry, two methods were analyzed: the method of extrapolating historical trends and the method of per capita water withdrawals.

Knowing the population of the study area in 2011 (514,378 inhabitants) and the volume of water withdrawn for industry (9.439 million m^3), the specific volume of water withdrawn per capita was calculated as 18.35 m^3/year/person.

Below are the projected water requirements for industry, for the time horizon 2021–2050, considering the three forecast scenarios of economic growth, without considering the coefficients for reducing consumption.

Table 3
Projected water requirements for the industry for the time horizon 2021–2050, for the study area (mil.m^3)

Study area	Scenario	Year (forecast horizon)			
		2021	**2030**	**2040**	**2050**
Paltinu reservoir	Minimal scenario	9,803	10,747	11,426	11,778
	Baseline scenario	10,082	11,732	13,280	14,534
	Maximal scenario	10,655	13,547	16,610	19,473

The environmental demand, or ecological flow in Romania is computed using Ro-Eflow (1) Method and is calculated based on the multiannual average monthly inflows in the Paltinu Dam section. The ecological flow has 3 components: quantity, dynamic, and real-time operation.

Using the average monthly flow rates for the period 2021–2050 (30 years), the minimum annual average monthly flow rate with 95% assurance (Q95%) of 0.928 m^3/s was calculated, and then the ecological flow values for each month of the year – Qeco monthly – were determined.

The 12 resulting monthly values of the ecological flow were subsequently grouped into three types of regimes based on the distribution of the monthly ecological flow values and the minimum annual average monthly flow rate with 95% probability, resulting in the characteristic values of the ecological flow specific to low, mean, and high hydrological regimes, as follows: Qeco low waters = 1.73 m^3/s, Qeco mean waters = 2.13 m^3/s, and Qeco high waters = 3.23 m^3/s.

For future period the climate change scenario the dynamics of the water resource was done assuming that the hydrological forecast will be 100% accurate. Therefore, the forecasted ecological flow values, in order to simulate the implementation in real-time, were assimilated with the simulated flows for the period 2021–2050.

2.3. "Water resources – water demand" balance in climate change conditions

The "resource-demand" water balance at the dam section of the reservoir for the period 2021–2050, under the climate change scenario, was determined as the difference between the average monthly inflows into the reservoirs for the period 2021–2050, estimated under the climate change scenario, and the required flow to meet the water demands of users (population and industry/irrigation) and environmental requirements (ecological flow) under the same scenario.

The flow balance calculations in the analysis sections are carried out for three scenarios:

- Minimal Scenario:
    - Water resource under the climate change scenario;
    - Projected water demand—water supply to users (population, industry/ irrigation) under the minimal climate change scenario;
    - Ecological flow calculated based on flows under the climate change scenario (for low, medium, and high flows) and the dynamics of the water resource under the climate change scenario, assuming that the hydrological forecast will be 100% accurate (using estimated values under the climate change scenario to distribute the three ecological flow values over the entire analyzed period).
- Baseline Scenario:
    - Water resource under the climate change scenario;
    - Projected water demand—water supply to users (population, industry/ irrigation) under the baseline climate change scenario;
    - Ecological flow calculated based on flows under the climate change scenario (for low, medium, and high flows) and the dynamics of the water resource under the climate change scenario, assuming that the hydrological forecast will be 100% accurate (using estimated values under the climate change scenario to distribute the three ecological flow values over the entire analyzed period).
- Maximal Scenario:
    - Water resource under the climate change scenario;
    - Projected water demand—water supply to users (population, industry/ irrigation) under the maximal climate change scenario;

- ○ Ecological flow calculated based on flows under the climate change scenario (for low, medium, and high flows) and the dynamics of the water resource under the climate change scenario, assuming that the hydrological forecast will be 100% accurate (using estimated values under the climate change scenario to distribute the three ecological flow values over the entire analyzed period).

Results:

For the minimal scenario at the Paltinu Dam section, under the climate change scenario, water surpluses will mainly occur from April to August, while water deficits will occur from January to March and from September to December.

For the baseline scenario at the Paltinu Dam section, under the climate change scenario, water surpluses will mainly occur from April to August, while water deficits will occur from January to March and from September to December.

For the maximal scenario at the Paltinu Dam section, under the climate change scenario, water surpluses will mainly occur from April to September, while water deficits will occur from January to March and from October to December.

2.4. RESERVOIR OPERATION RULES CHART IN CLIMATE CHANGE CONDITIONS

The operation graph is a tool for managing the volumes of a reservoir, developed based on quantitative water flow management calculations, providing rules for reservoir operation. The operation graph includes The Line of Functioning in an Assured Regime (LFRA), The Line of Introduction of Restrictions (LIR), The Line of Limiting Discharges (LLD) of the reservoir, the volume in the reservoir, and the water demands that must be met through reservoir operation. Below is the conceptual model [2] for calculating the lines of the operation graph:

Line of Functioning in an Assured Regime (LFRA) is calculated in reverse chronological order and represents the water volumes required in the reservoir at the beginning of each month during assured years to ensure that the users' needs are met at the required flow level and desired assurance degree.

The LFRA calculation starts from the value "0," meaning that at the end of the calculation period, emptying the reservoir is allowed. The following formula is used:

$$V_{ij} = V_{i,j+1} - 2,63 * B_{ij} \tag{1}$$

where:

- V_{ij} represents the water volume required in the reservoir at the beginning of month j in year i,

- V_{ij+1} represents the water volume required in the reservoir calculated for the previous month j+1,
- B_{ij} represents the water balance at the beginning of month j in year i.

The calculation is performed in the form of a matrix, with rows representing the months of the year and columns representing 30 years.

(For example $V_{nov\ 2017} = V_{dec\ 2017} - 2,63*B_{nov\ 2017}$, $V_{oct\ 2017} = V_{nov\ 2017} - 2,63*B_{oct\ 2017}$, and so on).

The Line of Functioning in an Assured Regime (LFRA) is represented by the maximum multiannual monthly volumes obtained by applying formula (1).

During deficit periods, restrictions are introduced regarding the flow rates provided.

The Line of Introduction of Restrictions (LIR) represents the water volumes below which restrictions are imposed in years when it is not possible to meet the water demand at the desired assurance level (non-assured years). The calculation is performed in chronological order using the following formula:

$$V_{ij} = V_{i,j-1} + 2,63*B_{ij} \tag{2}$$

where:

- V_{ij} represents the volume of water below which restrictions are imposed at the end of month j of year i during dry years,
- $V_{i,j-1}$ represents the volume of water calculated in the previous month,
- B_{ij} represents the water balance at the beginning of month j of year i.
- The restriction line is represented by the minimum monthly volumes below which restrictions are imposed on the allocation of water volumes required for consumptive uses and environmental use.

The Line of Limiting Discharges (LLD) is calculated in reverse chronological order and represents the maximum water volumes allowed in the reservoir at the beginning of the month, without the risk of losses through spillage. The LLD is constructed only if at least one of the served uses has a recirculation system. The calculation of the LLD starts from the value corresponding to the maximum ordinate of LFRA (LFRAmax). The LLD is calculated using the formula:

$$V_{ij} = V_{i,j+1} - 2,63*B_{ij}^{Q_{inst}} \tag{3}$$

where:

- V_{ij} Represents the maximum water volume allowed in the reservoir at the beginning of month j in year i,

- $V_{i,j+1}$ Represents the water volume existing in the reservoir calculated in the previous month, i.e., the volume that must be present in the reservoir at the end of the current month.,
- $B_{ij}^{Q_{inst}}$ Represents the surplus or deficit of the current month jjj in year iii, under the assumption that the usage is operating at the maximum usable flow rate

The estimation of the impact of climate change on the operation of reservoirs is carried out by plotting the operation graph, taking into account the estimated water resource under the assumption of climate change, the forecasted water demands of the users, and the achievement/maintenance of environmental objectives.

2.5. Updating the operating chart of the Paltinu reservoir, considering the achievement/maintenance of environmental objectives and climate change

The development of the reservoir operation graph, considering the forecasted water demands of users, the achievement/maintenance of environmental objectives, and the estimated water resource under the assumption of climate change, was carried out by following the steps outlined in Figure 1.

The plotting of the characteristic lines of the operation graphs (LFRA and LIR) under the climate change assumption was performed for three scenarios: the minimal, the baseline, and the maximal scenario [3].

Fig. 2
The operating chart of the Paltinu reservoir in the current situation, considering the achievement/maintenance of environmental objectives
Le graphique de fonctionnement du réservoir de Paltinu dans la situation actuelle, en tenant compte de l'atteinte/maintien des objectifs environnementaux.

The Paltinu Dam is a gravity-arch dam that provides the necessary water to meet multiple uses, including:

- Supplying drinking water to the cities of Câmpina and Ploiești
- Hydropower
- Flood protection;

From the perspective of the class and category of importance, the Paltinu Dam corresponds to class 2 and category B, with of “special importance” in a classification depending on the dam-associated risk, R_D=0.38. This is proportional to the risk level and is defined in terms of 3 composite indexes taking into account dam characteristics, dam behaviour, and dam failure consequences. The design flow is Q=435 m^3/s, while the check - up flow is Q=718 m^3/s, with a 20% safety margin.

The estimated average monthly inflows into the Paltinu Reservoir for the time horizon 2021–2050, considering climate change, as well as the projected water requirements for satisfying water consumption uses (for population water supply and industry), as well as the environmental use (ecological flow), were used in the flow balance calculation in the three scenarios.

The characteristic lines of the operating charts for the Paltinu reservoir, under the assumption of climate change, were drawn for three scenarios – the minimal scenario, the baseline scenario, and the maximal scenario represented in Figures 3, 4, and 5.

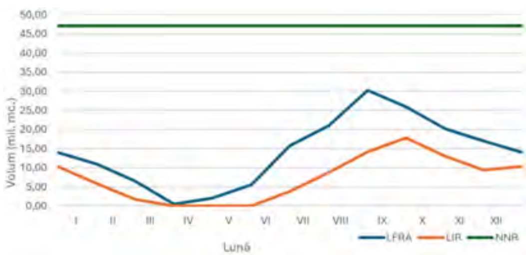

Fig. 3

The operating chart of the Paltinu reservoir, considering the projected requirements, including the environmental one, for the time horizon 2021–2050, in the minimal scenario

Le graphique de fonctionnement du réservoir de Paltinu, en tenant compte des exigences projetées, y compris celles environnementales, pour l’horizon temporel 2021–2050, dans le scénario minimal.

Fig. 4
The operating chart of the Paltinu reservoir, considering the projected requirements, including the environmental one, for the time horizon 2021–2050, in the baseline scenario.
Le graphique de fonctionnement du réservoir de Paltinu, en tenant compte des exigences projetées, y compris celles environnementales, pour l'horizon temporel 2021–2050, dans le scénario de base.

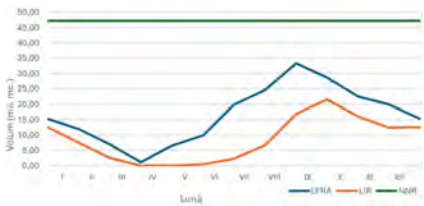

Fig. 5
The operating chart of the Paltinu reservoir, considering the projected requirements, including the environmental one, for the time horizon 2021–2050, in the maximal scenario.
Le graphique de fonctionnement du réservoir de Paltinu, en tenant compte des exigences projetées, y compris celles environnementales, pour l'horizon temporel 2021–2050, dans le scénario maximal.

3. CASE STUDY 2

The Stânca-Costești Dam is a complex hydraulic development, with a particularly long retention front (over 3 km), formed by dams of different types, connected or separated by higher sections of the natural terrain.

All structures have a crown elevation of 102.50 maBSL.

From the right bank (Romania) to the left bank (Republic of Moldova) follow one another: a buttress dam continued with a gravity one, the high waters spillway, the main dam made of earth fillings, a reinforced concrete dam, coffered, and an earth fill dam, which closes an old quarry.

The border between Romania and the Republic of Moldova passes through the pressure node located in the body of the main dam.

The evacuation of high flows, at maximum level in the reservoir (98.20 mABSL), is ensured by a surface spillway (6 openings equipped with weirs - 1580 m^3/s; 4 bottom outlets 1000 m^3/s; and a reserve intake).

According to the 2nd class of importance, in which the dam is included, the characteristic floods considered in the design phase were:

- For the design flow $Q_{1\%}$ = 2940 m^3/s; $V_{1\%}$ = 3000 m^3/s;
- For the check – up flow $Q_{0.1\%}$ = 4400 m^3/s; $V_{0.1\%}$ = 4640 m^3/s.

The Stanca-Costesti dam is rated in category “B” of “special importance” in a classification depending on the dam-associated risk, R_D=0.37.

During the operation period, several important floods were recorded, the characteristics of which are shown in Table 4. The highest inflow was recorded in 2008, and the highest volume of floods in 2010. In both cases, the reservoir level exceeded the overflow sill level.

In 2008 the level above the spillway sill was 2.77 m and by maneuvering the flood gates it was possible to evacuate the additional flow compared to the bottom outlet capacity. The incident recorded on this occasion was the subject of a series of special analyses. In 2010 the level was only 1.45 m above the spillway sill and the maneuvering of the gates for the discharge of the reservoir was no longer necessary.

Characteristics of the large floods recorded in the period 1995–2020 and their mitigation in the Stânca–Costești reservoir is shown below in Table 4.

Table 4
Characteristics of the large floods recorded in the period 1995–2020 for the study area (mil.m^3)

Date	**$Q_{max\ afl}$ (m^3/s)**	**Max Level (maBSL)**	**$V_{highflood}$ (hm^3)**	**$Q_{max\ ev.}$ (m^3/s)**	**$Q_{max\ ev.}/Q_{max\ afl.}$(%)**	**Duration (days)**
April 1996	1150	92.68	1080	518	45	31
April+July 1998	2410	92.36	-	605	25	105
August 2005	2640	92.14	554	564	21	5
May+June 2006	1180	93.43	560	483	41	15
July+August 2008	3380	98.27	840	800	24	8,5
June+July 2010	2310	96.95	1700	710	31	24
June 2020	2400	93.64	940	630	26	15

The flood of June 2020 had a flow slightly higher than the 2010 flood and lower than that of the floods of 2008. It was the third major flood mitigated in the Stânca–Costești reservoir, after the floods of 1996 and 2010, being taken over in very good conditions, by a good operation of the structure, based on the measurements provided by the variation of the reservoir level and the discharged flows, evaluated based on the evacuation capacities graphs as a function of reservoir levels, for all dam equipment (HPPs, bottom outlets, reserve intake) and correlated with the downstream situation.

It is noted that, although the maximum flow rate was estimated at 2400 m^3/s, the maximum flow discharged downstream was 630 m^3/s. The result is a reduction of around 70% of the value of the maximum peak-flow. By accumulating in the reservoir an important volume, it was possible to keep the discharge on the Prut River downstream of the dam at lowest possible values, in order to avoid flooding of the downstream areas.

During the 2008 flood routing, the dam performed well. However, there were recorded two local incidents:

- flooding of the loading chamber and the access gallery related to the spillway flood gates;
- special activation of the flows collected in the drainage gallery, especially in the branch under the high water's spillway:

The atypical behaviour during the floods led to urgent restoration works to prevent such phenomena and to upgrade the safety of the barred front, which was completed in the first stage in 2015. The works carried out for the "Safety and rehabilitation of facilities" at the Romanian bank got final acceptance in May 2016,

It should be remarked that overall, the seepage flows measured downstream are relatively small compared to the size of the barred section and that both the flows and the piezometric levels are dependent on the reservoir level which has not changed during operation so far.

Considering the modification of the hydrology of the Prut River as a result of the floods in 2008 and 2010, characterized by maximum flow rates and exceptional flood volumes, the decision regarding reservoir operation becomes difficult under the conditions of a non-permanent attenuation tranche, which is relatively limited compared to the calculated or verified flood volume. The volume of the reservoir in the upper part (only very minimally affected by the silting process) is characterized by the following values.

Table 5
Capacity curve of the reservoir (upper zone)

H(mdMN)	**Volume of the reservoir**	**Mitigation volume face to NNR(mil. m^3)**
90,8 (NNR)	735	0
95,5 (cota crestei deversoarelor)	1060	325
98,2 (Elevation of the flap weir crest, considered $H_{1\%}^{\max}$ at commissioning)	1285	550
99,5 (cota $H_{0,1\%}^{\max}$)	1400	665
102,5 (crest level)	1700	-

In other words, the attenuation volume at a 1% exceedance probability of the maximum flow is 550 million m^3 (volume up to the crest elevation of the weirs), compared to the volume of 1150 million m^3 for the 2008 flood, in the period from July 24, 6h – August 4, 18h, and the volume of 1616 million m^3 for the 2010 flood, in the period from June 23, 6h – July 17, 18h. It is worth mentioning that these two floods are characterized by a maximum flow close to 1% in 2008, and a maximum volume of approximately 1% in 2010.

The difference between the volume of these floods and the storage capacity in the non-permanent tranche must be compensated by the volumes discharged through the high-water spillways, whose capacity, however, is limited.

In the case of a relatively limited non-permanent attenuation tranche compared to the calculated or verified flood volume, the operating rules are based on the situation of the reservoir levels, the flow rates recorded at Rădăuţi-Prut (the entry into Romania), as well as the hydrological forecast for the next 3–5 days. The calculation of the precipitation layer across the entire hydrographic basin, as well as the estimation of the runoff layer and consequently the flood volume, allows for making correct decisions even before flood flows are recorded at the Rădăuţi-Prut hydrometric station.

Depending on the forecast volumes entering the reservoir in the coming days, as well as the situation of the levels in the reservoir, the operating rules are adapted, moving successively from the rules corresponding to the 10% flood to the rules for the 1% flood, and then, if necessary, to those for the 0.1% flood.

Regardless of the flood evolution, initially, the operating rules are those of the 10% flood. At elevation 91.00, the decision is made based on the forecast whether to adopt the rules corresponding to the 1% flood. Similarly, at elevation 95.50 mASL, a decision is made whether to continue with the rules for the 1% flood or switch to the rules for the 0.1% flood [4].

The operating decision depends not only on the water level in the reservoir but also on the flood hydrological forecast for the upcoming days.

4. CONCLUSIONS

For the Paltinu Reservoir, the water requirements for water-consuming uses, specifically water supply for the population and industry/irrigation, as well as for environmental use (ecological flow calculated using RoEflow Method [1]), can be met both under current climate conditions and under the assumption of climate change.

The assumptions considered for the current situation were:

- The water resource under current climate conditions;
- The current water requirement – water supply for the population and industry in the current situation and the ecological flow calculated based on the flow rates and dynamics of the water resource under current climate conditions.

The assumptions considered for the climate change scenario were based on three scenarios: minimal, baseline, and maximal, using the water resource under the climate change hypothesis, the projected water requirement – water supply for water uses (population, industry/irrigation) in the climate change hypothesis, in the three scenarios, and the ecological flow calculated based on flow rates under the climate change hypothesis (for low, mean, and high waters) using the dynamics of the water resource [3].

The forecast for the water requirement for water-consuming uses was made for three forecast scenarios (minimal, baseline, maximal), depending on fertility rate, economic growth for the water requirement forecast for the industry, and the projected irrigated area for the water requirement for irrigation.

Considering that the water requirements for water-consuming uses, as well as the environmental use – the ecological flow from the Paltinu Reservoir, can be met 100% under both the current climate conditions and the climate change hypothesis, the unallocated volume for water uses up to the Normal Retention Level (approximately 10 million m^3) could be used to increase the flood attenuation tranche for flood protection of the downstream localities and/or for electricity production. In the future, it is desired to reevaluate the legal, technical, and economic regulations regarding water resource management, quantitative and qualitative, in the context of climate change.

Regarding the cross-border Stânca-Costești hydraulic development, the actual Operating rules dated from the dam’s construction and were concorded with the former USSR.

New operation rules are under common elaboration with Moldova (sharing the dam and reservoir), based on and motivated by the emergencies that occurred in time and the political changes.

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GENERAL REPORT ON QUESTION 108

RAPPORT GÉNÉRAL SUR LA QUESTION 108

COMMISSION INTERNATIONALE DES GRANDS BARRAGES

VINGT-HUITIEME CONGRES DES GRANDS BARRAGES
CHENGDU, MAI 2025

QUESTION 108

DAMS AND RESERVOIRS FOR CLIMATE CHANGE ADAPTATION

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GENERAL REPORTER

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TABLE OF CONTENTS

1. SUMMARY

1.1. The challenges of adapting to climate change

Question 108 is entitled “Dams and reservoirs: adapting to climate change”. Dams and reservoirs (and levees for flood protection) are affected in three ways by climate adaptation:

- Our infrastructure *contributes* to societal adaptation in a context marked by the increasing penetration of intermittent energy sources and greater climate variability (droughts, floods).
- However, their *adaptability* to future climates must be assessed, meaning their capacity to continue delivering the expected services.
- Their *robustness* in future climates must also be evaluated, ensuring their ability to withstand new hazards.

The dams and levees we design and build have a role to play in 2050, 2100 and beyond. Reflecting on their adaptation to climate change requires humility, as **anticipating future conditions is challenging**:

- Climate change is driven globally and depends on the amount of Greenhouse Gases (GHG) emitted into the atmosphere. Several emission scenarios are described by the IPCC, ranging from RCP2.6 to RCP8.5.
- The IPCC uses these scenarios to create **global climate projections**, but these models include uncertainties, particularly in high-emission scenarios, where potential tipping points could trigger unexpected climatic phenomena.
- The **local climate impacts** (temperature, precipitation, river flows, etc.) can be modeled based on these global models. This scientific work results in projections of future local climates, which form the basis for water resource evolution scenarios.
- **Future water demand** will also evolve due to physical factors (changes in evapotranspiration) and societal changes (penetration of intermittent renewable energies, changes in agricultural practices, dietary habits, urbanization, etc.). Demand evolution scenarios must also be considered.
- Thus, there is **significant uncertainty** in predicting the future state of water resources, demand, and climatic hazards in each country by 2050, 2100, and beyond. Additionally, two issues are expected to become particularly important, adding to the uncertainty: biodiversity and international cooperation.
- Measures necessary to prevent **biodiversity** collapse will mobilize part of the available water resource, potentially preventing the construction of some dams and allocating some of the storage volume for ecological purposes. The fraction of freshwater dedicated to biodiversity could be very high.
- Climate change does not reduce the total volume of available freshwater (it may even increase it), but it makes it more erratic and unevenly distributed geographically. **International cooperation**, especially between neighboring

countries, could play a major role in mitigating future crises (heatwaves, droughts) through water-sharing mechanisms. Unfortunately, it is difficult today to rely confidently on such cooperation.

1.2. Adaptation measures already implemented in several countries

Climate change is already occurring, and societies are taking adaptation measures, highlighting the increasing challenges **dams, reservoirs, and levees** will face. Some examples, drawn from contributions to this report:

- Extreme flood events stronger than in the past, and new hazards (Glacial Lake Outburst Floods - GLOF), potentially threatening dams and dikes, have occurred or are anticipated.
- In many countries, recognizing that climate change will cause water availability irregularities, authorities are implementing resource mobilization strategies, notably through surface reservoirs.
- Some countries or regions have experienced prolonged droughts to the extent that dam reservoirs no longer fill, preventing them from providing expected services for several consecutive years. This situation casts doubt on their adaptability for future decades, leading these affected regions to focus on water conservation and demand reduction.
- The penetration of intermittent renewable energy sources (notably wind and solar) increases the need for electricity storage on various timescales. Flexibility is required to react to rapid fluctuations, intra-daily storage for solar, and storage over several weeks or months. Numerous pumped-storage hydroelectric projects (PSH) are under construction worldwide. Adaptation projects for hydroelectric plants to improve flexibility (intra-hour scale) are also underway.
- The increasing frequency of floods is leading some dam operators to reassess their operating conditions to increase available storage volume for flood management and protection of downstream populations. Improvements in flood forecasting technologies allow for substantial benefits in some cases.
- In some countries, run-of-river hydroelectric production (without storage capacity) is losing its appeal when there is no natural or artificial upstream reservoir ensuring regulated flows. This is because more frequent and prolonged droughts make hydropower generation less predictable, and because, when hydropower is intermittent and exposed to droughts, other renewable energy sources (RES) may be better options.

1.3. General principles for adaptation

Against this backdrop and taking into account the experiences of a number of countries, a **number of principles** can be drawn.

The solutions of the past are no longer necessarily the right ones: a "good dam project" of 20 years ago is no longer necessarily a "good project today", because of the context imposed by climate change and the sustainability requirements of dam projects. There are no universal solutions: the driver of change is global, but climatic variations and adaptation solutions differ greatly from one country to another. Thus, it is necessary, in each country or region, to **reassess resources, needs, and hazards** over the appropriate timeframes (2050, 2100, and beyond) to be able **to propose suitable adaptation measures**. This preparatory work is essential before any large-scale project.

The experience of countries currently most exposed to resource scarcity provides useful guidance on the strategies to be implemented more broadly in regions where climate change is increasing the risk of droughts. **Measures to control and reduce water consumption are essential**: measuring and quantifying consumption, refining water-sharing rules, reducing demand by combating wastage, adopting water-saving measures in all sectors, and preparing for crises.

In addition to these measures, it is often necessary to implement ways of **mobilizing resources**, whether through existing reservoirs or new ones.

Many existing reservoirs can be optimized. The purposes for which they were designed can be revised, for instance, by using hydroelectric reservoirs for electricity storage and grid stability rather than solely for electricity production, or by revising water-sharing rules to allocate more water to securing water supply or supporting biodiversity, possibly at the expense of electricity production or conventional irrigation. It is also possible to optimize reservoirs' operation, provided that relevant data can be collected (such as soil and groundwater moisture or other measurements to anticipate water demand) and adjust management rules accordingly, snow stock measurements to anticipate future inflows, or the installation of flood forecasting tools to facilitate preventive drawdowns and enhance flood protection. Finally, it is possible to optimize the distribution of resources through **interconnections** between reservoirs and **water transfers** from wetter to drier regions.

A major issue in a context of resource scarcity is water sharing. It is important to implement analysis methods that do not give excessive priority to commercial, monetizable uses. To this end, economic approaches used to assess projects should systematically **account for both positive and negative externalities**. The social cost of carbon is one such externality, but it is not the only one. It is also important to properly assess positive externalities such as securing water supply, supporting agriculture in times of drought, providing energy storage and flexibility to the power grid, and preserving biodiversity.

New storage capacities will have to be considered in many parts of the world. These will contribute to the adaptation of societies through multiple functions:

energy storage and the ability to compensate, at least in part, for the intermittency of wind and solar energy; the establishment of reserves to secure water supply during dry seasons; the provision of ultimate reserves for serious crises; and, if designed for this purpose, enhanced flood protection.

These new capacities can be achieved by raising existing dams or by constructing new ones. When undertaking new projects of this type, it is essential to avoid maladaptation. In particular, it is necessary to ensure that future water resources will be sufficient to fill these reservoirs and that sedimentation will not negate the benefits of the project within a few years or decades. It is also crucial to verify that the sustainability parameters of the new project are sound. If a new storage project is not sustainable in environmental and social terms, it may be counterproductive in the broader context of climate change adaptation and should be abandoned in favor of a better project.

Water is unevenly distributed around the world. Climate change is not expected to reduce the total volume of free freshwater available globally (excluding glaciers and polar ice caps), but it will modify its distribution, likely intensifying spatial irregularities. There is therefore a physical rationale for establishing mechanisms of **international cooperation**, particularly between neighboring countries, to mitigate the effects of these changes. These mechanisms, including treaties and agreements, could help absorb some of the effects of climate change and limit the social and political tensions that could arise from it.

1.4. Technical advances and other new ideas

Current and future projects often differ from those of 20 or 50 years ago. Among the emerging ideas, some are particularly relevant for adaptation.

Off-river water storage is an interesting concept from three perspectives: sedimentation, sustainability, and also evaporation (as it is possible to have greater average reservoir depths). This type of solution is not suitable in all topographical and hydrological contexts, but projects of this kind are becoming increasingly common worldwide, for various uses. The reservoir is fed by gravity or pumping, which significantly limits sedimentation issues and reduces the barrier effect on the main watercourse. It can be located in areas with lower social and environmental impact. The dam enclosing the reservoir can be built using materials excavated from the basin itself. One key issue is the watertightness of the basin, which requires careful evaluation on a case-by-case basis.

Pumped-storage hydropower plants widely and successfully utilize this off-river storage option. Waterproofing solutions are evolving: while bituminous concrete linings were almost systematically used in the past, several major projects now employ exposed geomembranes. The increasing penetration of solar and wind energy will drive the construction of many such structures. This raises the question of expanding their application, including low-head pumped storage plants for countries without significant elevation differences, and coastal pumped storage plants for islands and possibly continental coastal regions.

The integration of hydropower with solar energy is progressing further. The combination of **hydro and solar** power presents new opportunities. In recent years, projects have emerged to install floating solar panels on dam reservoirs. Solar power benefits from the available water surface and, in the case of hydroelectric dams, from existing substations and transmission lines. While these projects remain relatively rare, they introduce new technical challenges related to anchoring floating solar islands and assessing their impact on dam safety. The industry, particularly ICOLD, is actively addressing these safety concerns.

Beyond simply sharing reservoir space and transmission infrastructure, hydro-solar hybridization can lead to new approaches for generating reliable and abundant renewable energy. In its Full Solar Hydro (FSH) form, hydrosolar technology enables the development of a controllable renewable power plant that does not rely on water resources, making it a major alternative to thermal power plants. In its Highly Hybridized Solar Hydro (HhSH) version, it reduces pressure on water resources without any loss in electricity production, improving the multi-use potential of existing and future reservoirs.

Underground water storage is an older concept that has already been implemented in some places, either for subsurface storage in alluvial aquifers or deep storage in suitable rock formations. The question now arises whether this storage method could be further expanded. Preliminary analyses suggest that its applicability may be limited, but further study is warranted.

A broader issue is **the role of the sea**. Seawater desalination is already a reality in many countries facing freshwater scarcity. A pumped-storage facility using seawater has been built and operated for 20 years in Japan, and other projects are under study. New offshore basin projects are being considered for tidal power generation or electricity storage. Above all, thousands of kilometers of levees have been constructed to protect against marine submersion, and these structures will need to be adapted in the coming decades in response to rising sea levels. The need to protect coastal populations will become increasingly critical.

2. INTRODUCTION

Georges Annandale : "*I agree that we should focus on an "adaptive" response. In my opinion, we can try as much as we can to change the trend in climate change* *but will not be successful because, in my opinion, we are already beyond the point of no return*."

Peter Rae: *"There are no magic solutions. Importantly, it is necessary to recognize that practices developed by experience over the past decades will no longer be relevant to the future climate."*

2.1. Question 108 title

Question 108 is entitled "Dams and reservoirs: adapting to climate change". The call for papers under this question includes the following items:

1. Dams for Pumped Storage: specific features, design, examples of implementation
2. Off-river dams for water storage and flood protection
3. Offshore dams and tidal power plants
4. Dams for recharge of aquifers and other new concepts
5. Floating solar on dam reservoirs - opportunities and risks.

The title of question 108 is very broad, whereas the sub-questions are quite specific.

2.2. Approach adopted

As part of the development of this General Report, the chosen approach was to refine the formulation of Question 108 while broadening the scope of reflection beyond the technical aspects listed in the sub-questions.

The reformulated question is as follows: *What ideas and solutions can be proposed for the design and operation of dams and reservoirs to adapt to the future context of 2050 or 2100*? This *future context* is primarily characterized by an increase in greenhouse gases and, consequently, a rise in the Earth's average temperature, with varying impacts on climate and hydrology depending on the region. It is also marked by phenomena induced or exacerbated by climate change, including the widespread use of solar and wind power, the biodiversity crisis, and potential social or geopolitical tensions.

The question is primarily focused on *adaptation* to future conditions. However, ideas and solutions that contribute to mitigating climate change should be prioritized, as both mitigation and adaptation are necessary.

2.3. Contributions

The general report for this question is based on three main sources:

- reports submitted by national committees, which are referenced in §7.1,
- personal contributions from around thirty experts and dam practitioners worldwide, whose names are listed in §7.2
- general bibliographic references, drawn from ICOLD studies or other organizations, and listed in 7.3 and 7.4

2.3.1. *National committee reports*

22 reports were received from national committees. These reports are listed below, by theme.

Adapting to climate change

N°	TITLE	COUNTRY	CONTENTS
R2	Sediment and flood management at a planned multipurpose reservoir in a peri-glacial environment	Switzerland	A major new dam project at the site of a glacial retreat, to ensure winter energy security and other uses
R6	Changement climatique en France : une adaptation nécessaire des barrages et réservoirs, vision nationale et exemple local	France	Outlook for climate change in France; impact on hydropower production; presentation of an adaptation project involving raising a dam.
R10	Potential of Romanian dams to adjust to changing environment	Romania	Changes in reservoir use in Romania (reduced demand), and future roles (flood protection)
R14	Quantifying the impact of changing climate on dam operation: a review for engineering practitioners	Canada	An academic review of advanced modeling tools for simulating the effects of climate change and adapting reservoirs' management
R20	Dams for energy transition and need for pumped storage and hydroelectric projects in India	India	The assessment of reservoir needs in India for the energy transition, particularly the requirements for pumped-storage hydropower (PSH) facilities.
R22	Adaptation of the reservoir operation rules in the context of climate change	Romania	The evaluation of the adaptability of two large reservoirs to climate change, particularly in terms of flood protection.

Pumped Storage (PSH)

N°	TITLE	COUNTRY	CONTENTS
R5	Etanchéité des barrages et réservoirs de STEP : spécificités, conception et retours d'expérience	France	A comprehensive review of watertightness solutions for pumped-storage hydropower (PSH) basins.
R7	Innovative design and feedback of waterways from a major pumped storage project in arid region	France	Presentation of specific design elements for a PSH facility: hydraulic optimization of intakes and lining of the waterway.
R8	Adaptations to the design of Abdelmou-men pumped-storage scheme during the construction phase	France	Presentation of specific design elements for a PSH facility: exposed geomembrane, turbine design, and closed-loop water supply system.
R11	A case of potential Burera-Ruhondo PSH scheme in Rwanda, Africa	Rwanda	Description of a potential PSH develop-ment site in Rwanda.
R15	Excavation and filling technology for deformation control in highly water-bearing multilayer reservoir basins	China	Description of specific challenges related to the excavation of PSH reservoirs.
R16	Landscape signage for pumped storage dams	China	Ideas for promoting PSH facilities among local populations through the adoption of appropriate signage.
R17	Innovative technology and application research on anti-seepage of pumped storage power station reservoir basin	China	Lining solutions used in the Jurong PSH (geomembranes + bituminous concrete) and Kokhav Hardayen PSH (geomem-brane) reservoirs.

Off-river reservoirs

N°	TITLE	COUNTRY	CONTENTS
R9	Le Canal Seine-Nord Europe, projet hydraulique majeur en France	France	A presentation of a major new navigation project in Europe, including the issue of water resources mobilization.
R13	Olifantspoort off-channel storage dam – critical storage to augment water supply	RSA	An example of an off-river dam, with specific developments on the dam typology: multi-arch masonry structure.
R21	Connection of the Libouš surface quarry with the Nechranice reser-voir	Czech Re-public	Description of a project to flood a large abandoned mine, as an extension of an existing reservoir.

Floating solar

N°	TITLE	COUNTRY	CONTENTS
R12	Reflections on the management of energy projects based on immature technologies: the case of a FPV pilot project	Norway	Reflections on the innovative nature of floating solar projects on dam reservoirs.
R4	Towards FRcold guidelines for the realization of floating PV plants on dam reservoirs	France	A presentation of the work carried out by the French working group on the topic of floating solar, with a focus on risk analysis.
R19	Introduction to the world's first 100-meter-deep floating photovoltaic project in southeast Asia	China	The presentation of the Cirata floating power plant, a major example of a project on a dam reservoir.

Aquifer recharge, underground dams

N°	TITLE	COUNTRY	CONTENTS
R1	Sand dams: the case for greater collaboration between the dam industry and non-governmental organizations	Australia	Kenya - Feedback on an aquifer recharge dam, of the "sand dam" type, established through NGO-engineering cooperation.

New hazards, risk analysis

N°	TITLE	COUNTRY	CONTENTS
R3	Wildfire impact on dam and reservoir landslide safety risks considering future climate	Australia	An assessment of the increased hazard and new risks posed by wildfires
R18	Safety-risk-assessment-of-a-hydropower-dam-based-on-risk-matrix-method	China	Risk analysis presentation for a dam in China

2.3.2. *Individual contributions*

The individual contributions have enriched the overall reflection.

This text owes much to these contributions. The author of the report sincerely thanks the contributors for the depth and quality of their insights, and in particular, Michel Lino for his feedback on the entire text. When a section explicitly and fully incorporates an idea developed by one of the contributors, it is referenced using a code with the contributor's initials in the following format: [XX], as described in §7.2

2.4. Note on the time horizon

The general discussion presented in this report considers the time horizons of 2050 and 2100.

Thus, it does not focus on immediate adaptations to current challenges but rather on long-term trends that should emerge over time. This approach has been adopted because decisions made today will have consequences for several decades and, more likely, for over 100 years. It was not deemed reasonable to evaluate a time horizon beyond 2100. However, new projects and major modifications to existing structures must be designed to ensure their functionality for at least 100 years or more - some authors and projects even aim for a 200-year lifespan.

2.5. Two central concepts: uncertainty and local effects

The global trajectory of the increase in average temperature remains uncertain, as it depends on political and societal choices. The local and concrete manifestations of this global trend - such as heatwaves, droughts, and floods - are even more difficult to predict for each region and country.

As a result, determining the infrastructure needs for the adaptation of future societies is challenging. Reflection and technical solutions must be developed while accounting for this uncertainty. In particular, priority can be given to:

- “No-regret” strategies aimed at reducing vulnerability to climate change, which remain relevant regardless of how climate conditions evolve.
- “Flexible” strategies which allow for the operation of systems and structures to be adjusted based on actual observed changes.

2.6. Definitions

The definitions used in this report are as follows.

Adaptation (of our societies): the process of adjusting to the current or expected climate, and to its consequences, whether direct (such as heat waves, wildfires, droughts, and floods) or indirect (such as social and geopolitical tensions).

Adaptability (of our structures): the ability of dams, reservoirs and levees to continue fulfilling their functions, by 2050, 2100 and beyond. This involves assessing the effects of climate change on the functionality of these structures. (This report does not cover the other aspect of adaptability, which is robustness: the physical resistance of structures to new hazards.)

Contribution to adaptation (of our societies): The ability of dams, reservoirs, and levees to help societies adapt to climate change and its consequences, thereby reducing their vulnerability. This involves assessing the impact of these structures on society. The report highlights that dams and levees must play a role in this regard. For this reason, short-term benefits or profitability must sometimes be set aside in favor of long-term performance (cf. § 4.6.4).

Ecological footprint: A measure of the pressure exerted on resources and ecosystems. It quantifies the biologically productive land and water area required to produce the resources consumed by an individual, population, or activity, as well as the area needed to absorb the waste generated, considering current technologies and resource management practices. This footprint is expressed in global hectares (gha), meaning hectares with an average productivity level. The footprint of a structure can be assessed through life cycle analysis.

Contribution to mitigation: The ability of dam, reservoir, and levee projects to limit climate change and, more broadly, the ecological footprint of societies - for example, by enabling the replacement of fossil fuel-based electricity production with renewable energy sources.

Sustainability (of our structures): The ability of dam, reservoir, and levee projects to minimize their own ecological footprint (independently of their potential positive mitigation effects). To some extent, sustainability can be assessed through life cycle sustainability assessment (LCSA) methods. A comprehensive evaluation also requires environmental and social impact assessments (ESIA) and stakeholder consultation.

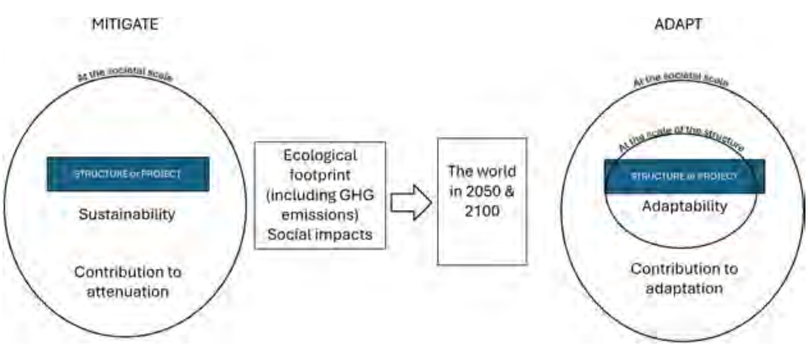


Fig. 1
Mitigation and adaptation

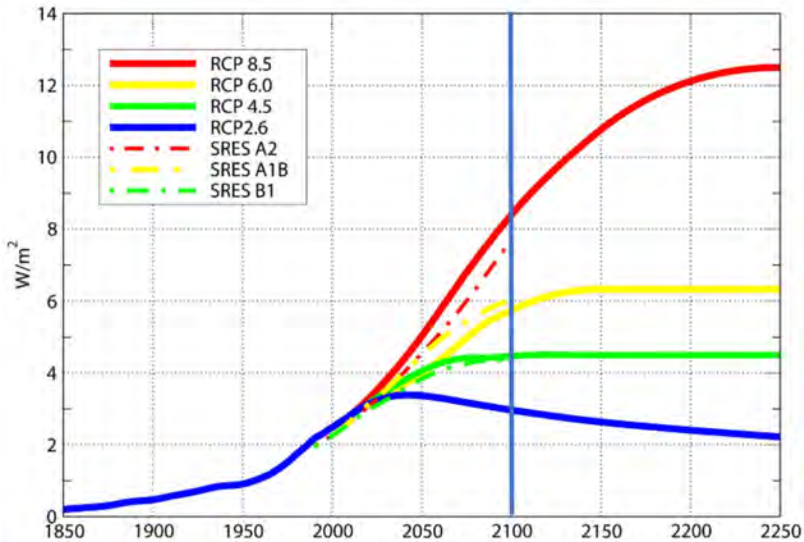


Fig. 2
The four IPCC RPC scenarios

Climate scenarios: These refer to the four RCP scenarios: RCP8.5, RCP6.0, RCP4.5, and RCP2.6, which have replaced the former SRES scenarios. RCP stands for *Representative Concentration Pathway*, with the numbers indicating the radiative forcing (in W/m^2 by 2100) - that is, the deviation from the pre-industrial radiative balance. RCP2.6 is the scenario that includes greenhouse gas (GHG) reduction policies and limits the temperature increase to 2°C above 1850 levels.

Hydroclimatic projections: An assessment, at the scale of a country or a specific territory, of the consequences of climate scenarios on the water cycle. This evaluation requires localized modeling to reach a relevant working scale. These projections may also incorporate other change factors, such as demographic trends or economic development.

Resilience: the ability of societies to cope with large-scale critical events (e.g. severe drought, major flood, earthquakes, large wildfires, etc.).

3. CHALLENGES OF ADAPTING TO CLIMATE CHANGE

3.1. Climate change is driven globally, but manifests locally

3.1.1. *Global drivers*

Climate change is directly linked to a nearly singular parameter: the amount of greenhouse gas (GHG) emissions, which can, in a first approximation, be expressed as an increase in the planet's average temperature.

The recently published Bulletin 200 [23] updates the current state of knowledge. The probability of keeping global warming below 1.5°C (compared to 1850 levels) is now almost zero. Notably, the year 2024 surpassed this threshold for the first time. Projections for the end of the century indicate temperature increases ranging between 1.4°C and 4.4°C.

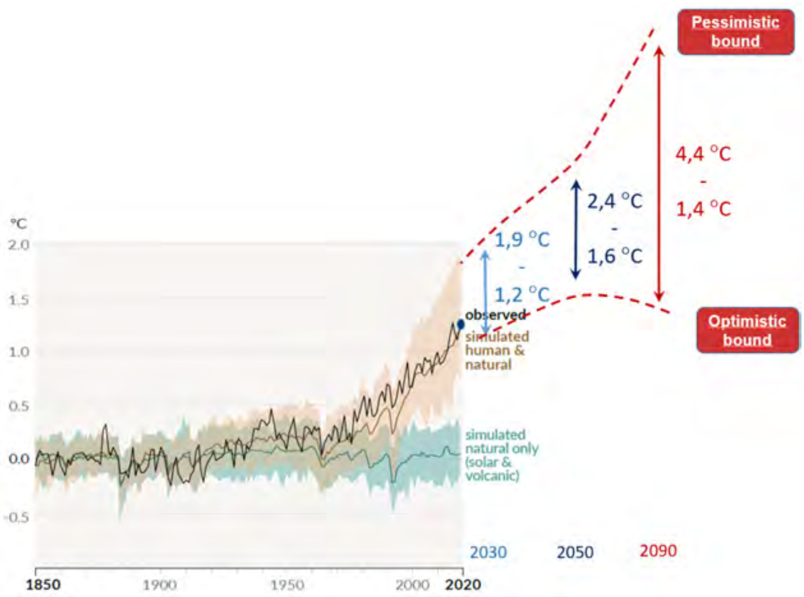


Fig. 3
Most likely global warming scenarios (source: IPCC WG.1 Climate science report (AR#6) – Aug. 2021 ; ICOLD – Q107 : General Report Aelbrecht D. (2022))

3.1.2. *Uncertainties and local variability, but more droughts*

The consequences of climate change can vary significantly at the scale of each country and region, particularly concerning water resources. The figures below, taken from [27] illustrate:

- The expected changes in annual precipitation volume in a +4°C warming scenario. The calculated mean value is framed by the 5% and 95% uncertainty bounds of this assessment.
- The probability of an increase in drought years under a +4°C warming scenario.

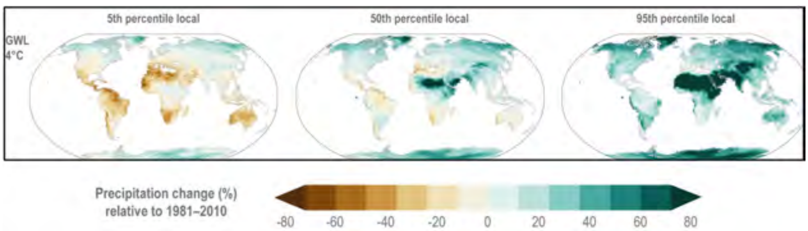


Fig. 4
Figure 4.10 from[27] : projected change in mean annual precipitation: mean and 5% and 95% percentiles.

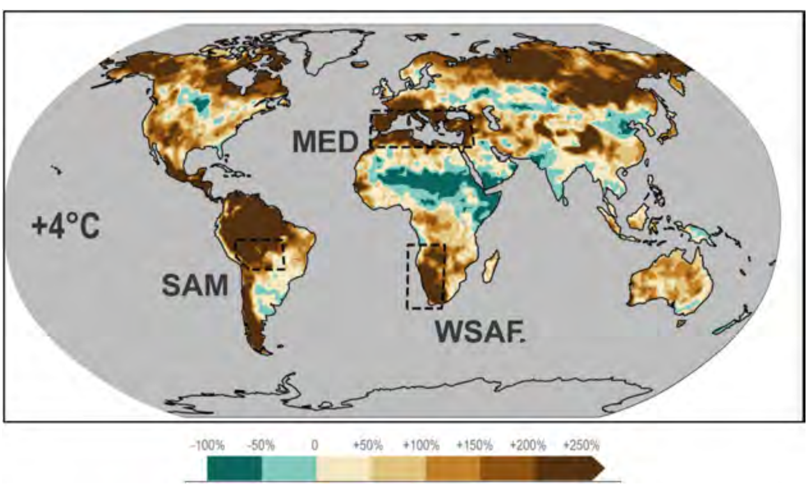


Fig. 5
Figure 4.18 from [27] : projected change in the probability of a very dry year

Fig. 4 illustrates the high uncertainty associated with future precipitation estimates (significant difference between the 5% and 95% percentiles) as well as the substantial variability from one region to another. Fig. 5 shows that the probability of drought years affecting agriculture is increasing in most regions.

3.1.3. *Relationship with dams and levees*

The relationships between climate change and dams and levees are well understood:

- Dams can contribute to climate change mitigation by generating carbon-free energy and facilitating the integration of intermittent renewable energy sources (such as wind and solar) through energy storage and grid support services.
- Climate change affects the water cycle, particularly in terms of droughts and floods. Dams and levees influence this cycle, with both positive and negative impacts. They play a role in limiting the effects on societies and potentially on biodiversity. At the same time, they must be adapted to these new conditions. Consideration must be given to:
  - Increased variability in interannual averages.
  - The intensification of extreme events.
  - Hydrological uncertainties linked to climate models.
- Climate change is causing sea level rise, which also impacts coastal erosion. Dams influence coastal erosion, often negatively, by reducing sediment flow. However, dams and levees near or in marine environments can also have a protective role for human settlements and must be adapted to these changing conditions.

3.2. Increased hazards

The exposure of dams and levees to new or increased hazards is not one of the topics examined in this report. However, it is worth briefly recalling that this is a central theme, by illustrating it with a few aspects. This overview is not exhaustive.

Floods and intense rainfall

The IPCC report AR6_FAQ8.2[37] expresses the scientific consensus on this matter. Climate change is already altering the location, frequency, and intensity of floods. In coastal areas, sea level rise exacerbates coastal flooding, especially when combined with heavy rainfall. Global warming also intensifies precipitation by increasing the atmosphere's ability to hold moisture (7% more per degree Celsius). It also influences wind patterns, storm formation and trajectories, as well as precipitation events. These transformations will continue to reshape precipitation patterns as the climate warms. Although other factors, such as land use changes, also influence flood formation, the following statements from the IPCC report are noteworthy:

- *“An increased intensity and frequency of record-breaking daily rainfall has been detected for much of the land surface where good observational records exist, and this can only be explained by human-caused increases in atmospheric greenhouse gas concentrations.”*
- *“[...] even accounting for the many factors that generate flooding, when weather patterns cause flood events in a warmer future, these floods will be more severe.”*

Thus, on average, an increase in flood frequency and intensity must be expected, with aggravated impacts in coastal areas due to rising sea levels. Inland, changes in the trajectory of extreme weather events (such as thunderstorms, storms, and cyclones) should also be anticipated. This increase in flood frequency and intensity is not uniform across all continents. Local analyses can, to some extent, provide quantitative insights, particularly for floods with a return period of less than 100 years. However, the impact on exceptional and extreme floods - which are used to design spillway capacity - remains an area of active research.

Climate change is not the only factor requiring a reassessment of flood risks. Land use changes also play a major role. A relevant example is the Tietê River, which flows through São Paulo (population: 21 million). Dams were built on this river in the first half of the 20th century, when its watershed was mainly forested. However, as the city expanded, urbanization replaced forests with impermeable surfaces, altering runoff conditions. The urbanization process also increases the severity of flood-related disasters. Significant engineering works were necessary to adequately increase flood evacuation capacity. [FM]

The increasing frequency and intensity of rainfall also triggers landslides, mudflows, and debris flows, further compounding natural hazard risks.

Wildfires - Climate change is increasing the frequency of wildfires and expanding the geographic areas at risk. Q108-R3 [3] addresses this issue based on case studies from Australia and the United States, leading to the following key conclusions. Wildfires can disrupt dam operations and cause immediate damage; however, these immediate dangers are generally minor. The greater risks emerge after the fire, including the increased likelihood of erosion and landslides triggered by extreme rainfall. In Australia, studies have shown that the probability of landslides increases by an order of magnitude in the short term after a wildfire, until vegetation regrows. These landslides can directly impact reservoirs or trigger debris flows and flash floods. Quantitative data also suggest a significant reduction in soil infiltration capacity in burned areas, which further exacerbates the risk of runoff and erosion.

GLOFs - GLOFs represent a new threat associated with rising temperatures and glacial retreat. For example, the Teesta River GLOF in India on October 4, 2023, led to the failure of the Teesta III dam and widespread devastation. [DS]

Sedimentation - The increase in intense rainfall in many regions of the world, combined with the possible decline of vegetation in drought-affected areas, is likely to increase sediment transport in rivers, leading to accelerated sedimentation in certain reservoirs.

Not all countries have the same resources to cope with these new hazards. It is essential to strengthen capacity, particularly by raising awareness of the new risks to which older dams are now exposed due to extreme climatic events - risks that were not anticipated at the time of their original design. This is especially important in less developed countries. [AB]

3.3. Biodiversity crisis

The IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) is an international organization established to strengthen the interface between science and policy regarding biodiversity and ecosystem services. It published a global assessment report in 2019 [28] , from which the quotes presented in this section are taken.

The IPBES emphasizes that "*Nature is essential for human existence and good quality of life. Most of nature's contributions to people are not fully replaceable, and some are irreplaceable. Nature plays a critical role in providing food and feed, energy, medicines and genetic resources and a variety of materials fundamental for people's physical well-being and for maintaining culture*". Two key figures: *"more than 75 per cent of global food crop types [. . .] rely on animal pollination*"; "*Marine and terrestrial ecosystems are the sole sinks for anthropogenic carbon emissions, with a gross sequestration of [. . .] some 60 per cent of global anthropogenic emissions*".

"*Nature across most of the globe has now been significantly altered by multiple human drivers, with the great majority of indicators of ecosystems and biodiversity showing rapid decline. Seventy-five per cent of the land surface is significantly altered, 66 per cent of the ocean area is experiencing increasing cumulative impacts, and over 85 per cent of wetlands (area) has been lost."*

"*Human actions threaten more species with global extinction now than ever before. An average of around 25 per cent of species in assessed animal and plant groups are threatened, suggesting that around 1 million species already face* *extinction." "For terrestrial and freshwater ecosystems, land-use change has had the largest relative negative impact on nature since 1970, followed by the direct exploitation, in particular overexploitation, of animals, plants and other organisms, mainly via harvesting, logging, hunting and fishing."*

"Goals for conserving and sustainably using nature and achieving sustainability cannot be met by current trajectories, and goals for 2030 and beyond may only be achieved through transformative changes across economic, social, political and technological factors."

"*Nature can be conserved, restored and used sustainably while other global societal goals are simultaneously met through urgent and concerted efforts fostering transformative change."*

The IPBES proposes the following table as a summary of possible actions to promote freshwater biodiversity.

Approaches for sustainability	**Possible actions and pathways to achieve transformative change** Key actors: (IG=intergovernmental organizations, G=Governments, NGOs =non-governmental organizations, CG=citizen and community groups, IPLC = indigenous peoples and local communities, D=donor agencies, SO= science and educational organizations, P=private sector)
Improving freshwater management, protection and connectivity	• **Integrating water resource management and landscape planning**, including through increased protection and connectivity of freshwater ecosystems, improving transboundary water cooperation and management, addressing the impacts of fragmentation caused by dams and diversions, and incorporating regional analyses of the water cycle (e.g., IG, G, IPLC, CG, NGO, D, SO, P) {6.3.4.6, 6.3.4.7} {B1}. • **Supporting inclusive water governance,** e.g., through developing and implementing invasive alien species management with relevant stakeholders (e.g., IG, G, IPLC, CG, NGO, D, SO, P) {6.3.4.3} {D4}. • **Supporting co-management regimes for collaborative water management** and **to foster equity** between water users (while maintaining a minimum ecological flow for the aquatic ecosystems), and engaging stakeholders and using transparency to minimize environmental, economic and social conflicts {D4}. • Mainstreaming practices that **reduce soil erosion, sedimentation and pollution run-off** (e.g., G, CG, P) {6.3.4.1}. • **Reducing the fragmentation of freshwater policies** by coordinating international, national and local regulatory frameworks (e.g., G, SO) {6.3.4.7, 6.3.4.2}. • **Increasing water storage** by facilitating groundwater recharge, wetlands protection and restoration, alternative storage techniques and restrictions on groundwater abstraction. (e.g., G, CG, IPLC, P, D) {6.3.4.2} {B1, B3}. • **Promoting investment in water projects** with clear sustainability criteria (e.g., G, P, D, SO) {6.3.4.5} {B1, B3}.

Fig. 6
IPBES, Approaches for sustainability and possible pathways to achieve transformation change. [28]

Regarding dams specifically, IPBES mentions in Chapter 6 that dams have significant negative impacts on nature - particularly due to the barriers they create and the formation of reservoirs along rivers, which slow water flow. These impacts on nature and society are often not well compensated. However, IPBES also notes that dams can generate new benefits, such as habitats for protected species and refuge areas in the context of climate change.

Three key conclusions can be drawn from these findings:

- The biodiversity crisis is a major issue for humanity, with potentially severe consequences within just a few decades.
- Dams that create barriers and reservoirs along rivers have a major impact on freshwater biodiversity; alternatives should be carefully considered, taking this factor into account.
- Dams can also have positive effects on biodiversity; understanding these benefits is crucial to promoting them.

3.4. Experiences from different countries, affected or not

The case studies listed below provide specific insights on climate change adaptation strategies in different countries. The objective is not to present an exhaustive analysis of climate change effects or national adaptation policies but to share different approaches explored in various contexts.

In *England*, new reservoirs are being planned as part of climate change adaptation efforts. Climate models predict a decrease in water resources in the UK. Initially, it was believed that wetter winters would compensate for drier summers, but recent projections show this is not the case. Additionally, more water must be left in the environment to prevent severe ecological impacts on rivers and groundwater due to climate change. This is particularly relevant in southern England, where many chalk streams are considered ecologically significant habitats at both national and international levels. One key objective is to reduce withdrawals from chalk aquifers and the rivers fed by them. However, there is water available in rivers during winter, which can be stored in reservoirs and released for use in summer. These considerations support the development of off-river reservoirs, which are filled in winter and emptied in summer. Several such reservoirs are currently being proposed. [JW] and [71]

In *Australia*, between September 2015 and April 2016, Tasmania experienced an extreme drought, the most severe in 50 years. The situation worsened in December 2015 when the Basslink cable failed, preventing electricity imports from mainland Australia. By April 2016, water reserves had dropped to their lowest level (12.5% of total capacity). At the same time, wildfires devastated several regions of the island. Then, in June 2016, the situation reversed abruptly, with historic floods in northern Tasmania. Crisis management included several components: electricity production control using climate and hydrological models, voluntary industrial demand reductions, reactivation of gas-fired power plants, emergency deployment of 200 MW of diesel power, water quality and biodiversity monitoring, and wildfire prevention plans. These responses relied on prior preparedness measures. [RH].

In *Brazil,* the challenges related to climate change are diverse. From 1950 to 2010, hydropower dams in Brazil were built with large reservoirs for electricity generation. Since 2010, environmental considerations have led to the approval of only run-of-river hydroelectric dams. Over the past 20 years, Brazil has seen significant development of solar and wind energy. Now, historical large reservoirs compensate for the intermittency of solar and wind power, but they are reaching their capacity limits. There is a growing need for new reservoirs and pumped-storage hydropower (PSH) facilities. Additionally, droughts and floods have become more severe and frequent. For example, the floods of 2023 and 2024 in the coastal rivers of Rio Grande do Sul highlight this trend. BCOLD and the Brazilian National Academy of Engineering have issued a position paper calling for the construction of large multi-purpose reservoirs. [FM]

In *Canada*, electricity production is expected to increase after two decades of relative stagnation, leading to the development of wind, solar, and hydroelectric power plants. While Canada has abundant water resources, some regions experience water scarcity and rely on reservoirs for irrigation. Climate change in these areas is prompting discussions on changing crop patterns to adapt to new conditions. [PR]

In *China*, PSH are meant to play a very significant role. At present, coal-fired power generation accounts for nearly 60% of China's electricity supply, and the power industry contributes approximately 40% of the country's total carbon emissions. According to research, by 2035, China's installed capacity for wind and photovoltaic power could reach 3 to 3.8 TW, with a total storage capacity demand of 600 to 750 GW. Numerous PSH projects are underway and, by the end of 2023, the installed capacity reached 50.94 GW and 179 GW is under construction. [58]

Iran faces significant challenges due to climate change. The country is experiencing a notable decline in annual precipitation, prolonged droughts, and more frequent heatwaves. At the same time, sudden floods caused by intense rainfall on arid soils are becoming increasingly common.Due to irregular water resources, Iran has invested heavily in reservoir construction. However, many dams are now experiencing reduced water inflows, including Zayandeh Rood, Karkeh, Dez, Latyan, Karaj, Karoon 4, and Karoon 3. This has significant consequences for agriculture, electricity production, and drinking water supply. Other challenges include accelerated sedimentation in reservoirs and, for at least one of these dams, increased difficulty in managing sudden floods. Additionally, rivers, lakes, and wetlands are drying up, notably Lake Urmia, once the largest saltwater lake in the Middle East. Some cities are also experiencing subsidence issues. [AHN]

France has undertaken a comprehensive effort to prepare for future climate conditions and anticipate necessary adaptations. Climate scenarios have been developed to assess changes in climate and water demand. A particularly notable finding is the evolution of water consumption, largely driven by irrigation needs. Between 2020 and 2050, under the most unfavorable climate scenario (RCP8.5) with a dry spring and summer, water consumption could increase by 102% without policies promoting water conservation, and by 72% if appropriate public policies are implemented.Only a “disruptive” scenario (including a 50% reduction in meat consumption, a major shift in agricultural practices, widespread wastewater reuse, and reduced material consumption) would limit the increase in water consumption to +10% by 2050 under the worst climate conditions. This analysis suggests that major imbalances between water demand and availability should be expected by 2050, particularly in dry spring and summer scenarios.

India experiences highly diverse climatic conditions, with the summer monsoon playing a crucial role and exhibiting significant variability across different timescales. In recent years, the country has faced an increasing number of extreme weather events, such as the Teesta River GLOF in 2023, the flash flood in Chamoli district in 2021, and the severe floods and landslides in Uttarakhand in 2013 and Kerala in 2018. Additionally, repeated heatwaves and droughts have underscored the need for better climate resilience. In response, climate change projections have been developed for 2060 and 2100, led by researchers including Devendra Kumar Sharma and IIT, Ropar. These studies emphasize the importance of long-term adaptation strategies, including water storage through both small and large reservoirs, crisis management planning for climate disasters such as floods, heatwaves, and cyclones, as well as the interconnection of watersheds. Floodplain mapping, research on waterborne diseases, desalination projects, and the promotion of climate-resilient agricultural practices are also identified as key measures. These are not merely future recommendations - some adaptation actions are already being implemented. [DKS]

In *Japan*, flood risks are intensifying, leading to a growing focus on multipurpose reservoir management by integrating flood storage capacity into existing dams. To minimize the impact on hydropower generation, flood storage capacity is only activated when flood warnings are issued, achieved through the preemptive lowering of reservoir levels. For the remainder of the year, the full capacity is used for hydropower production. [TF] [TS]. Beyond flood management, Japan is also closely monitoring the effects of rising temperatures on water resources. Changes in snowmelt and precipitation patterns in mountainous regions are disrupting river flow regimes, affecting irrigation schedules for agriculture. Higher temperatures are increasing evapotranspiration, leading to greater water demand. Reservoirs are becoming more susceptible to eutrophication, while river water is warming in autumn, which negatively impacts aquatic ecosystems.

Morocco has experienced six consecutive years of low precipitation, leading to underfilled reservoirs that can no longer meet their intended demands. In response, the country has adopted a strategy to supply most major cities, including inland cities like Fez and Marrakech, with desalinated water, using renewable energy sources. The cost of desalination is expected to decrease to approximately €0.40/m^3 by 2030. Dams will continue to be used whenever possible, particularly for irrigation, as long as their storage capacity is not lost to sedimentation. However, hydroelectric production is expected to decline significantly. The role of dams is evolving, with a greater emphasis on flood protection, energy storage for renewables (PSH), and groundwater recharge in arid and semi-arid regions. Irrigation and drinking water will remain primary uses, given the significant infrastructure dedicated to these purposes. Many small dams have been built, particularly in semi-arid regions, to support irrigation, livestock water supply, and flood protection. However, declining water inflows, more intense floods, and increased sedimentation could render some of these small dams ineffective. In southern Morocco, alternative water resource mobilization should be considered. In addition to exploiting groundwater when available, potential solutions include brackish water treatment and atmospheric moisture condensation. This already challenging situation is further exacerbated by rapid urbanization, which leads to increasing water and electricity consumption. While water resources are declining, demand continues to rise. The solution lies in desalination combined with renewable energy sources. [AC]

In *Romania*, Apele Romane, the national water management authority, operates 125 large dams, while Hidroelectrica, the national hydropower company, operates 119 dams. According to report Q108-R10, water demand has steadily declined since 1990, from 20 km^3/year to approximately 8 km^3/year today. This reduction is attributed to structural economic adjustments, including the decline of industrial activity, the closure of non-viable irrigated areas (shrinking from 2 million hectares to 800,000 hectares), the implementation of water meters and usage fees, and leakage reduction initiatives. According to this report, the future role of dams needs to be redefined. There is now greater potential for flood protection and climate change adaptation, as both droughts and floods are expected to intensify. However, the decline in water consumption has significantly reduced revenue for dam operators, limiting their ability to take action. Q108-R10 also highlights the impact of sediment transport on reservoirs. Some dams are rapidly losing their useful storage capacity, while others are experiencing downstream erosion at their bases, posing a safety risk for large structures.

In *Slovenia*, Climate change is manifesting through rising annual average temperatures (+2°C since the 19th century), irregular precipitation, and extreme weather events such as floods and droughts. In August 2023, torrential rainfall concentrated over a 10-hour period saturated the soil, leading to the most severe floods in the country's history. The damage affected 176 out of 212 municipalities, with estimated losses of €9.9 billion. This event highlighted the positive contribution of certain flood management infrastructures. In 2018, a dry detention basin combined with an improved flood discharge channel was constructed upstream of Ljubljana. This system proved highly effective during the 2023 floods, preventing major flooding in the capital. On the Sava River, a cascade of five dams - built between 1993 and 2017 for both hydropower and ecosystem management - helped limit flood impacts through an adaptive management strategy, involving preemptive reservoir drawdowns and the controlled filling of floodplain areas. However, declining winter snowfall is reducing summer river flows, worsening water shortages. Although new dams have been proposed to enhance water retention capacity, strong public opposition continues to hinder these projects. [MK].

In *Switzerland*, glacier retreat is already underway. Since glaciers naturally function as water reservoirs, their shrinking volume will lead to a decline in stored water resources. To compensate for this loss, projects are being considered to increase reservoir storage capacity, allowing for snowmelt water to be captured in spring and gradually released throughout the year or over multiple years to mitigate drought periods. Several major dam-raising projects are currently underway or under study to enhance storage capacity. [AS]. One significant example is the Gornerli project, which is detailed in report Q108-R2 [2].

In *Tunisia*, dam reservoirs are typically designed to have a storage capacity approximately twice the volume of annual inflows. This sizing approach results from optimized calculations of “regulated volume”, adapted to the semi-arid climate, where high variability in water availability necessitates an interannual management strategy, allowing surplus years to compensate for drier years. However, this approach presents inherent drawbacks. Since nearly all river flows are captured, sediments accumulate rapidly, leading to a loss of reservoir capacity over time. Additionally, long water retention periods contribute to significant evaporation losses, which can represent a substantial portion of available water resources. Although Tunisia is not a vast country, it experiences considerable climatic variability across its territory. As a result, water transfer infrastructure has been developed to move water from wetter regions to areas facing resource deficits. Some of these reservoirs and interconnections serve as strategic reserves for prolonged droughts.

In Vietnam, the Mekong Delta has experienced successive droughts, which, combined with various factors affecting river flows and excessive groundwater pumping, have led to saltwater intrusion into freshwater aquifers. To address this issue, the government has prioritized increasing freshwater storage capacity, including the construction of off-river reservoirs as a mitigation measure. [MHTK]

4. GENERAL PRINCIPLES FOR ADAPTATION

4.1. Thinking ahead, exploring options, engaging in dialogue

The Netherlands is among the countries most exposed to climate change due to a very specific reason: a significant portion of its territory lies below sea level. The potential scenarios for sea level rise have major - if not existential - consequences for the country. Ongoing discussions in the Netherlands provide valuable lessons that can be applied in many other contexts. These reflections are outlined in the report "Room for Sea Level Rise" [16], which focuses on long-term horizons (2100 and 2200) and assumes pessimistic projections of a 2-meter sea level rise by 2100 and 5 meters by 2200. A consortium of researchers, experts, and decision-makers has proposed three conceptual adaptation strategies, each representing a distinct approach, while also identifying cross-cutting challenges. The three adaptation strategies are:

Accommodate: A gradual adaptation of land use and infrastructure to coexist with rising sea levels. This includes floating housing, salt-tolerant crops, and flood-resistant infrastructure. Key economic regions, such as the Randstad, would be protected for as long as possible, while a planned retreat to higher ground would be implemented over the long term.

Protect: A strategy focused on reinforcing existing infrastructure, including levees, dams, and pumping systems. It also involves expanding sand replenishment operations to maintain the coastline. Specific measures include closing or modifying estuaries with barriers, pumps, and temporary storage areas to manage river flooding.

Seaward: The construction of a large offshore coastal lake, enclosed by an external levee, to temporarily store river flows and reduce salinization (see Fig. 35). This approach would reduce the need for reinforcing inland infrastructure, but it would require significant investments to build and maintain these new structures.

The cross-cutting challenges are as follows: each approach requires vast areas for infrastructure, which must be planned now to keep options open for future generations; freshwater supply will become more difficult due to saline intrusion; implementation and maintenance costs will require major investments over several decades.

This work highlights several key themes:

- taking into account distant time horizons (in this case, 2200) with pessimistic scenarios to ensure options remain open from today;
- broadly exploring different approaches, as the most intuitive strategy ("Protect," gradually increasing the height of levees) is not necessarily the right one, since its adaptability to future conditions is uncertain (its feasibility beyond a 3-meter rise has not been confirmed);
- adopting a holistic approach that considers all societal aspects;
- ensuring a transparent process that involves societal stakeholders to develop shared strategies.

4.2. Key points

4.2.1. *Adaptation requires reducing vulnerability*

Vulnerability refers to the dependence of societies on the availability of water resources, electricity supply, and exposure to the effects of floods or rising sea levels.

It is not enough to simply increase control measures - such as mobilizing water resources, producing and securing electricity, or reducing water levels and flow rates in flood-prone areas. Efforts must also be made to reduce vulnerability by:

- Promoting water-use efficiency, particularly in regions where climate models indicate a decline in water resources or an increase in drought duration.
- Managing electricity demand and reducing peak demand.
- Decreasing flood vulnerability.

Droughts are a central issue. The case of Morocco (§3.6) is not isolated: in many regions, the annual volume of water resources is no longer sufficient to meet demand. It may be tempting to construct more storage reservoirs - often a direct request from both local populations and policymakers - but this is not always the best option. The difficult but necessary effort to reduce water demand is often required.

Regions affected by droughts have developed adaptation strategies (e.g., [66]). In general, these strategies follow several key approaches:

(a) Measurement and data-driven assessment:

- Improving quantification of water resources and consumption by sector, including environmental needs - a challenging but essential task.
- Establishing future projections at appropriate time horizons, such as 2050, 2100, and beyond for major infrastructure projects.
- Acknowledging the uncertainty margins in these assessments, which can gradually be reduced through instrumentation and knowledge acquisition.

(b) Developing water-sharing rules:

- Establishing a strategy to balance current and future water resources with demand.
- Implementing governance frameworks that enable enforcement, monitoring, and adaptation of water-sharing policies.

(c) Enhancing water-use efficiency (demand reduction):

- Preventing waste and reducing losses.
- Implementing water conservation programs across various sectors.

- Encouraging agricultural adaptation by promoting practice changes that align with current and future conditions.

(d) Improving resource mobilization:

- Utilizing storage solutions discussed in §4.3.
- Interconnecting reservoirs to allow resource sharing between water-surplus and water-deficit regions.
- Incorporating measures for water quality management.

(e) Crisis preparedness:

- Developing crisis scenarios and corresponding response measures.
- Establishing a crisis management unit.

Thus, for adapting to drought challenges, water resource mobilization is just one aspect of the broader strategy. Improving water-use efficiency often creates room for adaptation in resource management.

This conclusion also applies to adaptation measures for floods and sea level rise: efforts to reduce vulnerability must go hand in hand with measures to enhance protection and resource mobilization.

4.2.2. *Adaptability requires flexibility*

This section focuses on dams and reservoirs rather than protective levees.

It is self-evident that in a context of uncertainty, adaptability requires a degree of flexibility - the ability to make the best use of a structure, or a system of structures, under various resource availability scenarios and demand conditions.

Flexibility at the system level

Electricity

For electrical systems, it is necessary to diversify energy sources and limit exposure to climate variability. This strengthens the importance of regional interconnections, though these may have disadvantages in terms of energy sovereignty. It is essential to evaluate the impact of prolonged droughts - ranging from several weeks to several years - on hydropower production and to have strategies in place to manage such situations. Likewise, the impact of low sun-light and weak wind periods on solar and wind power generation must be assessed, with security storage reserves available in hydroelectric reservoirs as a potential solution.

Water supply

The same logic applies to water supply systems.

Interconnections between reservoirs or regions, where feasible, increase operational flexibility. This approach has been implemented in many countries and is exemplified by the São Francisco transfer project in Brazil, commissioned in 2022, which secures the water supply for the Northeast region (1 million km^2, 28% of the population, but only 3% of the water resources). The project consists of two canals (260 km and 217 km) with a design flow of 127 m^3/s. [FM]

Interconnections are widely used in regions where water resource availability varies significantly across different parts of the territory, and some areas experience chronic deficits. Examples include: Algeria, where water is transferred from mountainous areas to populated zones and central plateaus (1.5 km^3 per year) ; California, where water from northern rivers is transported to major southern cities (3 km^3 per year); China, where the South-North Water Transfer Project channels water from the Yangtze River (5 km^3 in 2022, estimated to reach 15 km^3 per year by 2030) ; Morocco, which is developing a major water transfer project from the North to the South (just under 1 km^3 per year) ; Tunisia, where water is transferred from the coast and north-west regions to Tunis and agricultural areas in the west and center of the country.

Redundant water sources provide security margins in cases where a structure becomes unavailable due to pollution of the reservoir or physical incidents affecting the dam.

In some cases, supplementary water sources that do not depend on rainfall have been effectively implemented, including recycled wastewater, groundwater extraction, and desalination. An example of this approach is the Western Australia Water Corporation's "Integrated Water Supply Scheme" (IWSS) [65], which supplies over 300 hm^3 annually through a combination of desalinated seawater, groundwater, surface reservoirs, and aquifer recharge using treated wastewater.

Flexibility at the project level

Electricity

For hydroelectric plants, flexibility refers to the ability to optimize the use of stored resources, allowing for shorter response times, a wider range of production variations, and longer storage durations.

The demand for flexibility is significant. The International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) predict that installed hydropower capacity will need to double by 2050 to support the integration of variable renewable energy sources and the decarbonization of power systems. A portion of this electricity will need to come from existing dams, either by increasing the capacity of current hydroelectric plants or by adding hydroelectric production to previously non-powered dams. [FLe] These adaptations have technical implications (on machinery and hydraulic circuits) as well as environmental implications (effects on downstream river ecosystems).

This evolving energy landscape and the uncertainties surrounding future developments are changing the way future hydropower projects are conceived.

Small hydropower plants, particularly those without storage reservoirs or with only small reservoirs, must be carefully assessed. They are, on average, more vulnerable to climate change impacts, especially in regions where climate change is increasing the frequency and intensity of droughts and low-flow periods. [MHTK] Their ecological footprint per MW stored or per kWh produced is also often higher than that of larger-scale projects.

Run-of-river power plants are losing economic viability in many geographic contexts (though not everywhere), especially when they lack upstream flow regulation through a reservoir ensuring annual and interannual stability. On unregulated rivers, these plants primarily provide base-load electricity generation, historically in combination with thermal power plants that ensured supply security during low-flow periods. With the rise of cheaper alternatives like solar and wind power, and the decline in thermal generation, run-of-river hydropower now faces increased scrutiny. These plants must now demonstrate an ability to provide dispatchable electricity, typically in day/night regulation alongside solar power, or offer sufficiently valuable ancillary services (such as frequency regulation and spinning reserves) to complement solar generation.

As a result, the economic viability of run-of-river plants on unregulated rivers is becoming increasingly difficult to justify, especially if low-flow periods significantly reduce available firm energy. [PR]. However, run-of-river plants remain relevant in several contexts: in regions where hydropower remains cheaper than wind or solar power ; in large power grids, where they contribute to diversifying intermittent generation sources ; on rivers where upstream storage (or favorable hydrological conditions) sufficiently limits the frequency and severity of low-flow periods.

Conversely, hydropower plants with reservoirs are becoming more valuable, thanks to their ability to store energy and compensate for the intermittency of solar and wind power. To fully leverage these advantages, installed capacity must allow for daily regulation, meaning design flow rates must be significantly higher than the river’s average flow - otherwise, no meaningful regulation is possible.

Flexibility also requires frequent variations in turbine flow rates. For hydroelectric plants, increasing flexibility involves modifications to turbines, generators, auxiliary systems, and possibly hydraulic circuits. Additional flexibility can also be achieved through the integration of battery storage. Advances in this field are numerous and exceed the scope of this report, but insights from the XFLEX project [36] may provide valuable lessons.

From a river management perspective, it is essential to ensure that flow variations imposed downstream are not excessively harmful to the environment. This can be mitigated by using intermediate storage before releasing water back into the river.

Water supply

For dams intended for water supply (drinking water, industrial water, irrigation water, and water for biodiversity), flexibility refers to the ability to adapt to future scenarios of water availability and demand.

Future climate conditions are often associated with greater variability, including stronger floods and more frequent droughts. In general, the greater the storage capacity, the better the ability to manage temporary imbalances between natural inflows and water demand. However, in certain climates, two side effects must be carefully considered: larger reservoirs trap more sediment (with potential negative consequences downstream), and larger reservoirs are more exposed to evaporation losses. In such cases, off-river storage solutions (§5.1) may offer suitable alternatives. The increase in storage capacity is discussed in §4.3.

Flexibility also depends on operational management. For a given storage volume, there are often significant opportunities to optimize reservoir operations, particularly by using predictive models to anticipate water inflows and water demand, especially for agriculture. This requires reliable data and appropriate models (§4.7). Climate models can provide some degree of seasonal climate forecasting (several months in advance). As long as it does not compromise dam safety, flexible reservoir management strategies could be considered, such as allowing temporary overfilling (beyond normal levels) in anticipation of a dry year. [TF]

For dams with ecosystem functions (such as those supporting biodiversity), flexibility also relies on on-site monitoring of ecosystem health and the alignment between available resources and ecological needs. This has been illustrated in the case of droughts in Tasmania, Australia (§3.4).

Flood protection

For dams designed for flood protection, flexibility consists of optimizing efficiency based on the available storage volume.

The first option is to increase the flood storage capacity, for example, by raising the structure, as illustrated by the case of the Lauch Dam in Q108-R6. When the reservoir volume remains unchanged, other options include:

- Increasing the acceptable downstream flood discharge, so that storage is only activated beyond a higher flow threshold.
- Adopting an adaptive management approach before the flood by implementing preventive drawdowns, as seen in Japan (§3.4), and adjusting dam operations during the flood based on real-time forecasts, as demonstrated in Q108-R22 with the Stânca-Costeşti Dam. Both approaches require reliable flood forecasting systems capable of predicting conditions several hours or even days in advance.

For dry dams, the flexibility described above may require the inclusion of gates in bottom outlets. This adds complexity and introduces a risk of operational errors in gate management, but it significantly improves efficiency. To prevent disputes with downstream communities, it is essential to establish clear and precise flood operation protocols that define gate operation procedures based on input parameters such as water level and discharge rate.

Multi-purpose Reservoirs

For multi-purpose reservoirs, flexibility involves the ability to adjust the allocation of water use over time. This may require modifications to infrastructure, such as raising dam height, and can also have financial and contractual implications, particularly if it involves reducing hydropower production to optimize other uses, such as energy storage, mitigating the impacts of droughts and floods, or supporting ecological functions.

In times of crisis, reservoirs can play a crucial role in enhancing societal resilience by ensuring water availability during severe droughts, supporting wildfire suppression efforts, and even serving as refuge areas during heatwaves. To ensure that this resilience function is effectively available when needed, it may be necessary to temporarily limit other uses, ensuring that the ultimate reserve remains accessible.

4.3. Fresh water storage

4.3.1. *Current overview*

Freshwater is scarce. The main quantities, in terms of stocks and flows, are known, albeit with a fair degree of uncertainty [32][33][34]. Water is stored on continents in various forms: surface water, soil moisture and peatlands, mountain glaciers, permafrost and underground ice, and groundwater. On average, 13 km^3 of water is present in the atmosphere at any given time.

These reserves must be considered in relation to their average residence time: 1,500 years for groundwater, 30 years for freshwater lakes, 1.8 years for soil moisture, 17 days for rivers, and 9.5 days for the atmosphere. Thus, in terms of annual flows, the key figures are presented in Table 1 below:

Table 1
Inventory of available freshwater volumes, in annual flow terms, as taken from [33]

COMPARTMENT	VOLUME (KM^3)	AVERAGE RESIDENCE TIME	ANNUAL FLOW (KM^3/ YEAR)
Antarctic ice sheets	25 million	10,000 years	2 600
Greenland ice sheets	3 million	5,000 years	600
Mountain glaciers	80 000 à 200 000	100 to 300 years	800
Permafrost	22 000		
Groundwater	15(from 7 to 330 million)	1,500 years	10 000
Freshwater lakes	176 000	30 years old	5 900
Soil moisture	122 000	1.8 years	70 000
Inland seas	105 000		
Water in the atmosphere	12 700	9.5 days	486 000
Water in rivers	1 700	17 days	36 800
Water in living cells	1 100	a few hours	

It is useful to highlight two additional figures related to this table:

- Each year, approximately 4,600 km^3 of water is consumed (source: [35]).
- The ICOLD Global Register indicates that the gross storage volume of reservoirs is 9,000 km^3. A significant fraction of this volume has been lost due to sedimentation, while another portion is unusable ("dead storage volume"). The usable storage volume is estimated to be around 5,000 km^3 or slightly more. Although this represents only a small fraction of the total volume of freshwater lakes, its much shorter residence time means that it accounts for a large proportion of the annual water flow

4.3.2. *Increasing storage when possible*

It is necessary to increase water storage capacity to enhance the usable annual flow.

This need arises because storage is a key instrument of flexibility (as discussed in §4.2.2). Despite essential efforts to reduce vulnerability §4.2.1, including improving water efficiency and conservation, these measures alone will not be sufficient in many parts of the world. As Felipe Lazaro from the World Bank states*, "*Water and water storage are essential elements for climate change adaptation, emission mitigation, and increasing resilience to uncertainty. These considerations are crucial to promoting green, resilient, and inclusive development and fulfilling commitments under the World Bank Climate Change Action Plan [...] As long-life infrastructure, [dams and reservoirs] provide substantial benefits to society by enabling water storage for drinking water supply, irrigation, electricity production, and flood mitigation.*" [FLa]

These conclusions have been supported by quantitative studies for Southern Europe, covering the entire northern Mediterranean coastline (case study CS9 of [24]). This region is already experiencing, and will continue to experience, a significant decrease in mean annual river flows and increased variability in flow patterns. A study of 16 major watersheds evaluated the impact of climate change on water resources. The results indicate that expanding storage capacity mitigates the reduction in water availability and reduces uncertainty in climate projections.

National Climate and Development Reports (CCDRs) provide insight into country-specific water management priorities. According to a 2024 World Bank analysis, increasing water storage capacity for hydropower, irrigation, and drinking water is the most frequently mentioned water sector action in the 52 CCDRs examined. Investment priorities vary by country. Some key interventions include: Expanding water infrastructure and multi-purpose water storage (Argentina, Iraq, Malawi, Kenya) ; Protecting groundwater resources and implementing managed aquifer recharge (Bangladesh, Ghana, Morocco) ; Investing in pumped-storage hydropower (Jordan) ; Developing rainwater harvesting systems (Ghana) ; Enhancing water distribution network storage (Jordan) ; Revising reservoir operations to better balance sectoral water demands (Kazakhstan) ; Diversifying water sources (Malawi) ; Implementing nature-based storage solutions (Kazakhstan, Philippines) ; Conserving and restoring natural water storage (Romania, Paraguay). All CCDRs emphasize the importance of enhancing the adaptability of water storage systems in response to increasing hydroclimatic variability and exploring ways to combine built infrastructure with nature-based solutions. [FLa]

However, as G. Annandale points out, "*As hydrologic variability increases, reliability will decrease. The only way to deal with this when using rivers to produce power and supply water is to increase reservoir storage. [. . .] The dilemma is that global storage is currently decreasing more rapidly due to reservoir sedimentation than what we are adding due to the construction of new dams*." [GA]

This observation reinforces the need to consider new storage solutions in many regions worldwide. This report examines storage options in surface reservoirs

*Translated from French

and, to some extent, aquifers (both shallow and deep). However, there are general limitations to storage, which are briefly discussed in the following section.

4.3.3. *The limitations of storage in reservoirs*

Societal Limits of Surface Reservoir Storage

Not all societies are willing to accept the construction of new water infrastructure. The arguments against new dams and reservoirs are well known:

- Dams disrupt natural ecosystems and, in some cases, can have negative social impacts, such as the submersion of land within reservoirs and the reduction of downstream river flows.
- Dams perpetuate an outdated model considered obsolete and, as such, may hinder adaptation. For example, when dams support irrigation in drought-prone areas, opponents argue that priority should be given to changing agricultural practices instead.

It must be acknowledged that dams, levees, and reservoirs are large-scale infrastructures that significantly impact both ecosystems and societies. These impacts must be properly considered through environmental and social impact assessments, as well as stakeholder consultations. This necessity is well recognized within the profession, as evidenced by documents such as the ICOLD “Position Paper on Dams and the Environment” [23] and the Hydropower Sustainability Standard initiative [38].

The debate on these issues is not always based on scientific data or rigorous methodologies. The dam engineering profession holds that, in some cases, opposition is driven more by systematic resistance than by objective, case-by-case analysis. Regardless of individual perspectives, this societal limitation must be accounted for in the present context. However, this may change in the future due to the increasing need for water storage worldwide and continued improvements by the dam industry in addressing environmental and social concerns.

Environmental Limits of Surface Reservoir Storage

The construction of a surface reservoir inevitably comes at the expense of certain aspects of biodiversity (§3.3). Additionally, a reservoir built for water supply - particularly for irrigation - means that large volumes of water will be consumed and no longer available for natural ecosystems and local populations. The case of the Aral Sea is a well-known example of this issue. A hydropower reservoir, on the other hand, does not consume water (aside from evaporation losses) but alters the river’s natural flow regime, leading to environmental and social impacts - though generally less severe than those caused by irrigation reservoirs.

As a result, every new reservoir involves a trade-off between its benefits (contribution to adaptation) and its costs (negative impacts that may hinder adaptation). In some cases, and strictly from the perspective of human adaptation to climate change, it may be preferable not to build new reservoirs.

Physical Limits of Surface Reservoir Storage

It may be tempting to increase reservoir storage capacity to allow for multi-year water storage. Some countries with highly variable and deficit hydrological conditions (such as Tunisia, §3.4), have adopted a strategy of large-capacity reservoirs, typically storing twice the volume of annual inflows. This has allowed Tunisia to stabilize its water resources compared to the natural variability of wadis, ensuring a more reliable water supply. However, this solution is not necessarily sustainable due to increased sedimentation and not always adaptable to future climate conditions. Future water scarcity risks and high evaporation rates could undermine this strategy. Therefore, the long-term reliability of such reservoirs must be carefully assessed under projected climate scenarios, with particular attention to sedimentation dynamics.

Off-river storage and interconnections provide alternative solutions that reduce or eliminate exposure to sedimentation and, in many cases limit evaporation losses thanks to a greater reservoir depth (see §5).

Physical limits of storage in underground reservoirs

Given the data in §4.3.1, it is tempting to consider expanding underground water storage in aquifers already in use. This approach presents a significant theoretical advantage: water stored underground does not evaporate and is largely protected from pollution. These considerations have led to the development of subsurface dams and aquifer recharge technologies, particularly in arid regions.

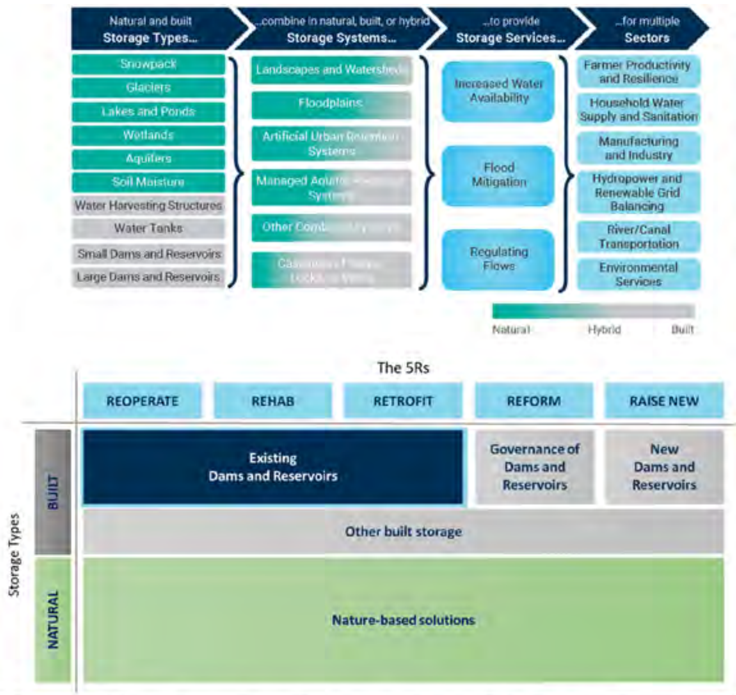
However, experience with these technologies has revealed various physical and economic limitations, as discussed in §5.5. These challenges explain why the large-scale deployment of underground storage remains limited. Nevertheless, the total potential storage volume in soils and rock formations is significant. Future technological advancements or improved understanding of physical mechanisms may lead to new possibilities for underground water storage.

4.3.4. *Storage strategies*

Diversifying Approaches

Given current and future storage needs, and considering the various limitations outlined above, it is reasonable to adopt a diversified approach.

The World Bank promotes a broad strategy known as the “5 Rs” approach [23]. In this framework: (a) Reservoirs associated with dams represent one of several storage solutions required, and (b) Constructing new reservoirs is only one option among others and should be explored alongside efforts to optimize existing infrastructure. This approach is illustrated in the following diagrams.



"Reoperate	Modify reservoir operations (or the management of a group of reservoirs) to improve efficiency in meeting demand.
"Rehab	Restore artificial or natural reservoirs to recover their capacity or extend their service life.
"Retrofit	Increase storage capacity (e.g., dam raising), add new functions, or upgrade facilities (e.g., hydroelectric generation, floating solar PV).
"Reform	Invest in institutional frameworks to improve storage management.
"Raise new	Develop new reservoirs, whether natural or constructed, surface or underground, large-scale or small-scale, centralized or distributed.

Fig. 7
The “Rs” of the Bank [29]

Regarding dam reservoirs, ICOLD Bulletin 200 [23] recommends prioritizing the improvement of existing infrastructure - through operational optimization and efficiency improvements - before considering more costly options such as dam raising, new dam construction, water transfer projects, or watershed reforestation initiatives.

Specific considerations for hydropower storage

There remains significant potential for new hydropower projects in many countries worldwide. This is notably the case in Africa, where less than 10% of the hydropower potential has been utilized. Among these, projects with reservoirs will generally offer greater adaptability than run-of-river projects, when the latter lack upstream reservoir regulation. However, it is reasonable to expect that hydropower projects will generally be outnumbered by wind and solar projects in future energy development strategies.

For example, Report Q108-R20 illustrates India’s renewable energy strategy, which emphasizes a mix of hydropower, wind, and solar energy development

Table 2
India’s renewable energy development strategy, Q108-R20

	CURRENT	**2030**	**2047**
Hydropower (excluding PSH)	47 GW	55 GW	87 GW
PSH	4 GW	19 GW	116 GW
Solar		293 GW	1200 GW
Wind		100 GW	436 GW

In some countries particularly well-suited for hydropower due to favorable hydrological and topographical conditions, hydropower will play a leading role in the future energy mix. In many other countries, however, its role will be more complementary, supporting other energy sources. This shift may lead to a redefinition of hydropower reservoirs, focusing on two key functions with high societal value:

- Facilitating the deployment of intermittent renewable energies by providing storage capacity and ensuring grid stability services.
- Accommodating other water uses that contribute to climate adaptation and support broader societal needs.

As stated in Q108-R20 regarding India’s strategy, “*[...] by 2047, India needs to construct around 1000 dams. Apart from meeting requirement of energy transition, these high dams with water storage will provide resilience and address environment vulnerability against droughts, mitigate the risk of flooding and reduce the frequency and extent of inundations and development of artificial wetlands. [...]. Increased Dams with reservoir storage capacity will help to tackle hydrologic variability and heightened risk and uncertainty due to climate change*”.

4.4. Limiting floods

4.4.1. *Integrated approaches*

Flood reduction along rivers can be achieved through various approaches, which can be combined:

- At the source, by promoting infiltration (reducing impermeable surfaces and slowing down runoff) and limiting erosion through watershed management. A historical example is Japan, which was almost entirely deforested by the end of the 19th century but is now heavily reforested.
- Along the river, by allowing floodplains to absorb excess water (“dynamic slowing”).
- Through storage in reservoirs to temporarily retain floodwaters.
- By constructing levees to contain floodwaters and protect vulnerable areas.
- Within flood-prone areas, by reducing vulnerability, which includes minimizing human risks and economic exposure in flood zones.

Reservoir storage and levees have demonstrated their effectiveness in numerous cases. However, it is also recommended to implement vulnerability reduction measures and infiltration improvement strategies, as these “no-regret” solutions remain effective regardless of flood conditions.

Near the coast, flooding can result from storm surges and tidal backflow into estuaries and rivers. Limiting coastal flooding and storm surges in rivers near the sea can also be achieved through a combination of measures:

- Coastal and river levees or storm barriers to prevent water intrusion.
- Vulnerability reduction measures in protected areas to minimize damage.
- Water level management techniques within flood-prone areas (see §5.4.1).
- Reservoir storage to regulate the flow of coastal rivers, thereby reducing peak discharges in protected zones.

General considerations on floodwater storage in reservoirs are presented in the next section. Section §5 outlines some new technical solutions that can be used for flood mitigation.

4.4.2. *Additional storage in dams*

In many cases, having storage capacity is an effective measure for reducing peak flood discharges. Three main options are commonly considered:

- Dedicated flood storage within a multipurpose reservoir, where part of the reservoir's volume is allocated to flood control while also serving other functions.
- Dry dams, which remain empty under normal conditions and are specifically designed for temporary floodwater retention. These are sometimes preferred for environmental reasons.
- Temporary flood storage in reservoirs intended for other uses, achieved through preventive drawdowns before anticipated flood events.

The effectiveness of dams and levees for flood protection is evaluated at the point of the protected assets. However, these assessments are not always straightforward. When dams are located far from flood-prone areas, their flood attenuation capacity may be reduced due to concurrent inflows from downstream tributaries.

The design and operation of flood control dams require careful attention to the downstream flood dynamics. The goal is to avoid threshold effects, where a dam transitions suddenly from highly effective flood attenuation to little or no flood reduction at the protected locations. To that end:

- Spillways, which regulate the conversion of maximum inflow into maximum outflow for floods of various return periods, should allow for a gradual increase in the maximum released discharge relative to the maximum inflow discharge. This helps maintain flood awareness among downstream populations.
- For any given incoming flood, the outflow hydrograph should have a controlled, gradual shape to prevent sudden flow increases that could catch downstream communities by surprise.

For dams primarily designed for flood protection, it is useful to explore design solutions that tolerate overtopping (allowing controlled overtopping without structural failure). This requires appropriate protective measures for the dam crest, downstream slope, and toe, ensuring the dam's ability to withstand moderate overtopping events. This approach provides two significant benefits:

- It can prevent the need for sudden and excessive floodgate releases, improving the gradual discharge of floodwaters.
- It offers an additional layer of safety, which is valuable for all dams due to hydrological uncertainties but is particularly relevant for flood protection dams, where spillway capacity is often lower than peak flood discharges.

This topic of controlled overtopping, especially complex for embankment dams, remains an active area of research that requires further technical advancements.

4.4.3. *Keeping in mind the limitations of flood storage*

Dams do not eliminate the effects of floods downstream; rather, they help mitigate them. As a result, major flooding events can still occur despite the presence of dams in a watershed. This has led, in some cases, to legal disputes, from which several key lessons can be drawn [PM]:

- Reliable upstream flood data during an event is crucial for decision-making.
- Clear communication protocols and mutual trust between stakeholders are extremely valuable in managing flood situations.
- Flood management plans should include:
  - Clearly defined objectives, roles, and procedures for operational actions.
  - Stakeholder consultation and transparent communication of the plan, including its limitations.
  - Explicit statements on the use and limitations of flood forecasts to manage expectations.
- If flexibility in flood management is possible, it must be explicitly stated in the plan; otherwise, strict adherence to the plan is necessary.
- Avoid over-promising the benefits of dams in flood events. Instead, communicate residual flood risks to reduce the element of surprise for downstream populations.
- Particular attention should be given to flood mitigation requirements to prevent unrealistic public expectations or demands.
- Public expectations evolve in an ever-changing context, requiring adaptability in risk communication and management strategies.

4.5. Promoting biodiversity

By their very presence, reservoir lakes can contribute positively to biodiversity. For instance, 54% of reservoirs in Slovenia are classified as sites where conservation measures have been implemented due to their ecological significance [MK]. Many artificial lakes are also designated as Ramsar sites of international importance. Additionally, IPBES highlights the positive contributions of reservoirs (§3.3).

Furthermore, operational practices play a crucial role. Proper dam and river management can have significant ecological benefits, as demonstrated by examples from different countries:

- Ensuring water supply during droughts: In Australia, special attention was given to ecological water needs during the 2015–16 drought management (§3.4).
- Improving ecological continuity (for fish migration and sediment transport): In Japan, sediment management practices have positively impacted biodiversity by fostering diverse and favorable habitats [TS].

- Enhancing the quality of released water: Reservoir bottom releases can have negative impacts, such as methane degassing downstream, unnatural water temperatures, and poor biochemical water quality [AH]. The use of multi-level intakes or surface water intakes helps improve water quality at release points [TS].

Promoting and supporting biodiversity is a key component of climate adaptation. This is an important subject, actively explored through research and experimentation, though it is not covered in detail in this report.

4.6. Governance: making the right decisions

4.6.1. *A question of methodology*

The decision-making context

New construction projects, as well as rehabilitation or modification of existing infrastructure, are being discussed and planned worldwide. A key issue is how decisions are made regarding both the necessity of these projects and their overall design [EH].

Decision-making should be based on clearly defined objectives, such as meeting water, electricity, or flood protection needs, enhancing resilience to extreme events, and improving environmental conditions. Given their structural importance, dams and levees should always prioritize their *Contribution to climate adaptation*. In many cases, their role in *Climate mitigation* is also a major objective. The decision-making process must consider all constraints, including *Adaptability* and *Sustainability*.

This raises governance and methodological questions: Who defines these objectives and constraints? Through what mechanisms are they integrated into the decision-making process?

Defining objectives and constraints

The definition of objectives and constraints falls under the responsibility of public authorities.

Experience has shown that there is a broad consensus on the need to integrate the objectives and constraints mentioned in the previous section. This consensus is reflected in ICOLD’s official positions. However, in practice, this consensus is often difficult to translate into concrete action. When a project is developed, short-term economic, financial, and social considerations tend to dominate the decision-making process.

To ensure that these objectives and constraints are effectively taken into account, they must be explicitly and legally mandated by public authorities. As Eric Halpin states: "*Laws and regulations which specify long term requirements for items like sustainability and climate change move these important topics outside the cost effectiveness of decision making, which is likely a must* " [EH]

Working methods

For several decades, the approach based solely on maximizing a single benefit (e.g., minimizing the cost of electricity production or the cost per cubic meter of regulated water) has been abandoned. Multi-criteria analyses have often been used, but they have faced criticism for at least two reasons: (1) Their subjective nature, which makes them susceptible to judgment biases, and (2) Their limitations in incorporating future climate scenarios, making them less adaptable to long-term decision-making. Current recommended approaches involve a combination of:

- Quantitative methods, including risk-informed decision-making (RIDM) and life cycle analyses (LCA and LCSA).
- Holistic approaches, such as environmental and social impact studies, as well as stakeholder consultations, particularly with affected populations.

These methods can be complex and resource-intensive, so their scope should be proportional to the importance of the decision being made. They also retain a degree of subjectivity, especially when considering indirect costs, benefits, and non-monetizable externalities. Some of these methodological aspects are explored in the following sections.

4.6.2. *Thinking in terms of sustainability*

Assessing sustainability

The development of new infrastructure or the modification of existing structures must integrate *Sustainability*, meaning minimizing environmental and social impacts. This report does not delve into these objectives, but it is important to note that, for equivalent services provided, projects can have varying degrees of environmental and social footprints.

Life cycle analyses (LCA) allow for comparisons between different options and help prioritize those that, among other factors, minimize greenhouse gas (GHG) emissions from construction and reservoir impoundment. However, GHG emissions are not the only factor in assessing the sustainability of a project. Following initiatives such as the Hydropower Sustainability Alliance, ongoing work within ICOLD will provide tools to further refine this evaluation.

Extending service life

General

A key parameter of sustainability is the service life of a reservoir. Doubling a reservoir's lifespan (extending it to 2D instead of D) effectively halves the environmental cost of construction. Over the total lifespan 2D, only one structure is built instead of two.

This calculation is somewhat simplistic and must be adjusted. It is preferable to emit 1 ton of CO_2 in 100 years rather than today; similarly, it is better to implement biodiversity-supporting measures now rather than in a century. As in financial models, there is an implicit discount rate to consider - efforts made today for climate change and biodiversity are more impactful than those postponed to the future.

This adjustment does not change the core assertion: while doubling a reservoir's lifespan does not precisely halve its environmental cost, it significantly reduces it.

Some dam reservoirs have remained operational for centuries, while others have become non-functional within just a few years or decades. There is room for optimization, and extending service life should be a key consideration in sustainable infrastructure planning.

Reservoir Sustainability: Sedimentation

Sedimentation management is a critical factor in the design and operation of dams, influencing sustainability, adaptability, and contribution to climate adaptation. A long-term vision - 100 years, 200 years, or even beyond - should be integrated into sedimentation management strategies. However, many projects still only consider a 20- to 30-year timeframe, aligned with the return-on-investment period of private hydroelectric developments. Additionally, climate change is expected to increase sediment transport, further emphasizing the need for comprehensive planning.

Sediment management is a challenging issue, but significant progress has been made. It must be integrated both in the design phase of new projects and in the operation of existing dams:

- Improved study methods, including sediment transport simulations (and in some cases with consideration for polluted sediment dissemination) help refine reservoir operation strategies.
- For new dams, experience has shown that, where feasible, bottom outlets should be designed to accommodate a 50-year flood event. This allows for effective sediment flushing operations. [AS]

- For cascading reservoirs, coordinated sediment management strategies along the entire system have proven beneficial.
- Erosion control at the source is particularly useful in many regions. Soil conservation measures not only help maintain soil fertility, biodiversity, and agricultural productivity but also reduce reservoir sedimentation. These are long-term efforts, but past success stories have demonstrated both short-term and long-term benefits.

Sediment management is extensively covered in several ICOLD bulletins (Bulletins 140, 147, 182, and 193) and is not further developed in this report.

Structural Sustainability: General design and building materials

It is both feasible and desirable to design dams with a lifespan well beyond 100 years. The service life of a dam depends on several factors: Design considerations: are aging factors identified, and is maintenance possible? Construction materials: are they prone to degradation over time? Resilience to extreme events: can the dam withstand major hydrological and seismic events? This objective concurs with the issue of dam safety.

These aspects extend beyond the scope of this report, but they remain crucial for long-term infrastructure planning.

Should environmental authorization procedures be accelerated and simplified?

According to Q108-R20, the pace of hydropower project development (including pumped storage plants – PSH) must be at least three times faster than the current rate. To achieve this, Q108-R20 recommends financial incentives and a simplification of environmental authorization procedures.

Financial incentives are certainly justified, given the non-monetized services provided by reservoirs and their long lifespan, which is poorly accounted for in interest rate and discount rate mechanisms. However, simplifying environmental authorization procedures is more controversial. Recognizing that large reservoirs have significant positive and negative impacts, it may seem justified to allow time for a thorough evaluation to ensure the best possible project. While the technical aspects of dam projects are increasingly well-managed, environmental considerations remain a major challenge.

Of course, the depth and scope of environmental assessments should be proportional to the project's environmental stakes. In particular, many off-river reservoirs (including closed-loop PSH reservoirs) have limited environmental impacts. The urgent need to deploy renewable energy and the parallel need for energy storage solutions likely justify accelerating approval procedures for these types of infrastructure.

4.6.3. *Accepting and covering the additional cost of adaptation*

Implementing better-adapted solutions comes at a cost: the initial investment may be higher than that of a short-term solution, which only addresses immediate needs without considering long-term adaptation. It seems necessary to accept this immediate cost, as future generations should not bear the burden of poorly adapted solutions.

Discount rate

This raises the issue of the “discount rate” used in economic evaluations for infrastructure projects related to climate change adaptation. This is a key topic, which can be illustrated as follows: the table below indicates the amount of avoided damages in 100 years that would be necessary to make an investment of €1000 today profitable, depending on the chosen discount rate.

DISCOUNT RATE	COMMENT	AMOUNT OF DAMAGE AVOIDED IN 100 YEARS
1.4%	Rate proposed by Nicholas Stern (including 0% “present preference” component).	€4,000
4%	Rate used in many infrastructure projects	€50,000
6%	Rate used in many infrastructure projects	€340,000

For Nicholas Stern, Chief Economist and Senior Vice-president of the World Bank from 2000 to 2003, and the economists of the IPCC, there should be no “present preference”, which justifies using a low discount rate. Conversely, other economic schools argue that a “present preference” is reflected in market interest rates, and therefore, it should be accounted for, leading to higher discount rates. This report does not seek to define a specific discount rate to be used. However, it highlights the following points:

- A 4% or 6% discount rate inevitably leads to designing infrastructure without much consideration for long-term and very long-term impacts.
- A 10% discount rate, which is sometimes observed, can be considered non-sensical for large-scale dam and reservoir projects that provide services for 100 years or more.
- Since 2006 (Stern Report), it appears legitimate to use significantly lower discount rates.

The debate on appropriate discount rates is complex. Since 2003, many countries have improved their approach to very long-term considerations (“social discounting”), adopting lower and declining discount rates over time. A comprehensive discussion on this topic can be found in [45].

However, these discussions often overlook another key aspect of long-term accounting: some actions are more effective if taken early (as explained in §4.6.2).

Therefore, a “discount rate” should also be applied to certain externalities, not just monetary costs, to give greater weight to immediate actions.

Developing Countries: Sharing the Costs

Developing countries do not always have the financial capacity to support the cost of large-scale infrastructure needed to ensure their adaptation to future climate conditions. Similarly, they may struggle to afford the additional investment required to make short-term solutions compatible with long-term sustainability. It seems legitimate for wealthier nations to contribute to these investment costs - or even fully cover the additional costs - for at least three key reasons:

- Wealthier nations have historically contributed the most to greenhouse gas emissions, by a very large margin.
- The sustainability of infrastructure, its contribution to climate mitigation, and its role in adaptation provide benefits for all of humanity, such as reducing global GHG emissions and supporting biodiversity. This justifies at least partial cost-sharing at an international level.
- It is the only way to make rapid progress toward the United Nations’ Sustainable Development Goals (SDGs). As Adama Nombre expresses it[†]: “This is about adapting to global climate change while also finding solutions to mitigate its effects, all while improving the living conditions of millions of men, women, and children who live in undignified conditions in developing countries.”

4.6.4. *Sharing water*

General considerations

In a context of water scarcity, it will be necessary to share or redefine water allocation in many regions worldwide. However, establishing fair distribution rules is challenging because:

- Water has multiple and often conflicting uses.
- Some uses generate revenue, while others do not. Electricity production, industrial water supply, and in some cases, agricultural irrigation for cash crops can finance or partially finance the construction and operation of reservoirs. However, this is not generally the case for water allocated to rural communities, environmental flow maintenance, or strategic reserves for drought resilience.

[†]Translated from French

An example is given by the Fomi/Moussako dam project on the Niger River in Guinea. This project is primarily justified by the objective of producing hydroelectricity—a renewable, dispatchable, and low-cost energy source—and supporting large irrigated areas in Mali. However, the potential consequences for the Inner Niger Delta, where the river's annual flood plays a crucial role in sustaining agropastoral resources and forms the foundation of livelihoods and societal structures for numerous populations, could be catastrophic. Therefore, it is essential to find a balance in the management of the future reservoir between optimizing electricity production and irrigated agriculture while preserving the natural flow regime of the river [ADB] [74].

This raises a fundamental question: what tools and frameworks are available to facilitate discussions and negotiations regarding water sharing?

A tool: Economic approaches

General framework: internalizing externalities

Modern economic approaches go beyond simply assessing investment and operating costs or measuring revenue from water and electricity sales. The concept of externalities has become central. According to Wikipedia, "*In economics, an externality or external cost is an indirect cost or benefit to an uninvolved third party that arises as an effect of another party's activity. Externalities can be considered as unpriced components that are involved in either consumer or producer market transactions. Air pollution from motor vehicles is one example. The cost of air pollution to society is not paid by either the producers or users of motorized transport to the rest of society.*"

Taking externalities into account ("internalizing externalities") means conducting a comprehensive assessment of project justification.

In the context of reservoirs and dams, externalities - both positive and negative - carry significant weight. However, they remain difficult to quantify and attribute, often leading to their undervaluation in project planning.

- Negative externalities include social and environmental impacts, such as land submersion and changes in river flow downstream. As a rough approximation, these impacts increase proportionally with the stored volume, water withdrawals from the river, and the flooded surface area.
- Positive externalities stem from the use of the resource, including indirect economic and social benefits from electricity production, reliable electricity supply, grid services (e.g., reducing the need for additional network investments), contributions to climate change mitigation through renewable electricity, flood reduction, low-flow support, and, in some cases, biodiversity conservation.

The cost-benefit balance of a project can then be expressed as:

$$\frac{B}{C} = \frac{\text{monetizable economic benefits} + \text{positive externalities}}{\text{monetizable costs} + \text{negative externalities}}$$

If we focus only on the numerator (benefits), the inventory of everything that has "value" is already quite extensive:

- Electricity generation, whose value (per kWh) depends on the level of reliability.
- Storage (in kW) that can be used to compensate for the intermittency of solar and wind energy, as well as grid services, whose value depends on availability and how it enables solar and wind energy development (or avoids the deployment of batteries).
- The supply of "commercial" water, meaning water for which users pay: drinking water, industrial water, and commercial agriculture. Its value may be close to the selling price - when water is not subsidized.
- The supply of water for subsistence: irrigation and non-commercial livestock farming, whose value is of the same order of magnitude as "commercial" water supply, even if the price is 0 or close to 0.
- Flood peak attenuation, whose value depends on the damages avoided for different flood return periods.
- Low-flow support for human needs (sanitation, fishing, way of life).
- Low-flow support for biodiversity, whose value aligns with the concept of ecosystem services, meaning all the services that nature provides to humans for free, which are often difficult to quantify.
- Strategic reserves in case of drought, with water volumes set aside for severe and prolonged drought episodes. This functions as a form of insurance: the water is not used except in exceptional circumstances. Its value is therefore very high but must be weighted by a low probability of occurrence.
- Amenity value, tourism, and landscapes.

Assigning values to each of these services is complex and necessarily involves a degree of subjectivity. However, it is essential to do so: quantifying these aspects helps to draw greater attention to externalities. When applied to real cases, this approach provides two key insights.

- The "value" associated with different economic, social, and environmental services tends to be of the same order of magnitude. To maximize the value of a project, all aspects must be considered. This finding aligns with the more qualitative approaches developed by certain organizations (for example, WWF [14]).
- A single cubic meter of stored water can be counted multiple times - for example, if it is released at the optimal moment to provide power capacity assurance, if it also contributes to low-flow support through a downstream compensation basin, and finally, if it is used further downstream to supply irrigated areas. Multi-purpose use increases the overall value of a project.

It is important to recognize that economic value is not the same as commercial or financial value. Water allocated for low-flow support, resilience during droughts, or subsistence agriculture may not have significant commercial value, but in certain cases, its overall economic value (including externalities) can exceed the economic value of hydroelectricity.

International cooperation

Many river basins are shared between neighboring countries. Strengthening regional collaboration in these shared basins should be encouraged, particularly in the areas of hydrological studies, climate research, and potential revisions of existing reservoir operation guidelines [AB]. This is especially necessary to mitigate tensions that may arise due to increasing irregularities in water resources.

4.6.5. *Sharing and enhancing space*

One of the key challenges of sustainability is land artificialization. Exploring solutions that minimize land use for human activities is essential. This could lead to seeking dam designs that reduce reservoir footprint while maintaining service levels. More importantly, it encourages thinking about how to optimize the use of reservoir surfaces. Floating solar panels, aquaculture, and fish farming are ways to enhance the value of these areas.

There may be other possibilities . . . Could we imagine additional uses for reservoirs, the dam itself, or shared infrastructure? Floating wind turbines on the reservoir, floating electrolyzers for hydrogen production, floating “gardens” for agriculture, or other innovative ideas? [AH]

4.7. Research and engineering: study requirements

4.7.1. *Data!*

Acquiring knowledge requires data, particularly to make informed choices regarding Sustainability and to optimize Adaptability and Contribution to Adaptation [JS] [JPT]. The following data sets need to be enhanced:

- Increased hydrometric (river flow) and hydrogeological (groundwater levels) data collection to better assess current water resources, detect trends, develop hydroclimatic projections ([23]), and define adaptation strategies.
- More comprehensive real-time monitoring of water resources, consumption, and soil moisture, allowing for improved reservoir operation under actual

conditions, forecasting capabilities, and informed decision-making in crisis situations.

- Improved meteorological and hydrological forecasting to support flood management decisions, including the possibility of pre-emptive reservoir drawdowns.
- Expanded water quality monitoring (physical, chemical, and biological parameters) in reservoirs to better understand and model reservoir dynamics (physical, chemical, and biological cycles) and to optimize water release quality for downstream ecosystems.
- Enhanced biological monitoring (using traditional methods and e-DNA) in and downstream of selected reservoirs to better understand the effects of reservoirs on biodiversity dynamics, leading to adapted reservoir management practices - such as environmental flow releases, artificial floods, and seasonal water quality adjustments.

4.7.2. *Reference models and scenarios: a necessity*

Adaptation strategies require the development of reference models and scenarios at the national or regional level to:

- Define the necessary mitigation trajectory, including the production of renewable electricity and storage requirements.
- Establish the required adaptation trajectory, setting adaptation contribution objectives and identifying adaptability constraints.

At the national level, this is a long, complex, and costly process.

General framework: Bulletin 169 and IHA guide

Bulletin 169 [24] outlines the recommended approaches for assessing the adaptability of a dam project in the context of climate change. It advises using IPCC methods to develop future climate scenarios, incorporating uncertainty by comparing a range of probable climate scenarios.

The IHA Guide [31] also recommends evaluating project performance under different future climate scenarios to select resilient design options and assess the extent of climate-related risks.

Approaches Discussed in the Reports of Question 108

Only one report presents the results of a climate change adaptability study. Report Q108-R22 illustrates the case of a dam reservoir in Romania. The authors analyze the future operation of the Paltinu Dam, considering both changes in water resources (based on a projection of the RCP 8.5 scenario) and changes in water demand under three hypotheses (minimum, average, and maximum). The dam serves multiple purposes: drinking water supply, industrial water use, and ecological support. The analysis is conducted for the 2050 horizon and is used to determine which portion of the reservoir will remain available for flood control.

Report Q108-R14, prepared by researchers from the National Research Council of Canada, takes a more general approach. It aims to provide a comprehensive overview of modeling methods for future conditions in dam reservoirs, drawing on findings from 165 bibliographic references. It covers various aspects, including water resource modeling, water demand forecasting, dam operation optimization, and structural adaptation. The report identifies research gaps and makes several key recommendations:

- Using advanced models to simulate future water resource availability.
- Developing integrated models that simulate societal evolution (demographics, agriculture, energy, etc.) to optimize water allocation, for instance, through dynamic programming models or stochastic optimization.
- Optimizing multi-purpose dam operation, integrating water supply, electricity generation, and flood management using advanced optimization algorithms.

The conclusions of Q108-R14 rightly emphasize that dams will need to adapt not only to changes in water availability but also to shifts in demand. Advanced optimization tools, when sufficient data is available, could enhance the management of stored water by improving resource allocation and flood mitigation performance. However, at least with current technology, it is essential to ensure that the use of advanced algorithms remains reasonable. The fundamental principles of dam management (such as operating rule curves and floodgate operation protocols) should be developed using simple, transparent approaches, ensuring they remain easily understandable and interpretable by humans. Advanced algorithms should only serve as secondary optimization tools.

Development of a Reference Framework: The Example of France

At the national level, it may be beneficial to establish a general framework that anticipates future needs and demands. Such a framework can then serve as a reference for all project developers, whether large or small. The example of France is presented here to illustrate this approach and highlight the scale of effort required to build a sufficient body of documentation.

Scenario Development: "Futurs Énergétiques 2050" : The "Futurs Énergétiques 2050" study explores energy mix scenarios designed to achieve carbon neutrality by 2050. This undertaking required an extensive modeling and synthesis effort to establish robust scenarios. The process spanned two years, involved dozens of experts, and required significant research and analytical work.

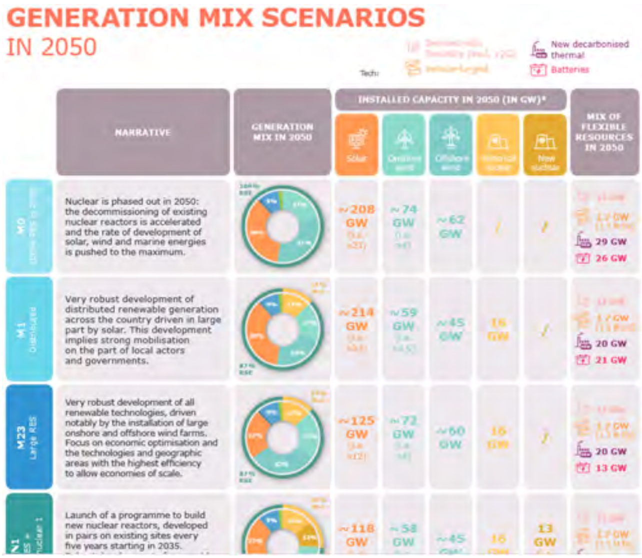


Fig. 8
Production mix scenarios: example of France, source [60]

Hydro-Climatic Simulation: Explore2. The Explore2 hydro-climatic simulation project brought together several research institutes over a four-year period (2021-2024). Report Q108-R6 describes the methodology and some of the key findings. The project aimed to develop climate projections at the scale of the French territory, based on greenhouse gas (GHG) emission scenarios. Three emission scenarios were selected: RCP2.6, RCP4.5, and RCP8.5, with RCP8.5 representing an extreme scenario where no climate regulation policies are implemented. These emission scenarios were then translated into climate projections through a multi-step modeling process: General Circulation Models (GCMs) simulate Earth’s overall climate ; Regional Climate Models (RCMs) downscale these simulations to refine projections at a smaller scale ; Hydrological models (up to nine models, depending on the region) simulate water cycle dynamics at a detailed level.

The outcome of this effort is the availability of hydro-climatic data covering the entire French territory, accessible to all relevant stakeholders. These datasets allow users to download a comprehensive set of hydrological variables and indicators for time horizons extending to 2100, with a high level of spatial detail. This provides the scientific foundation necessary to assess both adaptability and the contribution to adaptation in response to climate change.

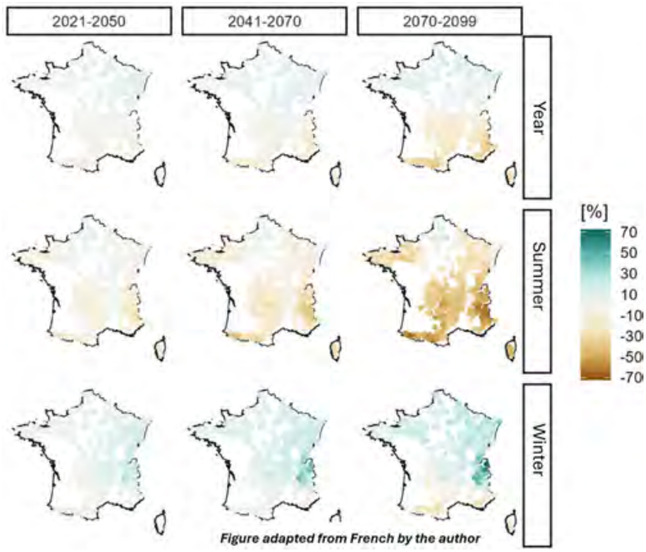


Fig. 9
France: Maps of Flow Changes (RCP8.5 Scenario, Average of 17 RCMs, Source [6]

The projections also assess the impact of climate change on hydropower generation.

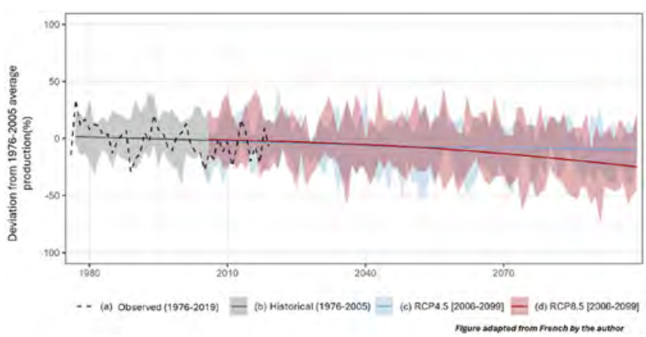


Fig. 10
Expected evolution of hydroelectric generation under the RCP4.5 and RCP8.5 scenarios [6]

Assessment of Future Water Needs: A study conducted by a team of researchers over 18 months [61] has resulted in the availability of projections for water demand evolution by watershed. The study distinguishes between withdrawals (the volumes of water extracted but immediately returned, as is the case for hydropower generation) and consumption (the volumes of water extracted but not returned to the natural environment, particularly irrigation water). By cross-referencing this data with the evolution of water resources, it is possible to develop quantitative local adaptation policies at the watershed level.

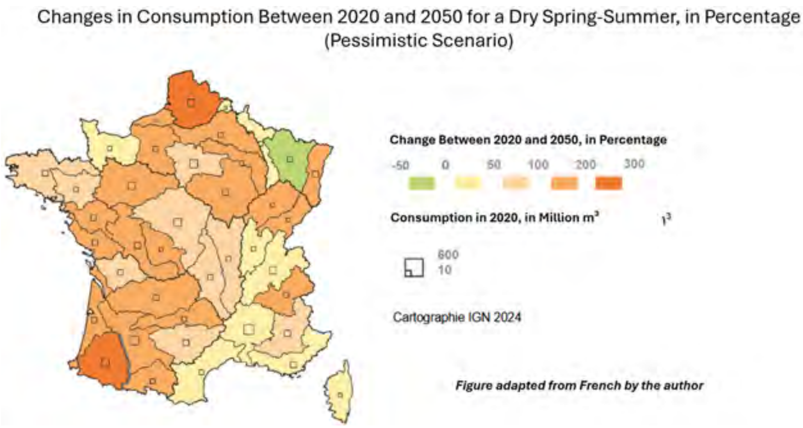


Fig. 11
Future Water Consumption Trends, Example of France, Source [61]

National Plan for Climate Change Adaptation: “Preparing France for +2.7°C in 2050, +4°C in 2100.” Within this national plan, a specific “Water Plan” includes 53 measures aimed at: organizing the efficient use of water, optimizing resource availability, and preserving water quality.

Other countries have conducted similar studies, always focusing on their specific challenges. For instance, the Netherlands has focused on adaptation strategies for sea level rise [67]

5. TECHNICAL SOLUTIONS

5.1. Off-river storage

5.1.1. *Overview, principles and benefits*

General considerations

Off-river storage consists of combining a river intake structure with a storage basin built outside the river's footprint. The storage basin is supplied by the intake, either by gravity or pumping.

This solution has been widely implemented for decades, with reservoirs of varying capacities. Off-river reservoirs have been constructed for diverse uses, including water supply reserves, flood protection, and energy storage. The main advantages are as follows:

- Minimized ecological footprint: The river intake is a relatively small structure that does not create a reservoir, thus preserving ecological continuity. The storage basin can be located in areas with fewer social and environmental constraints.
- Reduced sedimentation exposure: The system can be designed to limit reservoir sedimentation by allowing the passage of sediment-laden floodwaters and/or by ensuring sediment settling in the intake dam's reservoir, which can be easily flushed.
- Lower flood exposure: The intake dam can be designed to be overtopped or disappear during floods, reducing the need for costly spillways and ensuring better safety under extreme flood conditions.
- Reduced evaporation: For small and medium-sized basins, designs can incorporate a greater average depth than a standard dam, limiting evaporative losses (for a conventional reservoir, the average depth is approximately 25% to 50% of the maximum depth; for an off-river basin, the ratio can be significantly better).

The main disadvantages are as follows:

- Limited floodwater capture: The reservoir only partially captures floodwaters, potentially reducing available water resources and diminishing flood protection performance.
- Higher leakage risks: The reservoir is located outside the main floodplain, often above the water table, making it more susceptible to seepage and sometimes requiring full waterproof lining.

This type of facility is easier to implement in relatively flat terrain, particularly in plains. However, off-river reservoirs have also been successfully built in mountainous areas, particularly for energy storage purposes.

A note on sedimentation

Off-river reservoirs have long been constructed as a means to mitigate the issue of sedimentation in water storage facilities. However, sedimentation has broader implications and generates additional motivations for considering alternatives that incorporate off-river storage. For example, in large reservoirs across West and Central Africa, the volume of sediment is often negligible compared to the total controlled water volume. In such cases, there is little reason to divert or store sediment outside the reservoir. However, in Benin, the stability of the coastline is maintained by sediment transported through longshore drift, specifically the east-to-west movement of sandy materials driven by ocean swells. A portion of these sediments originates from coastal rivers. The annual volume of sediment transported along the Beninese coastline is estimated at approximately 600,000 cubic meters. The Ouémé River, a major waterway crossing the country, carries several hundred thousand cubic meters of sediment annually, representing a significant proportion relative to longshore drift. Proposed dam projects on the Ouémé River could disrupt the natural sediment transport, potentially blocking sediment volumes of a magnitude comparable to the longshore drift, leading to coastal imbalances. Alternative solutions that do not impact sediment transport, such as pumped storage hydropower (PSH) combined with solar energy, should be considered and evaluated against the benefits provided by conventional reservoirs built directly on the river. [ADB]

5.1.2. *Some recent examples*

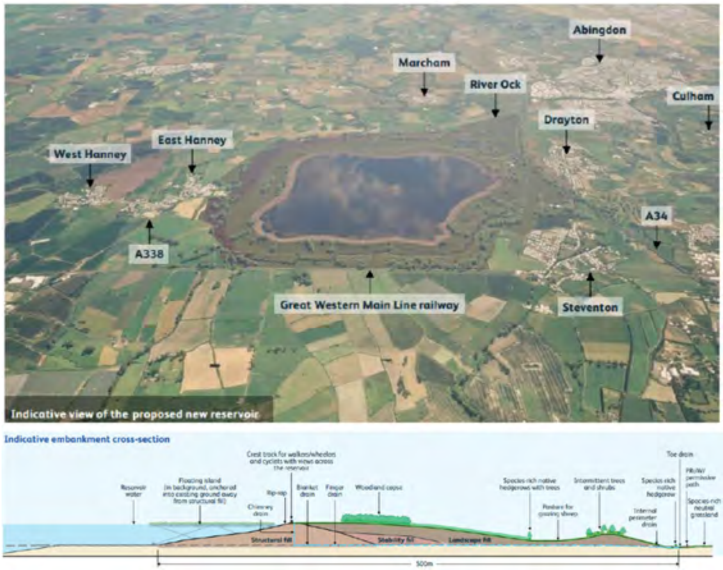


Fig. 12
South-East Strategic Reservoir project, UK, [70], figure communicated by [JW]

Live storage: 75 - 100 hm^3	Filling by: gravity and pumping	Function: water supply, drought support
Notes: This reservoir project is part of England's climate change adaptation plan (§3.4), specifically aimed at establishing strategic reserves for drought scenarios. Additional reservoirs of this type are also being considered. One key consideration was the return period of droughts to be accounted for in the reservoir's design. A 1% return period (droughts with a 1% probability of occurrence each year) was deemed insufficiently cautious, as it corresponds to a 26% probability of occurrence over a 30-year span. [JW]		

Fig. 13
Kenh Lap reservoir, Vietnam. The Kenh Lap Reservoir is formed by a natural branch of the Mekong River, enclosed at both ends by an embankment dam and an upstream regulation structure. Photo communicated by Michel Ho Ta Khanh

Live storage: 1 hm^3 (length 4.6 km; width 50 to 100 m; depth 2 to 3 m)	Filling by: gravity and pumping	Function: water supply
Notes: This reservoir is part of recent initiatives taken in response to increasingly frequent droughts in the Mekong Delta (potentially due to climate change). It is a solution well-suited to the local context (flat country and solution with no land use constraints). However, its effectiveness is limited by the extent of water level fluctuations (only 2 to 3 meters) and by evaporation. [MHTK]		

Fig. 14
Synopsis of the Seine-Nord Europe Canal and its water supply system, France; photomontage: illustration of a lock, with its water-saving basins and integrated pumping station, Q108-R9 [9]

Live storage (Louette basin): 14 hm^3	Filling by: pumping	Function: securing the canal's water supply in the event of drought
Notes: The design of the Seine-Nord Europe Canal has been chosen to minimize water withdrawals from the natural environment. There are no withdrawals from groundwater. Filling is carried out by pumping from the Oise River when its flow is sufficient. Off-river storage (Louette Basin) is used for low-flow periods of the Oise River. Water savings and recycling at the locks are achieved through water-saving basins and a pumping station. As a result, the only actual water consumption comes from seepage and evaporation.		

Fig. 15
Olifantspoort off-river reservoir, Republic of South Africa, Q108-R13. [13] [9]

<table>
<tr><td>Live storage: approx. 2 hm^3</td><td>Filling by: pumping</td><td>Purpose: secure water supply for the city of Polokwane and surrounding area (one million people)</td></tr>
<tr><td colspan="3">Notes: The city of Polokwane is supplied by various sources, including a pumped withdrawal from an adjacent watershed (Olifantspoort). High sediment transport has reduced the reliability of this pumped supply. The off-river reservoir project consists of three components: a new river intake weir with self-cleaning capabilities, a pumping station, and an off-river reservoir that serves as both a buffer volume and a sedimentation basin (subject to periodic dredging).Report Q108-R13 details the design elements of the intake structure (addressing sediment transport issues) and the unique characteristics of the reservoir’s closure dams, which are multiple-arch dams built using rubble masonry concrete.</td></tr>
</table>

Fig. 16
Lower basin of the Kokhav Hayarden PSH, Israel, Q108-R5 and Q108-R17

Live storage: approx. 3 hm^3	Lower reservoir of a PSH	Function: electricity storage
Note: At the end of 2023, Israel had developed approximately 6 GW of solar power, with solar energy accounting for 13% of its electricity production. The remainder of the country's electricity generation comes from thermal power plants, primarily fueled by natural gas. The expansion of solar energy is expected to continue, accompanied by a program for the construction of pumped-storage power stations. The Kokhav Hayarden pumped-storage power station has an installed capacity of 344 MW.		

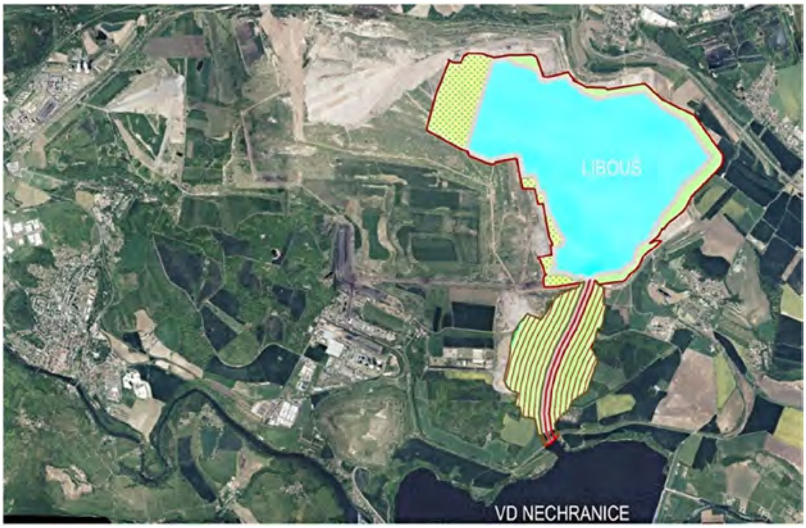


Fig. 17
Project for a connection via a canal between Nechranice Reservoir (at the bottom of the image) and the Libouš open-pit mine (in light blue), Czech Republic, Q108-R21. [9]

Libous reservoir (mine filling): 106 hm^3Nechranice reservoir: 288 hm^3	Filling by: gravity	Function: to increase the performance of the initial reservoir for flood protection and water supply.
In this particular case, the off-river reservoir (the mine to be filled) is directly connected to the main reservoir by a canal.		

5.1.3. *The Issue of reservoir watertightness*

In most cases, when off-river reservoirs are considered, artificial sealing is implemented across the entire reservoir area. This is, for example, the case for many pumped-storage reservoirs when they are disconnected from the natural environment. It is also the case for the various reservoirs of the Seine-Nord Europe Canal.

However, this is not always systematic, and it is useful to explore solutions without artificial sealing, particularly for large reservoirs. Some notable examples include:

- The upper reservoir of the Hatta pumped-storage plant, despite being in an arid environment, is not lined; efforts to limit leakage are achieved through grouting beneath the closure dams.
- The Khen Lap reservoir, illustrated in Fig. 13, is not lined; it benefits from at least partial sealing provided by fine sediments.
- The large off-river reservoirs built upstream of Paris for flood protection and low-flow support are not lined either - they benefit from predominantly clayey soil conditions.

In the case of the Olifantspoort Dam (Q108-R13), the rock foundation of the off-river reservoir is highly permeable. No artificial sealing was planned; however, extensive grouting work was carried out beneath the dams. In this particular case, it is worth noting that: (1) The water pumped from the river carries fine sediments, which could have a positive effect on overall watertightness ; (2) The off-river reservoir serves as a buffer basin, where the water residence time is short, meaning that leakage volume, relative to the transferred volumes, is lower than in a seasonal storage dam (or than in PSH reservoirs that recycle the water they use).

Off-river reservoirs can be enclosed simply by embankments built above natural ground level or through a mixed technique combining excavations within the reservoir with embankment construction to form the perimeter. This approach balances excavation and embankment volumes. Report Q108-R15 illustrates such a case for the lower basin of the Kokhav Hayarden pumped-storage plant in Israel. The excavation depth of the basin is approximately 20 m below natural ground, with a perimeter embankment height of 5 to 10 m. Some excavations occur below the water table, within clays and clayey silts, necessitating careful consideration of slope stability conditions. In this specific case, the water table was lowered using relief wells, and phased excavation was required to maintain slope stability, with 3-meter excavation steps.

In such configurations, the long-term stability of slopes must be carefully examined, particularly in scenarios where the water table is high. Ensuring the durability of drainage systems and any water table lowering measures is crucial (monitoring flow rates and pressures, designing drainage for maintenance accessibility). Additionally, slope stability should be assessed for potential accidental drainage failures.

There are also specific sealing considerations for pumped-storage reservoirs, which are addressed in §5.2.

5.1.4. *The "Overflow": A Cost-Effective Tool for Ultimate Safety*

Off-river reservoirs are largely protected from floods of the main river from which they are supplied. However, this does not mean they are entirely safe from floods, whether natural or artificial. They may be affected by floods from their own catchment area (in addition to direct rainfall on the reservoir and its embankments) and may receive excess water in case of a failure in the supply system (example of Taum Sauk dam failure), whether gravity-fed or pumped.

It is generally accepted that the flood safety of a large embankment dam must be ensured for very high return periods, such as 10,000 years (with an exceedance probability of less than 10^{-4} per year). However, it may be challenging to guarantee against all potential failures of the supply system, whether gravity-fed or pumped, with a failure probability lower than 10^{-4} per year. In such cases, installing a passive spillway below the crest of the embankment dam to evacuate excess water significantly increases the dam's overall safety.

5.2. Pumped-Storage Hydropower (PSH) plants

This report focuses on the infrastructure aspects (civil engineering, geotechnics) and the hydraulic components (reservoirs, water conveyance systems). It does not cover electrical and electromechanical equipment.

5.2.1. *Role and general principles*

A Major Development in the Coming Years

Pumped-storage plants (PSP) were initially built to complement nuclear power plants, which lacked flexibility.

In the current global context, where all countries are striving for decarbonization and the energy sector is making significant efforts to integrate an increasing share of clean but intermittent renewable energy sources (mainly solar and wind), the demand for energy storage and grid balancing services is rising dramatically. Pumped-storage hydropower remains the most efficient large-scale energy storage solution worldwide and can help mitigate climate change by reducing greenhouse gas emissions [LC].

For this reason, International Financial Institutions (IFIs) and Multilateral Development Banks (MDBs) offer numerous funding opportunities for projects or project components involving pumped-storage plants, provided these projects align with climate adaptation requirements [LC].

Many countries are incorporating pumped-storage plants into their energy development strategies. The case of India is detailed in Q108-R20:

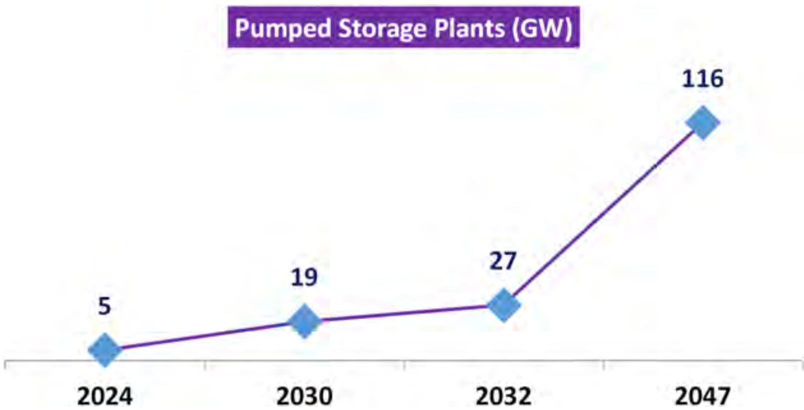


Fig. 18
Future projections of PSH in India, Q108-R20

Storage duration (and volume)

Pumped-storage hydropower (PSH) plants offer energy and power storage capacities well-suited to balancing solar intermittency - and to a lesser extent, wind intermittency - typically with storage durations ranging from a few hours to several dozen hours.

For a given power output, selecting the storage volume is a critical and complex issue. Several factors influence this choice, including the nature of the intermittent electricity sources in the grid, their geographical dispersion (which helps smooth fluctuations by leveraging diversity in number, type, and location), and local climatic conditions.

Studies conducted in Australia have highlighted the benefits of deeper storage reservoirs - that is, storage capacities measured in tens of hours, at least for some PSH plants in the grid [63]. The selection of storage depth also depends on the marginal cost of increasing reservoir volume. In certain cases, expanding storage capacity to several dozen hours is relatively straightforward and cost-effective, making it a worthwhile option. For example, the Snowy 2.0 project in Australia, which connects two existing reservoirs, has a storage reserve of 175 hours at full power.

Electric grids also require longer-term energy storage solutions, lasting one or more weeks or even several months. However, PSH plants are generally not economically viable for such long-duration storage. Instead, hydroelectric reservoirs provide longer-term storage where possible, complemented by thermal generation capacity, such as gas-fired power plants. For example, Switzerland is considering constructing a large new reservoir (Q108-R2) to enhance energy supply security in winter, with a 650 GWh storage capacity. This seasonal storage project would complement Switzerland's existing pumped-storage infrastructure.

Furthermore, the energy transition is leading to the phasing out of fossil-fuel-based electricity production (coal, gas). However, it may be prudent to retain some existing thermal capacity - or at least a portion of it - as backup generation in case hydraulic reserves become depleted.

Open-Loop vs. Closed-Loop Systems

Open-loop pumped-storage plants have at least one reservoir connected to the natural environment (a river or lake), while closed-loop PSH plants have both reservoirs disconnected from natural water sources, drawing water from the environment only for initial filling and to compensate for losses (leakage, evaporation). Both options have advantages and disadvantages [LC] [DBB]:

ADVANTAGES OF OPEN-LOOP SYSTEMS	ADVANTAGES OF CLOSED-LOOP SYSTEMS
Leverages existing reservoirs for the upper and/or lower basins, which helps: 1/ Reduce investment costs 2/ Enable improvement works on existing infrastructure within the project framework.	Disconnects reservoirs from the natural environment, minimizing environmental impact.
Allows for the creation of reservoirs that serve multiple functions within a PSH project: 1/ New multi-purpose reservoirs 2/ Expansion of existing reservoirs to enhance their multi-purpose role.	Disconnects reservoirs from the natural environment, reducing the risk of inadequate reservoir filling due to water shortages.(open-loop systems can be impaired when upstream or downstream reservoirs serve other purposes, e.g., hydroelectricity, water supply, flood control, and are subject to water level variations due to these other uses).
	Offers more opportunities for sitting a new PSH, optimizing impacts and topographical factors (head, length of hydraulic circuits).

As Luciano Canale states: "*Private sector developers with a narrow focus on the energy sector and strong commercial drivers may push for the climate-safer option of closed-loop but for public sector developer reusing/adapting existing reservoir for PSP may also provide opportunities to optimize and modernize public sector assets and improve their long-term sustainability. Dam heightening to create additional water volume for the PS scheme or sediment removal to gain active storage for the hydro-battery may be a win-win decision to satisfy the electricity storage demand and make the life of dams longer at the same time*

5.2.2. *Some recent examples*

Fig. 19
Kidston PSH in northern Queensland, Australia[63], Credit: Genex Power Limited

Capacity: 250 MW	Storage: 8h (2 GWh) at full power	Head: 181m - 218m
The project uses two open-pit disused gold mine pits. It is the first PSH to be built in Australia in decades. A solar power plant and a wind farm are also planned for the site. A lined rockfill dam raises one of the pits to form the upper reservoir.		

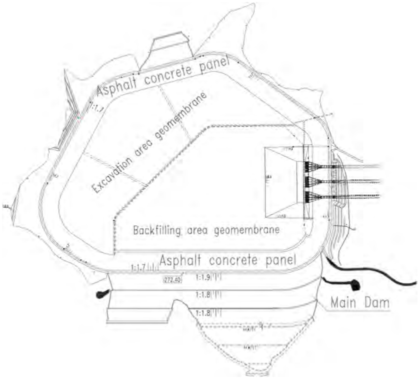


Fig. 20
Jurong PSH, Jiangsu, China, Q108-R17

Capacity: 6*225 MW		
Difficult geological conditions for reservoir sealing: karstic rock; upper reservoir closed by an AFRD dam, with a maximum height of 182 m (world record).		

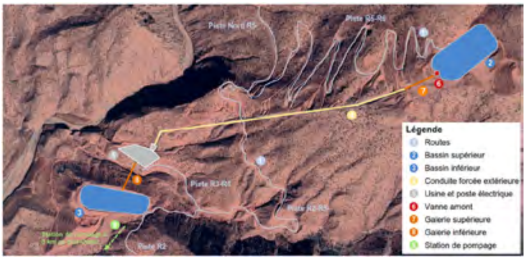


Fig. 21
Abdelmoumen PSH, Morocco, Q108-R8

Capacity: 350 MW	Storage: 5 hours at full power	Head: approx. 550 m
The commissioning of the Abdelmoumen PSH in 2024 follows the Afourer PSH, which has been in operation since 2004. The project aims to balance fluctuations in wind power generation. It has been designed for rapid switching between pumping and generation modes, enabling up to 20 start-stop cycles per day. In Morocco’s context of water scarcity, the closed-loop operation minimizes environmental impact and conserves water resources.		

5.2.3. *Optimizing costs and construction pace: Example of the pumped storage hydropower (PSH) construction policy in China*

China provides a significant example of an industrial policy for the development of PSH. A total of 179 GW is currently under construction, leading to efforts in streamlining and optimizing construction processes. At present, the investment cost (CAPEX) of these PSH projects ranges from approximately $700 to $1,000 per kW, with expected cost reductions of around 15%. The key levers for optimization are as follows [58]:

- Implementation of an incentive policy: improving remuneration mechanisms, supporting investment financing, and encouraging capital opening.
- Use of automated tools for identifying favorable sites (topography, hydrology, climatic conditions, optimization of storage placement within the grid).
- Use of automated tools for preliminary design of structures such as dams, reservoirs, caverns, and underground works, enabling optimization and standardization.
- Application of modern monitoring and compaction control technologies for embankment and Roller-Compacted Concrete (RCC) dams, including digitalization of construction sites.
- Optimization of specific technologies, including reservoir sealing systems (see §5.2.6); support structures for underground works; tunnel boring machines (TBMs), including for inclined or vertical shafts (shaft boring machines); raise boring for vertical and inclined shafts; lining for high-pressure tunnels; and high-capacity, high-head turbines and pumps.

5.2.4. *Exploring Low-Head (High-Flow) PSH Systems*

Challenges and Feasibility

Traditional PSH systems operate with head differences of several hundred meters. However, there is demand in regions where such elevations are unavailable. This is not an insurmountable challenge:

- In Alqueva, the PSH plant (4×128 MW) operates with head levels between 45 and 73 m, with turbine discharge capacities of approximately 190 m^3/s per unit.
- In La Rance, the tidal power station (240 MW) operates in both turbine and pumping modes under head levels below 10 m.
- Several PSH plants have been built or are under development with head levels below 50 m. For instance, at the existing Naussac dam in France, three reversible hydro units (3 MW in pumping mode, 2.65 MW in generation mode) were installed in 1998, with operating head levels between 32 and 57 m. Deriaz pump-turbines were selected for their ability to function efficiently across a wide range of flows in both pumping and generation modes.
- Initiatives have been launched to develop PSH projects adapted to flat countries, with head levels between 2 and 30 m, particularly in Northern Europe [42].

This approach appears highly promising for further development.

Additionally, report Q108-R11 discusses the case of Rwanda, where the hydro sector has seen significant growth. RWANCOLD's report highlights the potential of leveraging a unique configuration involving two volcanic lakes, Burera and Ruhondo, which are in close proximity and have a 100-meter elevation difference.

Twin Dams Concept

The "Twin Dams" concept involves two successive dams sharing a common reservoir. A power plant, located adjacent to the upstream dam, can pump or generate power under a head of a few meters to several dozen meters, handling large water volumes in a short time.

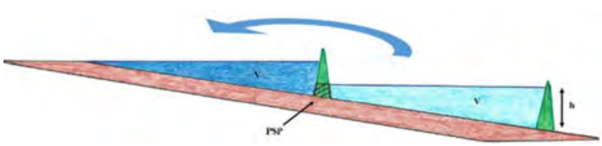


Fig. 22
Twin dams Concept [55]

These twin dams can be newly built or adapted from existing structures. The Bassieri project in Burkina Faso is an example of a new twin-dams project.

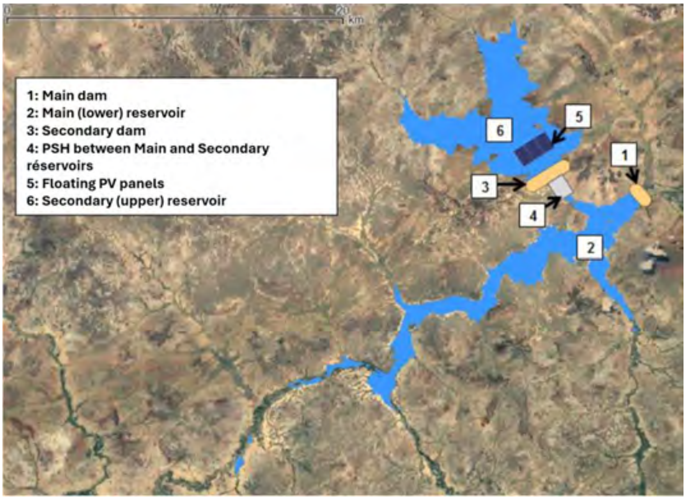


Fig. 23
Bassieri's Twin dams project

Capacity: 350 MWp solar, 120 MW pump mode, 85 MW turbine mode	Storage: 8h pump mode, 16h turbine mode	Average head: less than 15 m
The Bassieri project is a multi-purpose reservoir (660 hm^3) with primary functions including irrigation, electricity generation, potable water supply, fisheries, and aquaculture. The low available head in a flat topographical context severely limits the feasibility of a conventional hydropower plant attached to the dam. However, the twin-dam option increases the associated power generation capacity by a factor of 20, ensuring power reliability in all seasons, unlike a traditional hydropower plant. The design pumping discharge exceeds 1,000 m^3/s.		

Conceptually, this approach has been evaluated for large existing reservoirs such as Aswan and Kariba, where a new dam could divide the reservoir into two sections, integrating a new PSH facility. The resulting hydro-solar power stations would have significantly higher capacity and generation output than existing hydroelectric plants while freeing up water resources for other uses. [FLe]

5.2.5. *Utilization of seawater in Pumped Storage Hydropower (PSH)*

When freshwater resources become scarce, seawater can be considered as an alternative. Two main approaches have been explored and implemented: using seawater directly in hydraulic circuits or desalinating seawater.

In Okinawa, Japan, a PSH plant using seawater in its hydraulic circuit was commissioned. The plant had a capacity of 30 MW, a head of approximately 150 m, and a storage volume of around 0.5 hm^3. It was commissioned in 1999 but ceased operations in 2016 for non-technical reasons. There is significant interest in further developing this technology, particularly for coastal nations and islands. Issues related to corrosion and biofouling have viable technical solutions, inspired by practices in other industries ([46]), or such as those used in tidal power plants. For example, the La Rance tidal power plant has been operating in a saline environment for 60 years, and extensive documentation exists on its performance and maintenance. Several projects are currently under development worldwide.

The Salto de Chira PSH plant (200 MW) on the island of Gran Canaria (Spain) is fed by a seawater intake and a dedicated desalination system, which helps refill the existing Soria and Chira reservoirs without reducing volumes reserved for irrigation. This approach has also been selected for the Santiago PSH project (20 MW) in Cape Verde. [LC]

5.2.6. *Key technical aspects*

<u>Sealing solutions</u>

The following aspects complement the general discussion on sealing covered in §5.1.3.

The Q108-R5 report examines the sealing of PSH reservoirs and dams, drawing on case studies from approximately ten projects. It reviews three primary types of lining systems: Rigid upstream face linings (cement concrete, bituminous concrete, or, less commonly, vinyl tar) ; Well-graded Roller-Compacted Concrete (RCC) ; Geomembranes. The Q108-R17 report introduces an additional type: clay lining.

Three PSH reservoirs operated by EDF for over 50 years (Q108-R5) demonstrate the effectiveness of rigid face linings. The main challenges are concentrated in specific areas such as differential settlement zones, junctions, and interface connections. In these cases, drainage capacity and long-term performance are critical, and the report recommends: Enhanced drainage capacity ; Full accessibility for inspection and maintenance ; Monitoring systems for both drainage flow rate and pressure. One case study featured a double-lining system, found to be highly effective for projects where leakage poses significant risks.

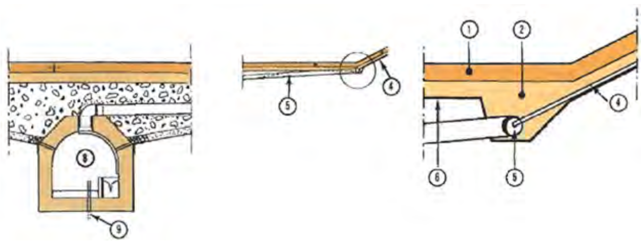


Fig. 24
Barrage de la Coche (Q108-R5) : (1) Primary Lining: Reinforced concrete slabs ; (2) Drainage: Porous concrete ; (6) Secondary Lining: PVC-P reinforced geomembrane - see Q108-R5 for a more complete legend

The Q108-R5 report presents the case of watertightness ensured by modern RCC for the closure dam of a PSP reservoir in an arid environment. The selected mix (modified Vebe index of 12 to 20s, optimization of aggregates to limit void index, high binder content including pozzolanic materials to achieve both an excess paste proportion and RCC with low susceptibility to autogenous shrinkage and early-age creep) allowed meeting the required performance criteria for a PSH dam that is watertight in its mass, with good strength and low final net long-term shrinkage. This allowed for wider spacing of contraction joints ; the joints are equipped with double waterstops embedded in GERCC. [Q108-R5]

The Q108-R5 report recalls that, until the mid-2010s, there was only one case of a PSH reservoir lined with a geomembrane: the Olivenhain RCC dam. Several recent references are described, each featuring an exposed geomembrane solution: Pico da Urze on Madeira Island in Portugal (rockfill dam), Kokhav Hayarden in Israel (compacted earth embankment, also presented in Q108-R17), Abdelmoumen in Morocco (embankment made of small rockfill, also presented in Q108-R8), and Pinnapuram in India (embankment made of large rockfill). In all these projects, the chosen geomembrane is PVC due to its mechanical properties and durability. The report details the solutions adopted to ensure proper support layer conditions and resistance to uplift of the exposed geomembranes.

Fig. 25
PSH of Kokhav Hayarden (left) and Abdelmoumen (right), Q108-R5, principle of lining by exposed geomembrane, with anchor strips, anchoring bands, and membrane installation.

The Q108-R8 report supplements the description of measures taken at Abdelmoumen to ensure the stability of the geomembrane against wind uplift: vents connected to the drainage system under the membrane generate a vacuum beneath it, and ballast blocks of concrete anchored at the crest of the embankment stabilize the most wind-exposed areas.

Fig. 26
PSP of Abdelmoumen, Morocco, Q108-R8, air extraction vents (left) and concrete ballast blocks (right) to ensure the stability of the geomembrane in case of storms.

The Q108-R17 report states that, in the case of the Jurong PSH (maximum water head of 180 m in the reservoir), the lining of the nearly horizontal bottom of the upper reservoir used other types of geomembranes: HDPE and TPO. The slopes of this reservoir were sealed with a bituminous concrete lining, and the junction between the geomembrane and the bituminous concrete lining was given particular attention.

Thin watertight linings in off-river dams, particularly PSH basins, are practical and efficient solutions. However, two key points of caution should be noted:

- Clay blanket linings can suffer from severe issues due to internal erosion, as the hydraulic gradients across the blanket thickness are significantly higher (much more than across a dam core, for example). Implementing safe filters and transitions is therefore a crucial aspect of such projects, especially when the blanket is placed in a rock context with potential cavities.
- Exposed geomembrane linings have a proven track record for watertightness in rockfill embankments. It is impossible to completely rule out the risk of membrane puncturing during the structure's lifetime, but in rockfill embankments, the only consequence is an increase in leakage until the membrane is repaired. The situation is different for geomembranes placed on low-permeability embankments with an immediate drainage layer beneath the membrane, such as at Kokhav Hayarden (Q108-R17). This is more challenging for two reasons: (1) maintaining the drainage system under the membrane over time is more difficult, and (2) in the event of significant membrane tearing, the drainage network may become saturated. For example, in the CSNE project (Q108-R9), the embankments consist of silts and chalk, which are low-permeability materials. Given the significant risk of membrane puncture by boats navigating the canal, it was deemed preferable not to provide immediate drainage under the membrane. Instead, percolation control was moved to the dam's axis, in the form of a filtration-drainage chimney.

Hydraulic circuits

Report Q108-R7 draws lessons from a pumped-storage project in an arid country, with a head of 150 m and a capacity of 2×125 MW. Two specific objectives were targeted: ensuring watertightness of the waterway (with a strict target in an arid region: losses limited to 150 l/min over the 1,200 m tunnel), minimizing head losses at intake structures, and reducing dead volume in both the upper and lower reservoirs. The selected solutions included a prestressed concrete lining with a waterproof membrane for the rock tunnel, and a triple modeling approach for the intakes: analytical calculations, numerical simulations, and physical models. The report provides a detailed presentation of these technical solutions.

Flexibility

The need for flexibility increases with the integration of intermittent renewable energies (wind, solar). The Abdelmoumen pumped-storage plant (Q108-R8) is a strong example: it is designed to handle frequent variations, with up to 20 start-stop cycles per day. The report highlights the specific challenges for electromechanical equipment, particularly turbines, and for the control-command system, which is optimized to minimize the duration of shutdown and restart sequences.

5.2.7. *Interest of CMDs for PSP reservoir dams [ML]*

The upper reservoir of a PSH plant, and sometimes also the lower reservoir in the case of a closed-loop PSH system, is formed by a large ring-shaped dam enclosing the reservoir. The most commonly used solution is a rockfill or earthfill dam with an upstream waterproof facing. However, hardfill gravity dams (Hardfill, CSG) offer several advantageous characteristics that make them a promising option for such projects:

- They have a reduced footprint, which is beneficial for a closed reservoir (good stored volume-to-dam volume ratio).
- They are tolerant to various and locally poor foundation conditions, which are often encountered in this type of setup.
- They are unaffected by uplift pressures, making them well-suited to frequent filling and emptying cycles, and generally offer a high level of safety.
- They can easily incorporate materials from the basin itself for the construction of the hardfill embankment.
- The integration of hydraulic functions is easier compared to earthfill dams.
- They are resistant to overtopping in case of accidental overfilling (see the previously mentioned Taum Sauk Dam failure).
- The construction rate of hardfill embankments can be very high.

This solution has been considered for the Gandi Sagar PSH project in India as well as for two large storage projects currently under preliminary study in South Africa.

5.2.8. *Reorienting Traditional hydropower production toward energy storage*

Pumped-storage plants are not the only means of compensating for the penetration of intermittent energy sources. Traditional hydropower plants are increasingly being used for this purpose.

This is the case for the Poatina hydropower plant in Tasmania, which is connected to Great Lake [64]. As this plant transitions to a more peaking-oriented operation, a re-regulation dam has been built downstream. Within the framework of climate change mitigation strategies and the transition to renewable energy, the operating regime of some traditional hydropower plants is shifting toward peaking operations, necessitating downstream re-regulation to stabilize water flows.

Fig. 27
Poatina Re-regulation Pond, Tasmania, Australia[64], Credit: Hydro Tasmania

Live storage: 1.5 hm^3		Function: regulating basin
Notes: This regulation basin was added downstream of the Poatina power plant, whose operation mode has changed to mitigate the impact of integrating wind farms in Tasmania. The increased frequency of starts and stops at Poatina have negative ecological impacts on the downstream river. The 1.5 hm^3 basin was built to mitigate these impacts; it is designed to smooth out 60% of the flow fluctuations caused by the plant's operations. [JW]		

5.3. Hydro-solar association

5.3.1. *Overview, principles and benefits*

General considerations

The principle of hydro-solar integration consists of combining the advantages of solar energy (abundant, increasingly affordable, and easy to develop) with those of hydropower (storable, dispatchable, cost-effective, and capable of providing grid services). This approach encompasses several concepts:\

- Floatovoltaics or FPV (Floating Photovoltaic): The use of dam reservoirs to install floating solar panels.
- VPP (Virtual Power Plant): A virtual power plant is created by the joint operation of hydroelectric reservoirs and solar power plants, managed by a single operator, with optimized grid injection.
- ShSH and HhSH (Slightly Hybridized Solar Hydro and Highly Hybridized Solar Hydro): Hybridization of hydro and solar on an existing hydroelectric dam. A solar farm is installed near or on a hydroelectric reservoir, and an EMS (Energy Management System) ensures the hybridization. ShSH and HhSH are distinguished by the power ratio between the solar farm and the hydroelectric plant installed capacities: the higher the ratio, the stronger the hybridization, and the greater the technical requirements for implementation. A two-phase approach can be considered for a given site: starting with ShSH and, after gaining operational experience, transitioning to HhSH.
- FSH (Full Solar Hydro) and Twin Dams: A hydro-solar power plant where electricity is primarily generated by solar energy, with regulation provided by hydropower. This can be implemented on either a hydroelectric or water supply dam.

The benefits of hydro-solar integration - and more broadly, hybridization - are now well recognized [CG]. This approach introduces two new ways of considering projects:

- With HhSH hydro-solar, reservoir operations can focus on non-energy services, while hydro-solar integration provides the energy component necessary for commercial viability.
- With FSH hydro-solar and Twin Dams, a new type of renewable power plant is created - one that does not consume water, is fully dispatchable, and is not limited by installed capacity. FSH and Twin Dams power plants can, globally, replace thermal power plants.

Thus, hydro-solar can play a crucial role in climate change adaptation. In its FSH version, it provides renewable, dispatchable electricity that is independent of water resources and can be deployed in many regions worldwide, particularly in sunny areas. In its HhSH and FSH versions, it reduces pressure on water resources without compromising electricity production.

Development of floating PV

Floating PV technology was initially developed for static water bodies (with no water level variations) and shallow depths. This technology has rapidly expanded.

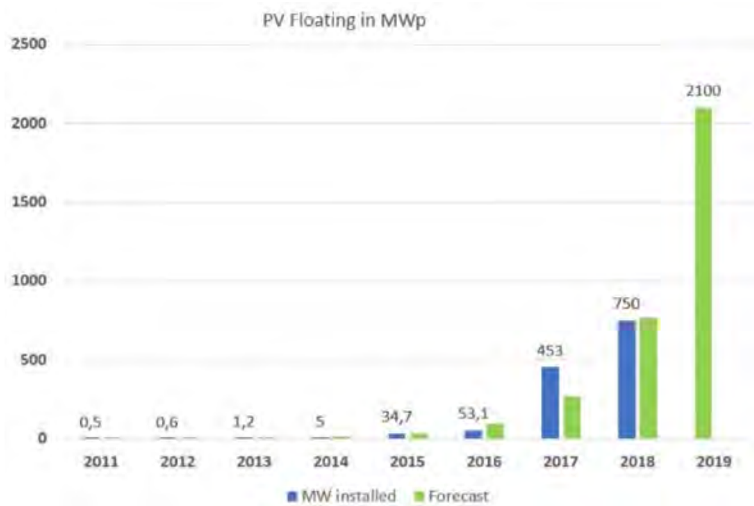


Fig. 28
Illustration from World Bank and SERIS Reports Showing the Rapid Growth of Floating PV [51]

Floating PV on dam reservoirs presents a significant potential for the expansion of this technology. However, it introduces new technical challenges: on larger reservoirs, waves are higher and more frequent; greater depths and water level variations complicate anchoring and mooring solutions; and the presence of a dam necessitates enhanced risk analyses for these installations.

Currently, only a few floating PV installations have been deployed on dam reservoirs. One country where this technology is rapidly expanding is India, with projects such as Ramagundam (100 MW in 2022), Kayamkulam (92 MW in 2022), Simhadri (25 MW in 2021), Rihand Dam (150 MW under installation), and Omkareshwar (600 MW under installation) [BD]. The Cirata project (Q108-R19) in Indonesia is a significant example of this type of development.

A comprehensive summary of floating PV can be found in [51], and an overview of the technical specifics of floating PV on dam reservoirs is available in [52].

Development of Hybridization

VPP-type hybridization is already being practiced by electricity utilities, who combine their various power sources to optimize electricity supply. Hydroelectric reservoirs are used to smooth out intra-hourly and intra-daily fluctuations in intermittent generation. FSH hybridization has found important applications, such as the Pinnapuram integrated power plant in India (Greenko Group, 1 GW of solar, 550 MW of wind, and 1.2 GW of pumped storage with 9 hours of storage capacity). Various ShSH and HhSH hybridization projects are under study.

A synthesis of the topic of hybridization can be found in [53].

5.3.2. *Technologies that still need to mature*

Floating solar is a relatively recent technology, with development beginning around the early 2010s. It was initially designed for shallow water bodies, generally of small size, with minimal water level variation and no dam structure.

Thus, floating solar on dam reservoirs differs in several ways. The anchoring, mooring, and floating solutions developed since 2010 are not necessarily suitable for the specific conditions of dam reservoirs, especially large ones:

- Depths can be significantly greater, and the designs have to adapt to water level fluctuations.
- Wave heights can be substantially larger.
- Large reservoirs experience more frequent waves of varying frequency and height, leading to fatigue on connectors.
- The consequences of an accident (e.g., loss of anchors) can be more severe.

Two reports provide feedback on these challenges: Q108-R12, covering a pilot project in Europe, and Q108-R19, detailing aspects of the Cirata project (145 MWp) in Indonesia. Report Q108-R12 highlights that the goal of the 2 MWp pilot project was to demonstrate the technical and commercial viability of a specific technology. The project consists of four 500 kWp units, installed on a floating island with a reinforced polymer or rubber waterproof membrane. The project was contracted through a 15-year Power Purchase Agreement (PPA). This pilot revealed multiple factors that could affect performance, including wave action, humidity, dust, and dirt accumulation. Report Q108-R19 describes the unique site conditions at Cirata Reservoir: depth of 100 meters; water level fluctuations of 20 meters; sediment deposits several meters thick at the reservoir bottom, with slopes exceeding 20 degrees in some areas. In this context, the chosen technical solution uses mooring via concrete deadweights equipped with metallic shear keys. The positioning of these mooring blocks is verified through an underwater positioning system (“Ultra-Short Baseline,” USBL), while operational monitoring is conducted via continuous GPS tracking of floating islands to detect drift.

Several other projects have been completed or are under development, employing different mooring and anchoring technologies, such as:

- Alqueva, Portugal: A European innovation program developed a mooring technology using highly elastic cables (Seaflex) to accommodate significant water level variations.
- Dau-Tieng, Vietnam: The reservoir's gently sloping banks create a large seasonally flooded area during high water levels. The project installed solar panels on poles in shallow water, designed to be submerged during peak flooding.
- Cheylas, France: A project under development for a dam reservoir with limited depth but significant water level variation (pumped storage basin). Instead of numerous concrete anchors, a small number of high-capacity anchors are used, offering better load distribution and improved adaptation to water level fluctuations.

Report Q108-R19 and these different approaches highlight some of the difficulties associated with mooring and anchoring floating PV platforms. The distribution of mooring forces depends on the precise position of the anchor blocks and varies with the combination of water level and wind orientation.

Learning from these innovative projects will help refine proven technologies tailored to the conditions of large dam reservoirs. Report Q108-R12 suggests establishing "innovation ecosystems" to develop and validate suitable technologies.

5.3.3. *New risks for dams?*

Floating solar panels on reservoirs may introduce new risks for dams. The strength of floating PV islands (anchoring, mooring, and connectors) is severely tested by winds and waves during storms, and several cases of island failure and drifting have been recorded.

This could impact dam safety. The greatest risk is the blockage of the spillway by drifting floating PV modules. Other risks include: additional forces on structures (e.g., intake towers) if impacted by a floating island; the risk of fire if a drifting island ignites; damage to a thin waterproof liner if struck by drifting PV panels.

As a result, efforts are being made to establish guidelines for floating PV projects on dam reservoirs. Two ongoing initiatives aim to publish guidance documents: the ICOLD Committee T is developing a bulletin, and the French Committee is preparing professional recommendations. Report Q108-R4 details the work of the French Committee, outlining key safety considerations for floating PV on dam reservoirs:

- Defining the necessary site reconnaissance surveys (geotechnical, wind, and wave conditions).

- Establishing design criteria, particularly regarding wind and wave parameters, and preparing a hypothesis report.
- Defining monitoring, inspection, and maintenance measures, especially for anchor systems.
- Clarifying the division of responsibilities between the dam operator and the floating solar plant operator (ensuring operational procedures are coherent between both entities).
- Implementing safety controls during critical installation phases.

This report concludes that specific risk analyses should be conducted before authorizing floating solar power plants on dams.

5.3.4. *Hybridization*

Beyond simply sharing reservoir surface area and transmission lines, hydro-solar hybridization can lead to new renewable power generation projects that provide both abundant and reliable electricity. Solar-hydro hybridization integrates a solar farm with a hydroelectric infrastructure, allowing for optimized electricity generation across multiple time scales.

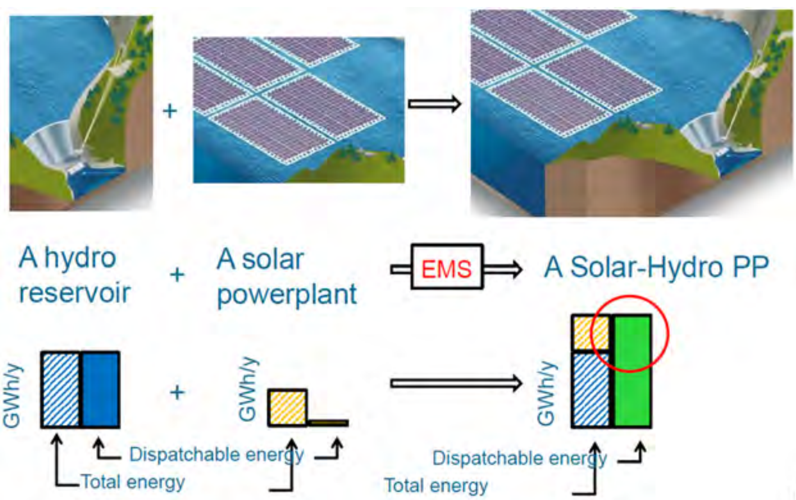


Fig. 29
Generic principle of Solar-Hydro hybridization [51]

Hybridization can be implemented in various configurations:

- Hybridization with a hydroelectric reservoir: ShSH and HhSH
    - ShSH (Slightly Hybridized Solar-Hydro): The installed capacity of the solar farm is limited; hydroelectricity compensates for solar production variability due to cloud cover without requiring significant modifications to hydraulic infrastructure. This was demonstrated in the Alqueva pilot project (Portugal).
    - HhSH (Highly Hybridized Solar-Hydro): The installed solar capacity is higher; hybridization requires faster and more significant variations in hydroelectric production, necessitating technical adjustments to turbines and the grid. This approach is currently under study for the Manantali project (Mali).
- Hybridization with dedicated hydraulic storage: FSH
    - FSH Type 1: A solar farm combined with a pumped storage power plant. This configuration enables energy storage for several hours and is suitable for large-scale plants, as implemented in Pinnapuram (India).
    - FSH Type 2: Integration of a solar farm, a pumped storage facility, and a reservoir dam, enabling storage on daily or seasonal scales. This approach is being explored for the Bassiéri project (Burkina Faso).

In all cases, the hybridized system is managed by an Energy Management System (EMS), which coordinates the production of the various components of the hybrid system. A key function of the EMS is handling fluctuations in solar production caused by cloud cover. In many climates, cloud coverage can reduce solar irradiance by 80% within minutes. The EMS adjusts hydroelectric production to absorb these fluctuations while considering technical and environmental constraints, particularly those limiting the rate of change (gradients) in turbine flow.

The EMS employs a combination of techniques: in ShSH, it optimizes power distribution between solar, hydro, and possibly batteries ; in HhSH, it also integrates ultra-short-term solar irradiance forecasting (5-15 min) to smooth fluctuations and uses solar curtailment (voluntary reduction of solar production on unstable sunny days) to mitigate abrupt variations.

Solar-hydro hybridization is naturally considered for intra-daily and daily timescales but can also be adapted for seasonal storage. Integrating long-term hydraulic storage allows production to be adjusted to seasonal variations in solar energy. Studies show that a hydraulic storage equivalent to 20 days of solar production can completely smooth solar output in Aswan (Egypt), while 6 days are sufficient in Brasília (Brazil), but 90 days are required in Paris (France) due to the significant drop in winter solar irradiance [53].

The figure below is an illustration of the Xiangbilin “hydro-wind-solar-storage-agriculture” hybrid clean energy base, developed in China.

Fig. 30
Xiangbiling "Hydro-Wind-Solar-Agricultural" Hybrid Clean Energy Base

5.4. Other pumping solutions

5.4.1. *Flood mitigation*

Pumping can be an effective solution for flood control in lowland rivers and estuaries. This method has been implemented in the Netherlands and New Orleans, as discussed in the chapter on "sea barriers" (§5.6).

This approach can also be explored for lowland rivers far from the sea, where the river slope is sufficiently low (typically less than 20–30 cm per km). It has been considered for the Seine River in Paris and the Île-de-France region, with different options compared to more traditional estuarine closure dams:

- Option (a): A pumping station combined with a gated weir to regulate water levels.
- Option (b): A matrix of hydrokinetic turbines operating in "propeller mode" to accelerate river flow.

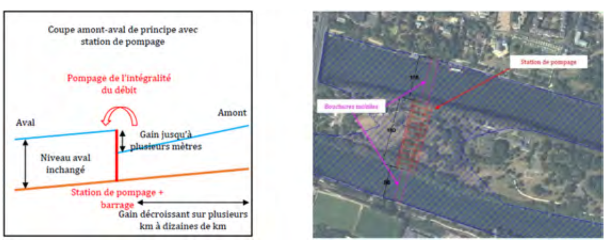


Fig. 31
EFEL "Extreme Floods Elevation Lowering system", option (a): using the pumping station method [56]

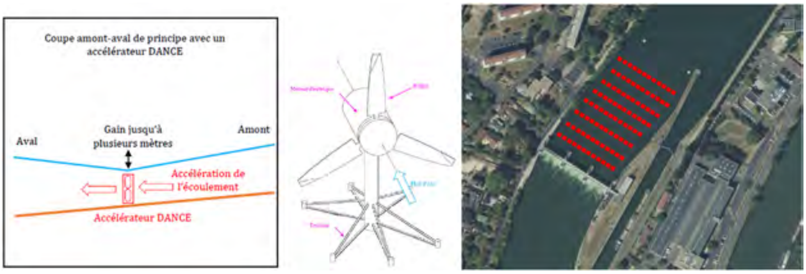


Fig. 32
EFEL “Extreme Floods Elevation Lowering system”, option (b): using the Propeller Matrix method

These options are still at the exploratory stage

5.4.2. *Seasonal storage reserves*

In recent decades, two major trends have emerged, which are expected to continue:

- The increasing penetration of intermittent renewable energy sources has led to periods of very low electricity prices.
- The growing irregularity of water resources has increased the economic and social value of stored water.

Both of these factors enhance the interest in pumping as a means of refilling existing reservoirs or new storage facilities. Pumping can either be continuous at a low flow rate or concentrated at specific times of the year (depending on river flow conditions and electricity prices). Potential applications include:

- Low, continuous pumping downstream of hydroelectric dams operating with large variations in turbine discharge, to refill the reservoir.
- Seasonal pumping during the rainy season from a neighboring river with high seasonal flows, to fill a large reservoir.

5.5. Aquifer storage and underground dams

5.5.1. *Overview, principle, and benefits*

Aquifers are widely used as a water resource worldwide. In many areas, they are overexploited. To mitigate these effects, the preferred methods involve promoting infiltration and limiting withdrawals. In addition to these approaches, numerous trials and projects have been conducted to recharge aquifers.

Aquifer recharge involves artificially increasing water volumes within an aquifer, whether it is a surface (alluvial) or deep aquifer. This concept presents significant advantages, at least in theory, particularly in arid or semi-arid climates: no evaporation, no volume loss due to sedimentation, and generally no need for a flood spillway. This approach has often been explored as a means of counteracting the effects of overexploitation and maintaining an accessible water reserve during the dry season [57]. It is also being considered as a way to replenish long-term and very long-term reserves by encouraging the infiltration of excess water in certain years (for example, California, where measures were implemented to optimize the infiltration of excess water during the winter of 2022–23).

Dams are sometimes used for this purpose:

- *Recharge dams* are sometimes used to facilitate groundwater replenishment.
- Dams have also been built to create new aquifers, known as *sand dams*. Many such structures - typically small - have been constructed, for instance, in Kenya.
- *Underground dams* serve a different function: they are not intended to increase infiltration volumes but rather to raise the water table level. Most of the dams built for this purpose have been designed for groundwater storage. In some cases, they serve as barriers to prevent the intrusion of saltwater near coastlines ("salt barrier") or even polluted water, thereby protecting freshwater aquifers.

The following sections distinguish between subsurface dams (which support storage in surface aquifers) and dams targeting deep aquifers.

It is generally observed that such projects remain relatively rare and that some have faced challenges or failures. However, Table 1 highlights the significant volume of underground resources, and thus, at least in theory, the potential benefits of improving aquifer recharge and underground storage. As Anton Schleiss states, "*Aquifer recharge dams will certainly be of greater interest in the future, but their implementation is complex and requires further R&D*" [AS].

5.5.2. *Surface aquifer storage*

Surface aquifer storage involves storing water within alluvial deposits using a dam that intercepts subsurface flows, maintaining an upstream-downstream water level difference. The following diagrams, developed by INOWAS [48], illustrate some of the applied concepts.

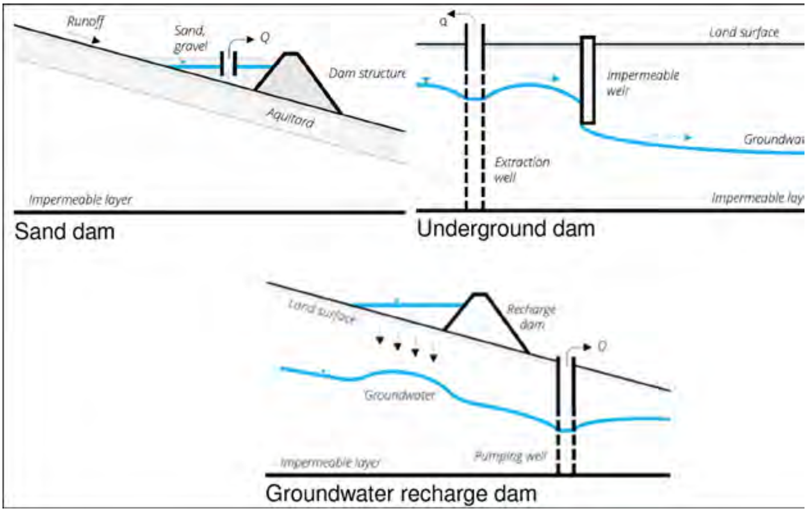


Fig. 33
Different types of dams to increase storage in surface aquifers [48]

Small Dams: Ensuring a Water Supply for Subsistence During the Dry Season

There are numerous small dams functioning as “sand dams” in the semi-arid regions of the Sahel in Africa, whether they were intentionally designed as such or simply resulted from local climatic conditions. In these cases, reservoirs dry up during part of the year, but a perched aquifer persists within the alluvial deposits of the reservoir [RS].

Report Q108-R1 explores the potential of sand dams as a water storage solution for arid regions. The authors note that a large number of these projects have been implemented by NGOs, which have observed that these underground reservoirs provide a useful water supply for local populations, particularly during drought periods. Additionally, the fact that groundwater does not attract mosquitoes is a significant advantage. However, a high failure rate is reported - around 50% - mostly due to fine sediments accumulating in the reservoir. Q108-R1 suggests increased cooperation between NGOs, which develop these projects, and dam professionals, who can contribute valuable expertise to reduce failure rates. The required expertise covers geology, hydrology, and sediment transport, as the reservoir must be small enough to prevent fine sediment deposition and to ensure that only coarse sediments accumulate behind the dam. A practical example of such a dam in Kenya illustrates these principles [1].

A variation of sand dams is the concept of "sponge riverbeds," developed in China. This method involves replacing riverbed alluvium with granular materials such as sand and gravel. As a result, the riverbed retains a significantly larger volume of water (up to 450 kg/m^3), thereby increasing underground water reserves protected from evaporation. Additionally, this approach improves surface water flow. This technique remains experimental, but it highlights the renewed interest in surface aquifer storage [JJ].

Large aquifers: mobilizing greater water resources

However, the resources provided by small dams remain limited. Only certain projects enable the mobilization of significant water volumes. These include underground dams and recharge dams.

Underground Dams – A 2016 inventory of projects identified only a small number of underground dam projects where the volume of water mobilized exceeded 10,000 m^3 per day, equivalent to 100 liters per second or 3 hm^3 per year.

Fukusato, Sunagawa, Minafuku (Okinawa, Japan)	Three underground dams built in the same valley.Aquifer: highly permeable Ryuku limestone horizon (3.5 10^{-3} m/s), thickness 10 to 70 m, porosity 10%.Sealed cut-off height: 16.5 to 50 m Annual production: 7 and 8 hm^3/year for Sunagawa and Fukusato (the smaller Minakafu was built as an experiment). Reservoir capacities: 10.5 - 9.5 and 0.7 hm^3
Nakhara (Okinawa, Japan)	Underground dam Aquifer: highly permeable Ryuku limestone horizon Annual production: 9 hm^3/year Reservoir capacity: 2 hm^3
Komesu (Okinawa, Japan)	Underground dam acting as a salt barrier. Significant height (69 m) Aquifer: highly permeable Ryuku limestone horizonAnnual production: 1.8 hm^3/year Reservoir capacity: 2 hm^3
Tadjemout (Algeria)	Underground dam Aquifer: sands and pebbles, in contact with a sandstone formation; permeability of alluvium: 10^{-3} m/s Annual production: around 6 hm^3/year The alluvial water table is fed by a spring in the sandstone.
Ssangcheon (S. Korea)	Aquifer: Coarse alluvium Annual production: around 12 hm^3/year The alluvial water table is fed by surface runoff (infiltration).

Several of these projects have been developed on the island of Okinawa, Japan, due to the specific topographical (rugged terrain) and geological (a highly permeable formation of a few dozen meters overlying an impermeable bedrock) conditions. This provides valuable feedback for similar conditions [47]. In general, four conditions are necessary for an underground dam to mobilize significant water resources:

- An underground reservoir:
    - Composed of coarse alluvium or highly permeable rock, typically with permeability greater than 10^{-4} m/s,
    - Of sufficient capacity: topographic volume available above the natural water table, multiplied by the accessible porosity.
- A hydraulic closure:
    - At the base and along the reservoir's banks, low-permeability geological formations (typically a permeability contrast of a factor of 100) or a sufficiently high water table level along the banks,
    - A natural barrier where an impermeable cut-off can be installed at a reasonable depth, with cases documented down to 70 meters.
- Adequate water supply to the reservoir:
    - Ideally, through direct underground flow, as seen in Okinawa,
    - Alternatively, through infiltration from surface water, though this presents clogging issues,
    - In all cases, verification of the annual underground water flow volume is necessary.
- Impact verification : in particular, assessing the impact of lowering the water table (both in elevation and annual flow) on downstream wells and boreholes

Recharge dams

Recharge dams create conventional storage reservoirs with systems that promote water infiltration. These include:

- Reservoirs located above the aquifer, on permeable strata, allowing stored water from the rainy season to infiltrate into the aquifer.
- Conventional reservoirs, from which controlled releases are directed toward infiltration fields, either natural or enhanced with infiltration wells.

It would be useful to conduct a review of large dams where groundwater recharge is the primary function. To the author's knowledge, no such comprehensive study is currently available. However, it is worth noting that many dams contribute to aquifer recharge due to leakage through reservoir banks.

Dam for deep aquifer storage

No significant examples of dams (in the sense of impermeable cut-offs) for deep aquifer storage were found during the preparation of this report. Artificial deep aquifer storage, known as Aquifer Storage and Recovery (ASR), involves injecting freshwater into deep aquifers. While it remains a relatively underutilized technology, several large-scale applications exist, particularly in the United States:

According to some publications [49] , the cost of this form of storage is of the same order of magnitude as surface storage by dams. This still has to be confirmed.

Table 3
Examples of deep aquifer storage, USA

	STORAGE VOLUME, HM^3	DAILY PRODUCTION CAPACITY, M^3/DAY
Las Vegas, Nevada	400	750,000
San Antonio, Texas	85	225,000
Calleguas, California	40	150,000

5.5.3. *Maintaining aquifer renewal through additional surface storage*

One way to ensure aquifer recharge is by reducing groundwater abstraction. The new reservoir projects in England (see §3.4) are specifically designed to reduce pumping from the chalk aquifer. This allows the aquifer to maintain its levels, even during the dry season, thereby naturally supporting its ecological functions, such as sustaining small streams and wetlands.

5.6. Offshore dams and sea barriers

5.6.1. *Overview, principles and benefits*

The term “sea barriers” or “sea dams” refers to structures that retain seawater. These barriers can serve various purposes:

- Coastal protection, such as the Delta Works barrier in the Netherlands.
- Tidal power generation, exemplified by the Rance Tidal Power Station in France.
- Energy storage, by creating an offshore reservoir for a pumped-storage hydropower system using seawater. While no such facility currently exists, initial experiments have been conducted with pumped-storage systems utilizing seawater, such as the Okinawa pumped-storage plant in Japan.

Fig. 34
Delta works, Netherlands

The general principle involves constructing a closure structure at sea, which may be supplemented by regulation structures such as gates, turbines, or locks.

Fig. 35
La Rance dam

Fig. 36
Sihwa dam, By Arne Müseler / www.arne-mueseler.com

The benefits of coastal protection are evident in low-altitude areas that are vulnerable to rising sea levels, especially where retreat options are unfavorable. In the Netherlands, levees have been designed to withstand events with a return period of up to 10,000 years (considering a combination of tidal levels and storm surges), protecting a quarter of the population.

The use of sea barriers for tidal power generation has historically been proven effective in coastal areas where tidal range exceeds 4 meters. Tidal power is a renewable, predictable, and economically viable energy source. Existing projects include the Rance Tidal Power Station (240 MW) in France and the Sihwa Tidal Power Plant (254 MW) in South Korea. New projects are under study in the United Kingdom (Swansea Bay, Mersey River), with capacities reaching several hundred megawatts. A feasibility study conducted in France [39][40] confirmed the potential of this technology and demonstrated that, under certain conditions, it could be viable even with lower tidal ranges (see “tidal gardens”, below).

Energy storage at sea operates similarly to pumped-storage hydropower (PSH) systems on land. Due to coastal dynamics, extensive cliff shorelines allow for the construction of reservoirs with embankments resting on shallow seabeds, which have been shaped by progressive coastal retreat. Marine reservoirs enable PSH projects with high turbine flow rates, short distances between upper and lower reservoirs, and potentially multi-day storage capacities in the upper basin.

Environmental concerns related to sea barriers and sea dams are complex, as coastal ecosystems are often rich and sensitive. However, two factors suggest that such projects are both feasible and potentially desirable.

- Coastal protection is already a necessity and will become even more so in the future due to increasing risks of coastal flooding - not only in the Netherlands but also in other vulnerable regions. Since coastal defenses will inevitably be required, it makes sense to consider additional services they could provide, such as energy production or storage.
- Many coastal areas are already highly anthropized or polluted, particularly near industrial zones, ports, or thermal and nuclear power plants. Notably, the Swansea Bay tidal project in the UK received support from NGOs due to its potential environmental benefits.

5.6.2. *Coastal protections: examples and ideas*

Rising sea levels pose complex challenges for coastal populations. The range of possible responses varies and must be tailored to local conditions:

- Managed retreat, where populations are relocated to safer areas.
- Storm protection, involving coastal erosion mitigation and the reinforcement of natural or artificial barriers, with an increasing focus on eco-engineering and nature-based solutions to prevent wave overtopping.
- Raising coastal defenses, through the elevation of existing protection structures.

This report does not aim to comprehensively address the topic but highlights cases where large-scale infrastructure solutions - true “barriers” against extreme water levels and storms - have been implemented.

The Netherlands is protected by the Delta Works dike system (1953-1985), a network of over 100 km of artificial dikes built to close off estuaries or protect specific zones. Mobile storm surge barriers manage the connection between rivers and the sea, allowing for controlled flood management. In 1993 and 1995, century floods on the Meuse and Rhine rivers caused severe flooding, prompting the implementation of the “Room for the River” program, which expands floodplains to absorb excess water during peak events. Pumping stations are necessary to return excess water to the sea. One such facility, Afsluitdijk, was recently renovated, increasing its capacity to 275 m^3/s with a head of 3.40 m. With continued sea-level rise, the Netherlands is considering modifications to its coastal protection system. One proposed solution, “seaward”, involves constructing a large offshore barrier, combined with very high-capacity pumping stations.

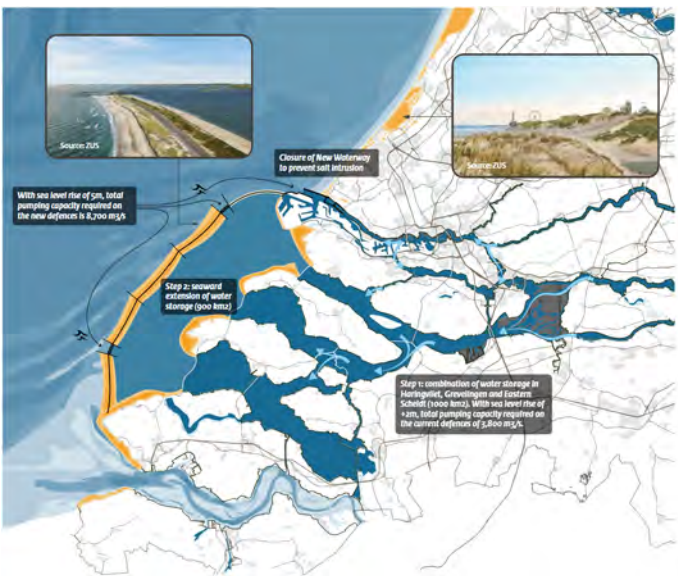


Fig. 37
Adaptation strategies for +4 or +5m sea level rise, seaward option, [67]

In the United States, the disaster caused by Hurricane Katrina led to major coastal flood protection projects in the Mississippi Delta. These projects needed to balance two key functions: allowing river discharge while protecting inland areas from sea storms, which combine sea-level rise and high waves. One of the key structures built for this purpose is the West Closure Complex, constructed by USACE (U.S. Army Corps of Engineers) and illustrated below. Similar to Dutch flood protection systems, this complex combines: closure walls or levees, a large mobile barrier, which remains open under normal conditions but closes during storms, a pumping station, capable of transferring the entire river discharge when the barrier is closed.

Fig. 38
The “West Closure Complex” system: illustration of the system (left)[69] ; system in operation during Hurricane Isaac (right) Photo by: PAO, USACE, New Orleans District

5.6.3. *Tidal energy: the Tidal garden concept*

Tidal energy has seen a renewed interest in recent years for two main reasons: it is a renewable and highly predictable electricity source ; rising sea levels create a growing need for coastal protection, which can be combined with power generation or energy storage.

One of the main limitations of conventional tidal power plants is their dependence on large tidal ranges to be economically viable. An alternative concept has been proposed under the name “tidal garden” [41]. These tidal gardens combine a tidal basin with channels equipped with stream turbines. The principle involves connecting large tidal basins (hundreds of square kilometers) to the sea through channels that are several kilometers long, where rows of stream turbines are installed. [FLe]

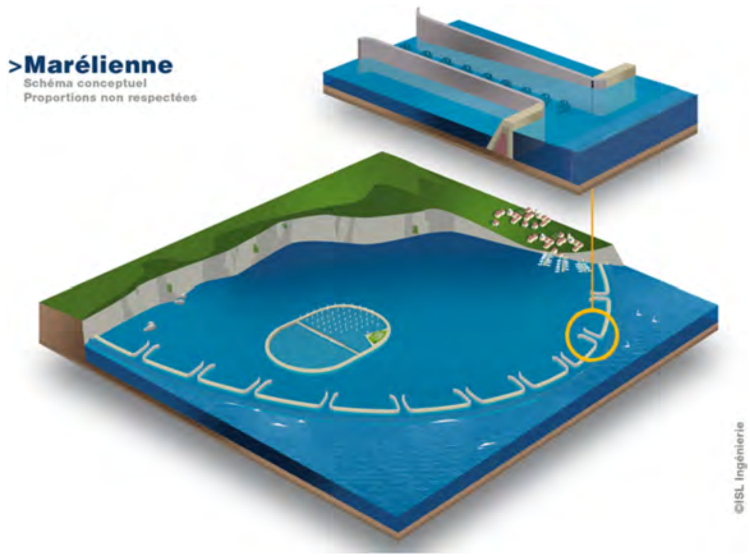


Fig. 39
The Tidal garden concept, © ISL ingénierie

At this stage, tidal gardens remain a conceptual development, but they offer several advantages:

- They operate effectively with lower tidal ranges compared to traditional tidal power plants (lower hydraulic head but higher flow rates).
- The channel system enhances hydraulic exchange between the tidal basin and the sea, reducing the artificial nature of the basin.

According to preliminary evaluations, this solution is particularly attractive for countries with lower tidal ranges, making it viable in approximately 15 countries worldwide, with an estimated global potential of 1,000 TWh/year. [FLe]

6. ACRONYMS

GHG: Green House Gas

IPCC: International Panel on Climate Change

RCP: Representative Concentration Pathway: the four global scenarios considered by the IPCC. RCP8.5; RCP6.0; RCP4.5; RCP2.6, the figures represent the radiative forcing (in W/m^2 by 2100), i.e. the deviation from the pre-industrial radiative balance.

GLOF: Glacial Lake Outburst Flood

GCM: Global Climate Model, see bulletin 200 for a definition.

RCM: Regional Climate Model, see bulletin 200 for a definition.

LCSA: Life Cycle Sustainability Analysis

ESAI: Environmental and Social Impact Assessment

IPBES: International Panel on Biodiversity and Ecosystemic Services

ShSH: Slightly Hybridized Solar Hydro (a solar farm and a hydropower plant, with the solar farm AC peak power around 20% to 40% of the hydropower installed capacity)

HhSH: Highly Hybridized Solar Hydro (a solar farm and a hydropower plant, with the solar farm AC peak power around 30% to 70% of the hydropower installed capacity)

FSH: Full Solar Hydro (a solar farm + a dedicated pumped storage)

PSH : Pumped Storage Hydro

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7.2. Personal contributions

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BARRAGES ET RESERVOIRS : ADAPTATION AUX CHANGEMENTS CLIMATIQUES

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TABLE OF CONTENTS

1. RÉSUMÉ

1.1. ENJEUX DE L'ADAPTATION AUX CHANGEMENTS CLIMATIQUES

La question 108 s'intitule « Barrage et Réservoirs : Adaptation aux changements climatiques ». Les barrages et réservoirs (et les digues de protection) sont triplement concernés par l'adaptation aux changements climatiques :

- Nos ouvrages *contribuent à l'adaptation* des sociétés, dans un contexte marqué par la pénétration des énergies intermittentes et par davantage d'irrégularité climatique (sécheresses, crues),
- A condition cependant de vérifier leur *adaptabilité* à ce climat futur, c'est-à-dire la capacité à toujours rendre les services attendus,
- Et à condition de vérifier leur *robustesse* dans le climat futur, c'est-à-dire leur capacité à faire face aux aléas nouveaux.

Les barrages et digues que nous concevons et construisons ont à jouer un rôle en 2050, 2100 et au-delà. La réflexion sur l'adaptation au changement climatique de ces ouvrages est nécessairement empreinte d'humilité, car **il est difficile d'anticiper ce que sera la situation future** :

- Le moteur du changement climatique est mondial, et dépend des quantités de Gaz à Effet de Serre (GHG, Green House Gases) qui seront émis dans l'atmosphère. Plusieurs scénarios d'émission sont décrits par IPCC*, de RCP2.6 à RCP8.5.
- Le GIEC utilise ces scénarios pour élaborer une ***projection* du climat futur** à l'échelle de la planète ; cette modélisation comporte des incertitudes, en particulier pour les scénarios de plus forte émission, car il pourrait y avoir des effets de seuil déclenchant des phénomènes climatiques inattendus et non pris en compte dans les modèles.
- Les incidences sur le climat local (température, précipitations, débits des cours d'eau, ...) peuvent être modélisés à partir de ces modèles globaux. Il s'agit d'un travail scientifique pouvant être délicat, qui aboutit à des projections du climat local futur, et qui sert de base à l'élaboration de scénarios d'évolution des ressources en eau.
- La **demande future en eau** va également évoluer ; pour des raisons purement physiques (modification de l'évapotranspiration), et également car le changement climatique et les évolutions sociétales (pénétration des EnR intermittentes, modification des pratiques culturales, modification des habitudes alimentaires, urbanisation, ...) modifieront la structure et le volume des besoins. Là également, des scénarios, d'évolution de la demande, doivent être considérés.

*Les acronymes sont explicités au §6

- Ainsi, il y a une **incertitude significative** dans l'anticipation de ce que seront, dans chaque pays, les ressources en eau, les besoins et les aléas climatiques, aux horizons 2050, 2100 et au-delà. A cette difficulté, il faut ajouter deux sujets qui devraient prendre une importance particulière et qui ajoutent à l'incertitude : biodiversité, coopération internationale.
- Les mesures nécessaires pour limiter l'effondrement de la **biodiversité** mobiliseront une partie de la ressource en eau disponible, en renonçant à la construction de certains barrages, et en affectant une partie de volume mobilisé par les barrages à cet usage ; la fraction de la ressource en eau douce à consacrer à la biodiversité pourrait être très élevée.
- Le changement climatique ne modifie pas le volume d'eau douce disponible (il pourrait même l'accroître), il le rend cependant plus erratique et géographiquement mal distribué ; la **coopération internationale**, et notamment entre pays voisins, peut donc être un facteur majeur d'amortissement de certaines crises futures (vagues de chaleur, sécheresses) par des mécanismes de partage de l'eau disponible – il semble malheureusement difficile, aujourd'hui, de pouvoir compter avec assurance sur une telle coopération.

1.2. Des mesures d'adaptation déjà à l'œuvre, dans plusieurs pays

Le changement climatique est déjà à l'œuvre, les sociétés prennent déjà des mesures d'adaptation, et cela permet de prendre conscience des enjeux auxquels les barrages, réservoirs et digues seront de plus en plus exposés. **Quelques exemples**, extraits des contributions reçues pour élaborer ce rapport général :

- Des épisodes de crues extrêmes plus forts que par le passé, et de nouveaux aléas (GLOF par exemple), susceptibles de mettre en danger les barrages et les digues, se sont produits ou sont redoutés.
- Dans de nombreux pays, constatant que le changement climatique génèrera de l'irrégularité dans la disponibilité de la ressource en eau, les autorités mettent en place des stratégies de mobilisation de la ressource, notamment par des réservoirs de surface.
- Dans certains pays ou régions, de longues périodes de sécheresse se sont installées, au point que les réservoirs des barrages ne se remplissent plus, ce qui les empêche de rendre les services attendus et cela pendant plusieurs années consécutives. Cette situation peut mettre en doute l'adaptabilité de ces ouvrages dans les décennies à venir. Cela conduit, dans les pays ou régions concernés, à une réflexion d'abord centrée sur les économies d'eau et la diminution de la demande en eau, ou la recherche de nouvelles ressources, dessalement de l'eau de mer, réutilisation des eaux usées par exemple).
- La pénétration des énergies renouvelables intermittentes (éolien et solaire notamment) renforce les besoins en stockage d'électricité, aux différentes

échelles de temps. Il y a besoin de flexibilité pour réagir aux variations rapides, de stockage infra-journalier pour le solaire, et à l'échelle de plusieurs semaines ou plusieurs mois. De nombreuses STEP sont en construction dans le monde. Des projets et travaux d'adaptation des centrales hydroélectriques pour plus de flexibilité (infra-horaire) sont en cours.

- L'augmentation de la fréquence des inondations conduit certains maîtres d'ouvrage à ré-examiner les conditions d'exploitation de leurs barrages, de sorte à augmenter le volume disponible pour stocker une partie des crues. L'amélioration des moyens de prévisions des crues permet dans certains cas des gains substantiels.
- Dans certains pays, la production d'électricité par les barrages au fil de l'eau (sans capacité de stockage) perd de l'intérêt lorsqu'il n'y a pas, en tête de bassin versant, un réservoir naturel ou artificiel assurant une régularisation des écoulements. D'une part car dans ce cas les plus grandes fréquences et durées des sécheresses rendent la production hydroélectrique moins prévisible ; d'autre part car, lorsque l'hydroélectricité est intermittente et exposée aux sécheresses, les autres EnR peuvent être de meilleures options.

1.3. Des principes généraux pour l'adaptation

Dans ce contexte, et compte-tenu des expériences vécues par un certain nombre de pays, il est possible de tirer **un certains nombre de principes**.

Les recettes du passé ne sont plus nécessairement les bonnes : un « bon projet » de barrage d'il y a 20 ans n'est plus nécessairement un « bon projet aujourd'hui », en raison du contexte imposé par le changement climatique, en raison des exigences de *soutenabilité* des projets de barrages. Il n'y a pas de recettes universelles : le moteur du changement est mondial, mais les déclinaisons climatiques et les solutions d'adaptations diffèrent beaucoup d'un pays à l'autre. Ainsi, il est nécessaire, dans chaque pays ou région, de **réévaluer les ressources, les besoins, les aléas**, aux horizons temporels adéquats (2050, 2100 et au-delà) pour être en mesure de **proposer les bonnes réponses** en termes d'adaptation. Ce travail préalable à tout projet d'envergure est indispensable.

L'expérience des pays actuellement les plus exposés à la rareté de la ressource donne des indications utiles sur les stratégies à mettre en œuvre plus globalement, dans les régions où le changement climatique augmente le risque de sécheresses**. Les mesures de maîtrise et réduction de la consommation en eau sont essentielles** : mesurer et quantifier les consommations, perfectionner les règles de partage des eaux, réduire la demande en luttant contre les gaspillages et en adoptant des mesures d'économie d'eau dans tous les secteurs, se préparer aux crises.

En parallèle de ces mesures, il y a souvent lieu de prévoir des moyens de **mobilisation de la ressource**, par les réservoirs existants ou par de nouveaux réservoirs.

Un nombre important des **réservoirs existants peuvent être optimisés**. Les usages pour lesquels ils ont été conçus peuvent être révisés : utiliser les réservoirs hydroélectriques pour le stockage de l'électricité et le soutien au réseau (flexibilité) plutôt que pour la seule production électrique de base ; revoir les règles de partage des eaux pour laisser plus de place à la garantie d'alimentation en eau ou au soutien à la biodiversité, au détriment éventuellement de la production électrique ou de l'irrigation courante. Il est également possible d'optimiser l'exploitation à condition de pouvoir collecter des données pertinentes : mesures d'état de l'humidité des sols et des nappes pour anticiper la demande en eau et ainsi actualiser les règles de gestion, mesures des stocks de neige pour anticiper les apports futurs, installation d'outils de prévision des crues pour pouvoir opérer des creux préventifs et renforcer le rôle de protection contre les inondations, ... Il est enfin possible d'optimiser la répartition des ressources par les **interconnexions** de réservoirs et les **ouvrages de transfert**, depuis les régions humides vers les régions sèches.

Une question majeure, en contexte de rareté de la ressource, est celle du partage de l'eau. Il est important de mettre en œuvre des méthodes d'analyse qui ne donnent pas une priorité excessive aux usages commerciaux, monétisables. A cet effet, les approches économiques utilisées pour l'évaluation des projets devraient systématiquement **valoriser les externalités**, positives et négatives. Le coût social du carbone fait partie de ces externalités, mais ce n'est pas le seul item. Il faut notamment valoriser avec justesse des externalités positives telles que : la sécurisation de l'alimentation en eau et le secours à l'agriculture en cas de sécheresse, les services au réseau électrique rendus par le stockage et la flexibilité, le soutien à la biodiversité, etc ...

De **nouvelles capacités de stockage devront être envisagées** dans de nombreux endroits du monde. Elles contribueront à l'adaptation des sociétés par de multiples fonctions : le stockage de l'énergie et la capacité à compenser (au moins en partie) l'intermittence des énergies éoliennes et solaires, la constitution de réserves pour garantir l'alimentation en eau lors des saisons sèches, la constitution de réserve ultimes pour les cas de crises graves et, si elles sont dimensionnées à cet effet, la protection contre les inondations.

Ces nouvelles capacités sont obtenues par surélévation de barrages existants, ou par de nouveaux barrages. Lorsque des travaux neufs de ce type, il faut éviter la « mal-adaptation ». En particulier s'assurer que la ressource en eau future sera suffisante pour remplir ces réservoirs, et que la sédimentation ne viendra pas annuler les bénéfices du projet en quelques années ou décennies. Et vérifier que les paramètres de *soutenabilité* du nouveau projet sont bons : s'il n'est pas soutenable (au sens de l'environnement et de la société) un nouveau projet de stockage peut être contre-productifs du point de vue global de l'adaptation au changement climatique et devrait être abandonné au profit d'un meilleur projet.

L'eau est inéquitablement répartie dans le monde. Le changement climatique ne devrait pas diminuer la quantité d'eau douce libre disponible globalement (hors glacier et banquise), mais il modifiera et probablement accentuera les irrégularités spatiales. Il y a alors une logique physique à établir des **outils de coopération internationale**, en particulier entre pays voisins, pour limiter les effets de ces modifications. Ces outils (traités, conventions, ...) sont de nature à amortir certains des effets du changement climatique, et à limiter les tensions sociales et politiques qui pourraient en résulter.

1.4. Des progrès techniques et d'autres idées nouvelles

Les projets actuels et futurs diffèrent souvent des projets d'il y a 20 ou 50 ans. Parmi les idées émergentes, certaines sont intéressantes dans l'objectif d'adaptation. Voici quelques-unes de ces idées pratiques :

Le **stockage de l'eau hors rivière** est une idée intéressante au triple point de vue : sédimentation, soutenabilité et, même si cela n'est pas intuitif : évaporation car il est possible d'avoir des profondeurs moyennes de retenue plus importantes. Ce type de solution n'est pas adaptée dans tous les contextes (topographiques et hydrologiques), mais il y a de plus en plus de projets dans le monde, pour tous les types d'usage. Le réservoir est alimenté par gravité ou par pompage : cela limite grandement les problématiques de sédimentation de la retenue, et limite l'effet d'obstacle sur le cours d'eau principal. Le réservoir peut être implanté dans une zone à moindre enjeux sociaux et environnementaux. Le barrage fermant le réservoir peut éventuellement être construit avec les matériaux prélevés dans la cuvette. Une question-clé est celle de l'étanchéité de la cuvette, qui mérite un examen au cas par cas.

Les **STEP** utilisent largement, et avec succès, cette option du stockage hors rivière. Les solutions d'étanchéité évoluent : historiquement il a été fait un usage presque systématique des revêtements en béton bitumineux ; désormais, plusieurs grands projets utilisent des géomembranes exposées. La pénétration du solaire et de l'éolien va conduire à la construction d'un nombre important de ces ouvrages. Cela conduit à poser la question d'étendre leur domaine d'application : STEP à faible hauteur de chute pour les pays qui ne disposent pas de reliefs importants ; STEP en bord de mer pour les îles et éventuellement les rebords continentaux.

L'association avec l'électricité solaire va plus loin. L'**association hydro-solaire** offre des opportunités nouvelles. Il y a depuis quelques années des projets d'installation de **panneaux solaires flottants** sur les retenues de barrages. Le solaire profite de l'espace offert par les plans d'eau et, dans le cas des barrages hydroélectriques, des postes et lignes de transmission. Ces projets, encore peu nombreux, mettent en évidence des défis techniques nouveaux pour l'ancrage des îlots de PV flottants et soulèvent la question de l'impact sur la sécurité des barrages. Des actions sont entreprises par la profession (et notamment la CIGB) pour traiter la question de la sécurité. Au-delà du simple partage de la surface du réservoir et des lignes de transmission, l'**hybridation hydro-solaire** peut amener des projets nouveaux de production d'électricité renouvelable, abondante et garantie. Ainsi, dans sa version FSH (« Full Solar Hydro », centrale solaire + STEP), l'hydrosolaire est une centrale de production d'électricité renouvelable, pilotable, ne dépendant pas des ressources en eau, et pouvant être développées dans de très nombreuses régions du monde : c'est une alternative majeure aux centrales thermiques. En version HhSH (« Highly hybridized solar hydro », centrale solaire + réservoir hydroélectrique), elle permet de diminuer la pression sur la ressource en eau, sans perte de production électrique, améliorant ainsi les possibilités de multi-usage de l'eau sur les réservoirs existants ou futurs.

Le **stockage souterrain** est une idée ancienne, déjà pratiquée dans certaines régions du monde, que ce soit pour du stockage en subsurface, dans les nappes des alluvions, ou du stockage profond, dans des formations rocheuses adaptées. La question se pose d'une extension du domaine d'application de cette méthode de stockage. Les analyses préliminaires tendent à montrer les limites de l'applicabilité du stockage souterrain, mais cela mérite certainement un examen plus attentif.

Une vaste question est celle de **la mer**. Le dessalement de l'eau de mer est une réalité dans de nombreux pays concernés par la rareté des ressources en eau douce. Une STEP utilisant l'eau de mer a été construite et exploitée pendant 20 ans au Japon, et d'autres projets sont à l'étude. De nouveaux projets de bassins offshore sont envisagés, pour la production marémotrice ou le stockage de l'électricité. Surtout, des endiguements de protection contre les submersions marines ont été déployés sur des milliers de kilomètres, et sont amenés à évoluer dans les décennies à venir en raison de l'élévation du niveau de la mer : les besoins de protection des populations vivant près des côtes vont être considérables.

2. INTRODUCTION

Georges Annandale : "*I agree that we should focus on an "adaptive » response. In my opinion, we can try as much as we can to change the trend in climate change but will not be successful because, in my opinion, we are already beyond the point of no return*. »

Peter Rae : *"There are no magic solutions. Importantly, it is necessary to recognize that practices developed by experience over the past decades will no longer be relevant to the future climate. »*

2.1. Intitulé de la question 108

La question 108 s'intitule « Barrage et Réservoirs : Adaptation aux changements climatiques ». L'appel à contribution sous cette question comporte les items suivants :

1. Barrages et réservoirs par pompage :spécificités, conception, exemples de réalisation
2. Barrages hors rivière pour stockage d'eau et protection contre les crues
3. Barrages en mer et usines marémotrices
4. Barrages pour la recharge des aquifères et nouveaux concepts
5. Installations photovoltaïques sur les réservoirs : opportunités et risques.

L'intitulé de la question 108 est très ouvert. Les sous-questions sont au contraire assez spécifiques.

2.2. Approche retenue

Dans le cadre de l'élaboration de ce Rapport Général, le parti retenu a été de tenter une formulation un peu plus précise de la question 108, tout en élargissant la réflexion au-delà des pistes techniques inventoriées par les sous-questions.

La question retenue est la suivante : *Quelles sont les idées et solutions que l'on peut apporter, pour la conception et l'exploitation des barrages et réservoirs, dans l'optique d'une adaptation au contexte futur, 2050 ou 2100* ? Ce *contexte futur* est d'abord marqué par une augmentation des gaz à effet de serre et donc de la température moyenne de la planète, avec des impacts variés, selon les régions, sur le climat et l'hydrologie. Ce contexte futur est également marqué par des *phénomènes induits ou renforcés* par le changement climatique : généralisation de l'électricité solaire et éolienne, crise de biodiversité, possibles tensions sociétales ou géopolitiques. La question est d'abord axée sur l'adaptation au monde futur. Cependant, les idées et solutions permettant d'*atténuer* le changement climatique sont également à mettre en avant, car il est nécessaire à la fois de viser *l'atténuation et l'adaptation*.

2.3. Contributions

Le rapport général de cette question utilise trois sources principales :

- D'une part les rapports transmis par les comités nationaux, et qui sont référencés au §7.1
- D'autre part, des contributions personnelles, proposées par une trentaine d'experts et praticiens des barrages, partout dans le monde, dont la liste est donnée au §7.2.
- Enfin, des éléments de bibliographie générale, issue des travaux de la CIGB ou d'autres organismes, et listés au 7.3 et 7.4.

2.3.1. *Rapports des comités nationaux*

22 rapports ont été transmis par les comités nationaux. La liste de ces rapports est donnée ci-dessous, classée par thématique.

Adaptation au changement climatique

N°	INTITULÉ	PAYS	CONTENU
R2	Sediment and flood management at a planned multipurpose reservoir in a peri-glacial environment	Suisse	Un grand projet de nouveau barrage à l'emplacement d'un retrait glaciaire, pour assurer la sécurité énergétique hivernale et d'autres usages
R6	Changement climatique en France : une adaptation nécessaire des barrages et réservoirs, vision nationale et exemple local	France	Perspectives de changement climatique en France ; incidence sur la production hydroélectrique ; présentation d'un projet d'adaptation par surélévation d'un barrage
R10	Potential of Romanian dams to adjust to changing environment	Roumanie	Evolution des usages des réservoirs en Roumanie (diminution des besoins), et rôles futurs (protection contre les inondations)
R14	Quantifying the impact of changing climate on dam operation: a review for engineering practitioners	Canada	Une revue académique des outils de modélisation avancée pour simuler les effets du changement climatique et optimiser la gestion des réservoirs
R20	Dams for energy transition and need for pumped storage and hydroelectric projects in India	Inde	L'état des lieux des besoins en nouveaux réservoirs en Inde, pour la transition énergétique, et en particulier les besoins d'équipements en STEP
R22	Adaptation of the reservoir operation rules in the context of climate change	Roumanie	L'évaluation de l'adaptabilité au changement climatique de deux grands réservoirs, en particulier vis-à-vis de la protection contre les inondations

Stations de Pompage-Turbinage (STEP)

N°	INTITULÉ	PAYS	CONTENU
R5	Etanchéité des barrages et réservoirs de STEP: spécificités, conception et retours d'expérience	France	Une revue complète des solutions d'étanchement des bassins de STEP
R7	Innovative design and feedback of waterways from a major pumped storage project in arid region	France	Exposé des éléments particuliers de conception pour une STEP : optimisation hydraulique et étanchéité du chemin d'eau
R8	Adaptations to the design of Abdelmoumen pumped-storage scheme during the construction phase	France	Exposé des éléments particuliers de conception pour une STEP : membrane exposée, conception de la turbine, alimentation en eau de la STEP en circuit fermé
R11	A case of potential Burera-Ruhondo PSH scheme in Rwanda, Africa	Rwanda	Description d'un site potentiel de développement d'une STEP au Rwanda
R15	Excavation and filling technology for deformation control in highly water-bearing multilayer reservoir basins	Chine	Description des enjeux particuliers liés aux excavations des bassins réservoirs de STEP
R16	Landscape signage for pumped storage dams	Chine	Idées de promotion des STEP auprès des populations, par l'adoption d'une signalétique adaptée
R17	Innovative technology and application research on anti-seepage of pumped storage power station reservoir basin	Chine	Solutions d'étanchéité retenues sur les STEP de Jurong (géomembranes + béton bitumineux) et Kokhav Hayarden (géomembrane)

Réservoirs hors rivière

N°	INTITULÉ	PAYS	CONTENU
R9	Le Canal Seine-Nord Europe, projet hydraulique majeur en France	France	Une présentation d'un grand projet neuf de navigation, en Europe, y compris la question des ressources en eau mobilisées
R13	Olifantspoort off-channel storage dam – critical storage to augment water supply	RSA	Un exemple de barrage hors-rivière, et des développements spécifique sur la typologie du barrage : multivoûte en maçonnerie
R21	Connection of the Libouš surface quarry with the Nechranice reservoir	Rép. Tchèque	La description d'un projet de mise en eau d'une grande mine abandonnée

Solaire flottant

N°	INTITULÉ	PAYS	CONTENU
R12	Reflections on the management of energy projects based on immature technologies: the case of a FPV pilot project	Norvège	Des réflexions sur le caractère novateur des projets de solaire flottant sur les réservoirs de barrage
R4	Towards FRcold guidelines for the realization of floating PV plants on dam reservoirs	France	Un exposé des travaux du groupe de travail français sur le sujet du solaire flottant (et focus sur l'analyse des risques)

(*continued*)

Continued

N°	INTITULÉ	PAYS	CONTENU
R19	Introduction to the world's first 100-meter-deep floating photovoltaic project in south-east Asia	Chine	La présentation de la centrale flottante de Cirata, exemple majeur de projet sur un réservoir de barrage

Stockage d'eau dans la nappe, barrages souterrains

N°	INTITULÉ	PAYS	CONTENU
R1	Sand dams: the case for greater collaboration between the dam industry and non-governmental organizations	Australie	Kenya - Retour d'expérience d'un barrage de recharge de nappe, de type "sand dam", établi en coopération ONG - Ingénierie

Nouveaux aléas, analyse de risques

N°	INTITULÉ	PAYS	CONTENU
R3	Wildfire impact on dam and reservoir landslide safety risks considering future climate	Australie	Une évaluation de l'augmentation de l'aléa et des risques nouveaux posés par les feux de forêts
R18	Safety risk assessment of a hydropower dam based on risk matrix method	Chine	L'exposé d'une analyse des risques pour un barrage en Chine

2.3.2. *Contributions individuelles*

Les contributions individuelles ont alimenté la réflexion générale.

Ce texte doit beaucoup à ces contributions. L'auteur du rapport remercie vivement les contributeurs pour la richesse et la profondeur de leurs réflexions et, en particulier Michel Lino pour ses avis sur l'ensemble du texte. Quand un développement dans le texte reprend explicitement et entièrement une idée développée par l'un des contributeurs, cela est référencé par une codification reprenant les initiales, sous la forme suivante : [XX], et avec la codification décrite au §7.2.

2.4. Note sur l'horizon de temps

La discussion générale évoquée dans ce rapport traite des horizons 2050 et 2100.

Ainsi, on ne discute pas des adaptations à prévoir dans l'immédiat, pour les difficultés du moment, mais plutôt des tendances qui doivent se dégager à (un peu) plus long terme. Cette approche est retenue, car les décisions qui se prennent aujourd'hui engagent l'avenir sur plusieurs décennies et, plus probablement, sur plus de 100 ans.

Il n'a pas été jugé raisonnable d'évaluer un horizon temporel supérieur au-delà de 2100. Cependant, les projets neufs et les travaux importants de modification des ouvrages doivent bien être conçus de sorte à pouvoir assurer leur fonction pendant 100 ans et davantage – certains auteurs et certains projets visent d'ailleurs 200 ans.

2.5. Deux concepts centraux : incertitude et effets locaux

La trajectoire globale de l'augmentation de la température moyenne n'est pas connue, car elle dépend notamment des choix politiques et de société. La déclinaison locale et concrète (canicules, sécheresses, inondations) de la trajectoire globale, dans chaque région, dans chaque pays, est encore sensiblement plus difficile à prédire.

En conséquence, les besoins en ouvrages permettant l'adaptation des sociétés futures sont difficiles à cerner. Les réflexions et les solutions techniques doivent être menées en prenant en compte cette incertitude. En particulier, on pourra privilégier :

- les stratégies « sans regret » de réduction de la vulnérabilité au changement climatique : ces stratégies sont pertinentes quelles que soient les évolutions climatiques
- les stratégies « flexibles », qui permettent d'adapter l'exploitation des systèmes et des ouvrages en fonction de ce qui est effectivement constaté.

2.6. Définitions

Les définitions utilisées dans ce rapport sont les suivantes.

Adaptation (de nos sociétés) : démarche d'ajustement au climat actuel ou attendu, ainsi qu'à ses conséquences qu'elles soient directes (canicules, feux de forêts, sécheresses, inondations), ou indirectes (tensions sociales, tensions géopolitiques).

Adaptabilité (de nos ouvrages) : capacité des barrages, réservoirs et digues à continuer à remplir leurs fonctions, à l'horizon 2050, 2100 et au-delà. Cela consiste à examiner les effets du changement climatique sur les fonctions des ouvrages (le présent rapport ne couvre pas l'autre versant de l'adaptabilité, qui est la robustesse : résistance physique des ouvrages aux nouveaux aléas).

Contribution à l'adaptation (de nos sociétés) : capacité des barrages, réservoirs et digues à contribuer à ce que nos sociétés s'adaptent aux changements climatiques et à leurs conséquences, c'est-à-dire limiter leur vulnérabilité. Cela consiste à examiner les effets des ouvrages sur les sociétés. Ce rapport souligne que les barrages et les digues doivent jouer un rôle à cet égard. Pour cette raison, il faut parfois abandonner des bénéfices ou de la rentabilité de court terme au profit de performances à long terme (cf. §4.6.4).

Empreinte écologique : Une mesure de la pression exercée sur les ressources et les écosystèmes. Elle mesure les surfaces alimentaires productives de terres et d'eau nécessaires pour produire les ressources qu'un individu, une population ou une activité consomme et pour absorber les déchets générés, compte tenu des techniques et de la gestion des ressources en vigueur. Cette surface est exprimée en hectares globaux (hag), c'est-à-dire en hectares ayant une productivité égale à la productivité moyenne. On peut calculer l'empreinte d'un ouvrage grâce à l'analyse du cycle de vie.

Contribution à l'atténuation : capacité des projets de barrages, réservoirs et digues à limiter le changement climatique et plus globalement l'empreinte écologique des sociétés, par exemple en permettant de remplacer une production électrique à base d'énergie fossile par une production renouvelable.

Soutenabilité (de nos ouvrages) : capacité des projets de barrages, réservoirs et digues à limiter leur *Empreinte écologique* propre (indépendamment des éventuels effets positifs d'atténuation). Dans une certaine mesure, la *soutenabilité* peut être évaluée par les méthodes d'analyse en cycle de vie (LCSA) ; l'évaluation complète fait appel aux études d'impact (ESIA) et à la concertation avec les parties prenantes.

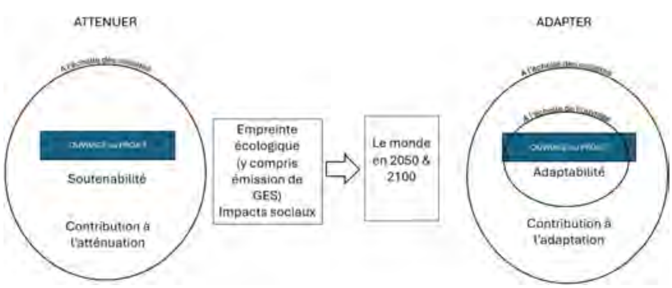


Fig. 1
Atténuer et Adapter

Scénarios climatiques : il s'agit des quatre scénarios RCP : RCP8.5 ; RCP6.0 ; RCP4.5 ; RCP2.6, qui ont remplacé les anciens scénarios SRES. RCP signifie *Representative Concentration Pathway* ; les chiffres représentent le forçage radiatif (en W/m^2 à l'horizon 2100), c'est-à-dire l'écart avec le bilan radiatif d'avant la période industrielle. Le RCP2.6 est le scénario qui intègre les politiques de réduction des GES et limite l'élévation de la température à 2°C par rapport à 1850.

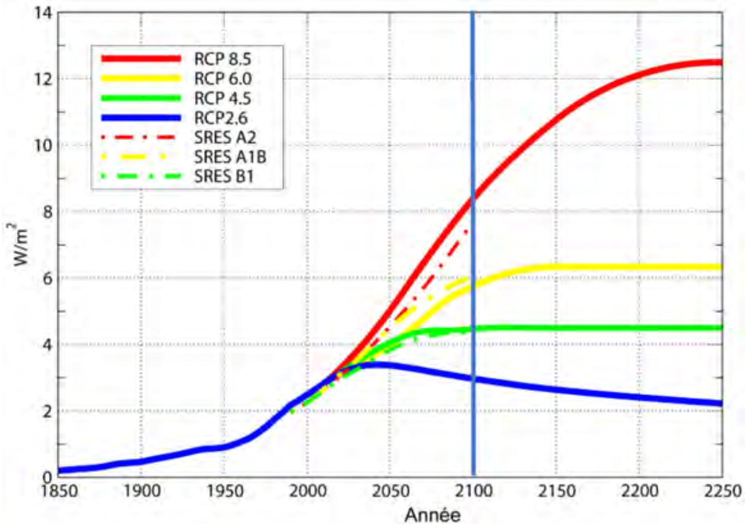


Fig. 2
Les quatre scénarios RCP de IPCC

Projections hydroclimatiques : évaluation, à l'échelle d'un pays, d'un territoire, des conséquences des scénarios climatiques, pour ce qui concerne le cycle de l'eau. Il s'agit d'une évaluation à l'échelle d'un pays, ce qui nécessite un travail modélisation local, pour descendre à une échelle de travail pertinente. Les projections peuvent intégrer d'autres facteurs de changement, tels que les aspects démographiques ou de développement économique.

Résilience : capacité des sociétés à faire face à un événement critique de grande ampleur (par exemple : sécheresse intense, crue majeure, séisme, grands feux de forêts, . . .)

3. ENJEUX DE L'ADAPTATION AUX CHANGEMENTS CLIMATIQUES

3.1. LE CHANGEMENT CLIMATIQUE EST PILOTÉ MONDIALEMENT, MAIS DÉCLINÉ LOCALEMENT

3.1.1. *Pilotage mondial*

Le changement climatique est directement lié à un paramètre quasi-unique : la quantité d'émissions de gaz à effets de serre, qui peut en première approximation, être exprimé sous la forme d'une élévation de température moyenne de la planète.

Le bulletin 200 [23], publié récemment, actualise l'état des lieux. La probabilité de maintenir le réchauffement global en dessous de 1,5°C (par rapport à l'année 1850) est désormais quasi-nulle. Notons que l'année 2024 a, pour la première fois, dépassé ce seuil. Les projections pour la fin du siècle conduisent à des réchauffements entre 1,4°C et 4,4°C.

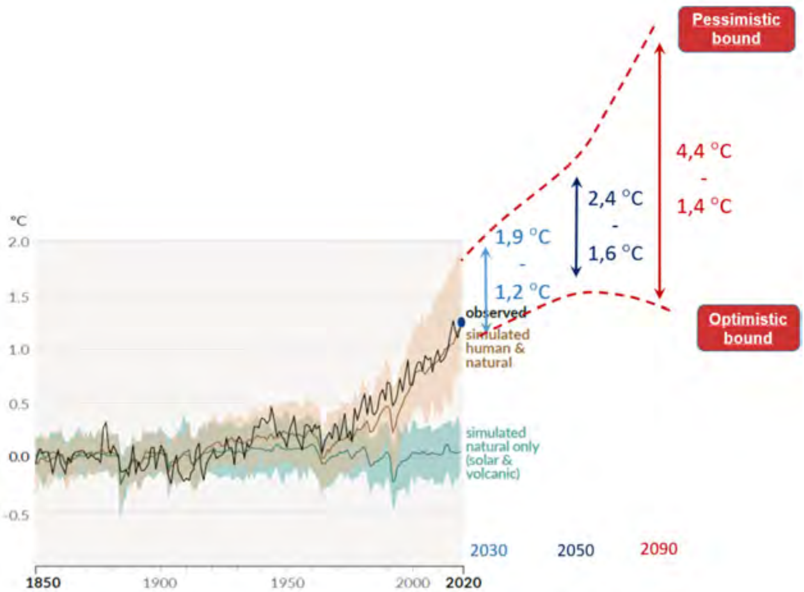


Fig. 3
Scénarios de réchauffement les plus probables (source: IPCC WG.1 Climate science report (AR#6) – Aug. 2021 ; ICOLD – Q107 : General Report Aelbrecht D. (2022))

3.1.2. *Incertitudes et variabilités locales, mais plus de sécheresses*

Les conséquences peuvent être très différentes, à l'échelle de chaque pays et région, en particulier pour ce qui est de la ressource en eau. Les figures ci-dessous, extraites de [27] illustrent :

- L'évolution attendue pour le volume annuel des précipitations, dans le cas d'un réchauffement de +4°C. La valeur moyenne calculée est encadrée par les bornes à 5% et 95% de l'incertitude de cette évaluation.
- La probabilité d'augmentation des années de sécheresse, dans le cas d'un réchauffement de +4°C.

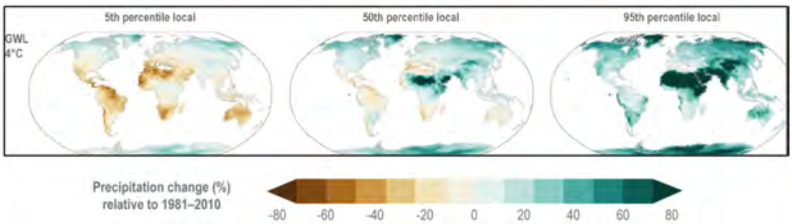


Fig. 4
Figure 4.10 de [27] : changement projeté pour les précipitations moyennes annuelles : moyenne et bornes à 5% et 95% de l'incertitude de cette évaluation

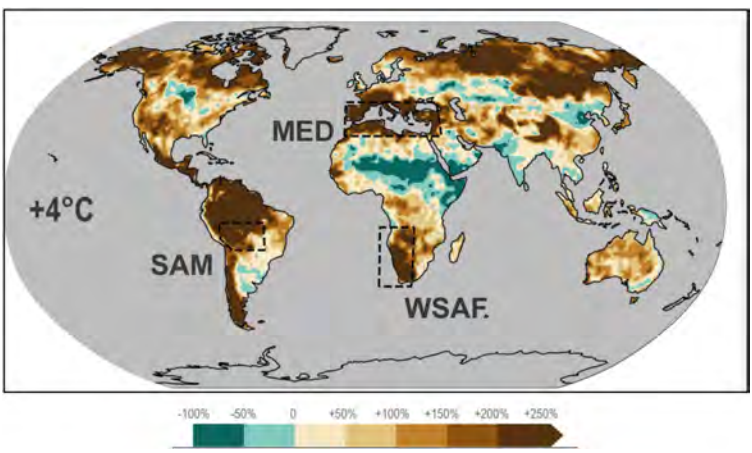


Fig. 5
Figure 4.18 de [27] : changement projeté de la probabilité d'une année très sèche

La Fig. 4 illustre la grande incertitude attachée aux estimations de précipitations futures (forte différence entre les centiles 5% et 95%) et, d'autre part, la grande variabilité d'une région à l'autre. La Fig. 5 montre que la probabilité d'occurrence d'années de sècheresse pour l'agriculture augmente dans la plupart des régions.

3.1.3. *Relation avec les barrages et les digues*

Les relations entre changement climatique d'une part, les barrages et les digues d'autre part, sont bien connus :

- Les barrages peuvent *contribuer à l'atténuation* du changement climatique, en produisant de l'énergie non carbonée, et en facilitant la pénétration des sources d'énergie décarbonée intermittentes (vent, soleil), par le stockage d'énergie et les services au réseau,
- Le changement climatique impacte le cycle de l'eau, notamment les sécheresses et les crues ; les barrages et les digues ont une incidence (positive, négative) sur ce cycle de l'eau ; ils ont un rôle à jouer pour limiter les effets sur les sociétés, et peut-être la nature (au sens de la biodiversité) ; ils doivent également être adaptés à ces conditions nouvelles. Il faut tenir compte :
  - de la plus grande variabilité des moyennes interannuelles,
  - du renforcement des évènements intenses (crues, sécheresses),
  - des incertitudes hydrologiques associées aux modèles climatiques.
- Le changement climatique provoque une élévation du niveau de la mer, ce qui a également des conséquences sur l'érosion des côtes. Les barrages ont une incidence sur l'érosion côtière (généralement négative, en limitant le flux de sédiments) ; les barrages et digues à la mer ou proches de la mer peuvent jouer un rôle positif de protection des enjeux humains ; ils doivent être adaptés à ces conditions nouvelles.

3.2. Augmentation des aléas

L'exposition des barrages et des digues à de nouveaux aléas, ou des aléas augmentés, ne fait pas partie des thématiques examinées par ce rapport. Cependant, il est utile de rappeler succinctement que cette thématique est centrale, en l'illustrant avec quelques aspects. Cet inventaire n'est pas exhaustif.

Crues et pluies intenses

Le rapport du GIEC, dans sa AR6_FAQ8.2 [37] exprime le consensus scientifique à cet égard. Le changement climatique modifie déjà la localisation, la fréquence et l'intensité des inondations. Près des côtes, l'élévation du niveau de la mer aggrave les inondations côtières, surtout lorsqu'elles s'accompagnent de fortes pluies. Le réchauffement climatique intensifie les pluies en augmentant la capacité de l'air à retenir l'humidité (7 % de plus par degré Celsius). Cela influence aussi les vents, la formation et la trajectoire des tempêtes, ainsi que la dynamiques des précipitations. Ces transformations continueront à redéfinir les caractéristiques des précipitations à mesure que le climat se réchauffe. Il est reconnu que d'autres facteurs affectent la formation des crues, notamment l'occupation des sols ; cependant :

- *"An increased intensity and frequency of record-breaking daily rainfall has been detected for much of the land surface where good observational records exist, and this can only be explained by human-caused increases in atmospheric greenhouse gas concentrations »*
- *"[. . .] even accounting for the many factors that generate flooding, when weather patterns cause flood events in a warmer future, these floods will be more severe"*

Ainsi, il faut considérer, en moyenne, une augmentation des fréquences et intensités des crues ; augmentation aggravée pour les zones côtières par l'élévation du niveau de la mer ; et, à l'intérieur des terres, s'attendre à des possibles modifications des trajectoires des événements extrêmes (cellules orageuses, tempêtes, cyclones, . . .). Cette augmentation de la fréquence et de l'intensité des événements de crue n'est pas uniforme sur l'ensemble des continents : des analyses locales peuvent, dans une certaine mesure, fournir des indications quantitatives, en particulier pour les crues de période de retour plus petite que 100 ans. L'impact sur les crues exceptionnelles et extrêmes utilisées pour la justification des évacuateurs de crue demeure un sujet de recherche.

Le changement climatique n'est pas la seule évolution conduisant à devoir réévaluer les crues : la modification de l'occupation des sols est un autre facteur majeur. Cela est par exemple illustré par le cas de la rivière Tietê, qui draine la ville de São Paulo (21 millions d'habitants) : des barrages ont été construits sur cette rivière dans la première moitié du XXème siècle, alors que le bassin versant était essentiellement boisé. L'extension de la ville a changé les conditions de ruissellement, remplaçant la forêt par des zones urbaines. L'urbanisation change également l'ampleur de la gravité en cas d'accidents. Il a fallu des travaux conséquents pour augmenter de manière adéquate la capacité d'évacuation des crues. [FM]

L'augmentation de la fréquence et de l'intensité des pluies est également de nature à provoquer des glissements de terrain, coulées de boue et laves torrentielles.

Feux de forêt - Le changement climatique augmente la fréquence des feux de forêt, et l'extension des zones géographiques qui y sont exposées. Q108-R3 [3] aborde cette question à partir de retours d'expérience en Australie et aux Etats-Unis, et suggère les principales conclusions suivantes. Les feux de forêt peuvent perturber le fonctionnement des barrages et causer des dommages immédiats ; ces dangers immédiats sont généralement mineurs, mais il faut considérer les risques nouveaux après l'incendie : l'augmentation de la probabilité d'érosion et de glissements de terrain déclenchés par des pluies extrêmes. En Australie, des études ont indiqué que la probabilité de glissements de terrain était augmentée d'un ordre de grandeur dans le court terme après un feu de forêt, jusqu'à ce que la végétation reprenne. Ces glissements de terrain peuvent générer des impacts directs sur les retenues, ou générer des crues de type coulée de boue ou lave torrentielle (« debris flow »). Des données quantitatives suggèrent également une diminution forte de l'infiltration dans les zones incendiées, ce qui est un facteur aggravant.

GLOF - Les GLOF constituent une nouvelle menace, liée à l'augmentation des températures et au recul des glaciers. Par exemple, le GLOF de la rivière Teesta, en Inde, le 4 octobre 2023 a provoqué la rupture du barrage Teesta III et des dégâts majeurs en aval. [DS]

Sédimentation - L'augmentation des précipitations intenses dans de nombreuses parties du monde, et l'éventuel recul de la végétation dans les zones affectées par la sécheresse, sont de nature à provoquer une augmentation des volumes de sédiments transportés par les rivières, et donc l'accélération de l'alluvionnement de certaines retenues.

Tous les pays ne disposent pas des mêmes moyens pour faire face à ces nouveaux aléas. Il apparaît utile de renforcer les capacités, en particulier la sensibilisation aux nouveaux risques auxquels sont exposés les vieux barrages en raison des événements climatiques extrêmes, depuis leur conception initiale, notamment dans les pays les moins développés. [AB]

3.3. Crise de la biodiversité

L'IPBES est une organisation internationale créée pour renforcer l'interface entre la science et la politique en ce qui concerne la biodiversité et les services écosystémiques. Elle a publié un rapport d'état des lieux en 2019 [28], dont sont extraits les citations présentées dans cette section.

L'IPBES rappelle que « *la nature est essentielle à l'existence humaine et à une bonne qualité de vie. La plupart des contributions de la nature aux populations ne sont pas intégralement remplaçables, et certaines sont mêmes irremplaçables. La nature joue un rôle critique dans la provision d'aliments pour les humains et les animaux, d'énergie, de produits médicinaux, de ressources génétiques, et de tout un éventail de matières essentielles au bien-être physique et à la préservation du patrimoine culturel des populations* ». Deux chiffres : *« 75% des cultures alimentaires mondiales [. . .] reposent sur la pollinisation animale* » ; « *les écosystèmes marins et terrestres sont les seuls puits des émissions anthropiques de carbone, avec une séquestration brute de [. . .] environ 60% des émissions mondiales d'origine anthropique* ».

« Dans la plupart des régions du monde, la nature a aujourd'hui été altérée de manière significative par de multiples facteurs humains, et la grande majorité des indicateurs relatifs aux écosystèmes et à la biodiversité montrent un déclin rapide. Au total, 75 % de la surface terrestre est altérée de manière significative, 66 % des océans subissent des incidences cumulatives de plus en plus importantes et plus de 85 % de la surface des zones humides ont disparu. »

« L'activité humaine menace d'extinction globale un nombre d'espèces sans précédent. En moyenne, 25 % des espèces appartenant aux groupes d'animaux et de végétaux évalués sont menacés, ce qui suggère qu'environ 1 million d'espèces sont déjà menacées d'extinction ». « Dans les écosystèmes terrestres et d'eau douce, le changement d'utilisation des terres est le facteur direct ayant eu l'incidence relative la plus néfaste sur la nature depuis 1970. Les écosystèmes d'eau douce sont, quant à eux, menacés par un ensemble de facteurs comprenant essentiellement les changements d'utilisation des terres, y compris l'extraction de l'eau, l'exploitation, la pollution, les changements climatiques et les espèces envahissantes. »

« Les trajectoires actuelles ne permettent pas d'atteindre les objectifs de conservation et d'exploitation durable de la nature et de parvenir à la durabilité, et les objectifs pour 2030 et au-delà ne peuvent être réalisés que par des changements en profondeur sur les plans économique, social, politique et technologique. »

« Il est possible de conserver, de restaurer et d'utiliser la nature de manière durable et, en même temps, d'atteindre d'autres objectifs sociétaux à l'échelle mondiale en déployant de toute urgence des efforts concertés qui entraînent des changements en profondeur »

L'IPBES propose le tableau suivant en synthèse des actions possibles pour promouvoir la biodiversité associée aux eaux douces.

Approches se rapportant à la durabilité	**Actions et voies possibles pour réaliser des changements en profondeur** Acteurs clés : (OI=organisations intergouvernementales, G=gouvernements, ONG = organisations non gouvernementales, GC=groupes de citoyens et associations communautaires, PACL = peuples autochtones et communautés locales, D=organismes donateurs, OSE= organisations scientifiques et éducatives, P=secteur privé)
Améliorer la gestion, la protection et la connectivité des eaux douces	• **Intégrer la gestion des ressources en eau et l'aménagement des paysages**, notamment en accroissant la protection et la connectivité des écosystèmes d'eau douce, en améliorant la coopération et la gestion des eaux transfrontières, en luttant contre les effets de la fragmentation causée par les barrages et les dérivations et en incorporant des analyses régionales du cycle de l'eau (par ex., OI, G, PACL, GC, ONG, D, OSE, P) {6.3.4.6, 6.3.4.7} {B1}. • **Soutenir la gouvernance inclusive de l'eau,** par exemple en élaborant et en mettant en œuvre une gestion des espèces exotiques envahissantes avec les parties prenantes intéressées (par ex., OI, G, PACL, GC, ONG, D, OSE, P) {6.3.4.3} {D4}. • **Soutenir les régimes de cogestion en vue d'arriver à une gestion concertée des ressources en eau et d'encourager l'équité** entre les utilisateurs de l'eau (tout en maintenant un flux écologique minimum pour les écosystèmes aquatiques), et mobiliser les parties prenantes et tirer parti de la transparence afin de réduire au minimum les conflits environnementaux, économiques et sociaux {D4}. • Institutionnaliser les pratiques qui **réduisent l'érosion, la sédimentation et le transport de polluants par ruissellement** (par ex., G, GC, P) {6.3.4.1}. • **Réduire la fragmentation des politiques relatives à l'eau douce** en coordonnant les cadres réglementaires internationaux, nationaux et locaux (par ex., G, OSE) {6.3.4.7, 6.3.4.2}. • **Accroître les stocks d'eau** en facilitant la recharge des aquifères, la protection et la restauration des zones humides et l'utilisation d'autres techniques de stockage et en imposant des restrictions concernant le prélèvement d'eaux souterraines (par ex., G, GC, PACL, P, D) {6.3.4.2} {B1, B3}. • **Promouvoir l'investissement dans des projets hydrauliques** selon des critères de durabilité bien définis (par ex., G, P, D, SO) {6.3.4.5} {B1, B3}.

Fig. 6
IPBES, Approches se rapportant à la durabilité et actions et voies possibles pour les réaliser. [28]

Concernant spécifiquement les barrages, l'IPBES mentionne, dans le chapitre 6, le fait que les barrages ont des impacts négatifs significatifs sur la nature (en particulier en raison des obstacles qu'ils constituent, et en raison de la formation de réservoirs le long des cours d'eau qui ralentissent les vitesses d'écoulement) et la société, qui ne sont souvent pas bien compensés. L'IPBES note que les barrages peuvent générer de nouveaux bénéfices, tels que : des habitats pour des espèces protégées et zone refuge dans le contexte de changement climatique.

Trois conclusions peuvent être tirées de ces éléments :

- la problématique de la crise de la biodiversité est une problématique majeure pour l'espèce humaine, qui peut entraîner des conséquences graves en quelques décennies,
- les barrages qui créent des obstacles et des réservoirs sur les cours d'eau ont une incidence majeure sur la biodiversité des eaux douces ; il faut examiner les éventuelles alternatives en tenant compte de ce facteur,
- les barrages peuvent avoir des effets positifs sur la biodiversité ; il est important de bien les comprendre, pour les favoriser.

3.4. Quelques retours d'expérience de pays, affectés ou non

Les retours d'expérience inventoriés ci-dessous présentent des éclairages particuliers sur <u>un</u> sujet, dans <u>un</u> pays. Il ne s'agit pas de présenter de manière exhaustive les effets du changement climatique ou les politiques d'adaptation du pays, mais de partager quelques pistes explorées dans différents contextes.

En *<u>Angleterre</u>*, de nouveaux réservoirs sont envisagés, avec pour objectif de s'adapter au changement climatique. Les prévisions des modèles climatiques pour le Royaume-Uni indiquent que les ressources en eau diminueront. À une époque, on pensait que des hivers plus humides compenseraient des étés plus secs, mais les dernières prévisions montrent que ce n'est pas le cas. De plus, il est nécessaire de laisser davantage d'eau dans l'environnement, sinon le changement climatique aura un impact sévère sur l'écologie des rivières et des eaux souterraines. En particulier, le sud de l'Angleterre compte un grand nombre de cours d'eau dans la craie, considérés comme des habitats importants au niveau national et international. Il existe un objectif de réduire les prélèvements dans les aquifères de craie et les rivières alimentées par ces aquifères. Cependant, il y a de l'eau disponible dans les rivières en hiver, qui peut être utilisée pour remplir les réservoirs et ensuite être libérée pour une utilisation en été. Tous ces éléments plaident en faveur de l'utilisation de réservoirs hors rivières, remplis en hiver et vidés en été. C'est pourquoi plusieurs réservoirs de ce type sont proposés. [JW] and [71].

En *Australie*, la Tasmanie a connu, entre septembre 2015 et avril 2016, une sécheresse extrême, la plus sévère depuis 50 ans. La situation s'est aggravée en décembre 2015 avec la panne du câble Basslink, empêchant l'importation d'électricité depuis le continent australien. En avril 2016, les réserves d'eau atteignaient leur niveau le plus bas (12,5 % de la capacité totale). Simultanément, des feux de forêt ont ravagé plusieurs régions de l'île. En juin 2016, la situation s'est inversée brutalement avec des inondations historiques dans le nord de la Tasmanie. La gestion de crise a inclus plusieurs composantes : pilotage de la production énergétique via des modèles climatiques et hydrologiques, réduction volontaire de la demande industrielle, réactivation de centrales à gaz, 200 MW diesel installé en urgence, surveillance des impacts sur la qualité de l'eau et la biodiversité, plans de prévention des incendies. Ces réponses s'appuyaient sur des préparations antérieures. [RH].

Au *Brésil*, les enjeux liés au changement climatique sont variés. De 1950 à 2010, les barrages construits au Brésil ont été accompagnés de grands réservoirs, pour la production d'électricité. Depuis 2010, des considérations environnementales ont conduit à n'autoriser que les barrages hydroélectriques au fil de l'eau. Depuis 20 ans, il y a un développement considérable du solaire et de l'éolien. Les grands réservoirs historiques compensent désormais l'intermittence du soleil et du vent, et ils sont en limite de capacité. Il faut de nouveaux réservoirs et des STEP. Par ailleurs, les situations de sécheresses et de crue (par exemple, 2023 et 2024 sur les fleuves côtiers de l'Etat de Rio Grande do Sul) deviennent plus graves et plus fréquentes. BCOLD et l'Académie nationale brésilienne de l'ingénierie ont signé un mémoire (« position paper ») appelant à ce que les grands réservoirs soient construits avec une vocation multi-usage. [FM]

Au *Canada*, la production d'électricité est appelée à augmenter, après deux décennies de relative stagnation. Cela conduit à envisager la construction de centrales éoliennes, solaires et hydroélectriques. Le Canada ne manque pas d'eau, mais quelques régions connaissent des périodes de rareté de l'eau, et utilisent des réservoirs pour l'irrigation. Le changement climatique dans ces zones conduit à envisager des changements de types de culture (« crop patterns »). [PR]

En *Chine*, les STEP vont jouer un rôle très important. Actuellement, la production d'électricité à partir du charbon représente près de 60 % de l'approvisionnement en électricité, et l'électricité contribue à environ 40 % des émissions du pays. Selon des recherches, d'ici 2035, la capacité installée de l'éolien et du photovoltaïque en Chine pourrait atteindre entre 3 et 3,8 TW, avec une demande totale de capacité de stockage de 600 à 750 GW. De nombreux projets de STEP sont en cours et, à la fin de l'année 2023, la capacité installée avait atteint 50,94 GW et 179 GW étaient en construction.[58]

En *Iran*, le contexte général est difficile. Le pays connaît une réduction significative des précipitations annuelles, des sécheresses prolongées, et des vagues de chaleur plus fréquentes. Par ailleurs, des inondations soudaines, causées par des pluies intenses sur des sols arides, se multiplient. En raison de l'irrégularité des ressources en eau, l'Iran a beaucoup investi dans la construction de réservoirs. Actuellement, des diminutions d'apport en eau sont observés sur un nombre significatif de barrages, parmi lesquels par exemple Zayandeh Rood, Karkeh, Dez, Latyan, Karaj, Karoon 4 et Karoon 3. Il y a des conséquences parfois importantes pour les usages, agriculture, production d'électricité, eau potable. Sont également observées des accélérations de la sédimentation, et pour au moins un de ces barrages, des difficultés accrues à gérer les crues soudaines. Il faut aussi noter l'assèchement de rivières, lacs et zones humides, notamment le lac d'Ourmia, autrefois le plus grand lac salé du Moyen-Orient, et des problématiques de subsidence dans certaines villes. [AHN]

En *France*, ces dernières années sont marquées par l'élaboration d'un travail en profondeur de préparation du pays au climat futur, pour anticiper son adaptation. A cet effet, des scénarios ont été construits pour évaluer l'évolution du climat et des besoins en eau. Parmi d'autres, une information particulièrement notable est l'évolution de la consommation en eau, qui est notamment influencée par les besoins en eau d'irrigation. Entre 2020 et 2050, dans la configuration climatique la plus défavorable étudiée, c'est-à-dire avec la projection climatique la plus pessimiste (RCP8.5) et pour un printemps-été sec, la consommation en eau augmente de 102 % en l'absence d'incitations à la sobriété, et de 72 % si des politiques publiques adaptées sont mises en œuvre. Dans un scénario intermédiaire, les consommations sont multipliées par plus de deux dans près d'un quart des bassins versants. Seul un scénario dit « de rupture » (réduction de 50% de la consommation de viande, forte réorientation des pratiques agricoles vers des variétés culturales adaptées, réutilisation massive des eaux usées, recyclage et diminution de consommation de biens matériels) permet de contenir l'augmentation des consommations (+ 10 % par rapport à 2020) dans la configuration climatique la plus défavorable étudiée.Nous pouvons tirer de cette analyse le fait qu'il faut s'attendre à des déséquilibres majeurs entre besoins et ressources à l'horizon 2050, dans le cas des printemps et été secs.

L'*Inde* est un pays avec des zones climatiques très variées, et avec un facteur climatique clé, la mousson d'été, qui présente des variations importantes à toutes les échelles de temps (de la saison à quelques dizaines d'années). Ces dernières années ont été marquées par des événements extrêmes plus nombreux : GLOF de Teesta river en 2023, crue-éclair dans le district de Chamoli en 2021, crues et glissements de terrain dans l'Uttarakhand en 2013 et dans le Kerala en 2018, vagues de chaleur et sécheresses répétées. Cela a motivé l'élaboration de projections de changement climatique, avec des évaluations aux horizons 2060 et 2100 (Devendra Kumar Sharma and IIT, Ropar). Cette étude recommande des propositions d'adaptation pour le long terme : le stockage d'eau (petites et grandes retenues), la préparation de plan gestion de crise pour les catastrophes climatiques (crues, vagues de chaleur, cyclones, . . .), l'interconnexion des bassins versants, la cartographie des zones inondables, les recherches sur les maladies liées à l'eau, le dessalement, la promotion de techniques culturales adaptées aux conditions futures. Il ne s'agit pas simplement de recommandations pour le futur : les actions doivent être entreprises dès maintenant, et certaines le sont déjà. [DKS]

Au *Japon*, les problématiques d'inondation sont majeures, et se renforcent. Il y a une tendance à développer du multi-usage pour les barrages en service, en introduisant une capacité de stockage des crues. Pour ne pas trop pénaliser la production hydroélectrique, la capacité de stockage des crues n'est libérée qu'en cas d'annonce de crue, par abaissement préventif de la retenue ; le reste de l'année, la pleine capacité est utilisée pour l'hydroélectricité [TF] [TS]. Par ailleurs, une attention particulière est portée aux conséquences directes et multiples de l'élévation des températures : modification du régime neige / pluie / fonte en montagne, ce qui a des effets sur le régime des rivières et, par conséquent : perturbation du calendrier d'irrigation des cultures ; augmentation de l'évapotranspiration donc des besoins en eau ; plus grande propension à l'eutrophisation des retenues ; échauffement de l'eau dans les rivières en automne, ce qui est préjudiciable à la vie aquatique.

Le *Maroc* vient de vivre 6 années de suite de faibles précipitations et des barrages peu remplis, incapables de répondre aux besoins pour lesquels ils ont été conçus. Désormais, la stratégie au Maroc est de se donner la possibilité d'alimenter la plupart des grandes villes, y compris les villes intérieures comme Fès ou Marrakech avec de l'eau dessalée, moyennant l'emploi d'une énergie renouvelable (à noter : la diminution du coût du dessalement, qui devrait approcher 0,4€/m^3 avant 2030). Les barrages, tant qu'ils n'ont pas perdu leur capacité de stockage par alluvionnement, continueront chaque fois que possible à être utilisés, notamment pour l'irrigation. Par ailleurs, la production hydroélectrique est appelée à diminuer de façon significative. Le rôle des barrages évolue donc : davantage de protection contre les inondations ; du stockage de l'énergie renouvelable (STEP) ; et l'alimentation des nappes souterraines dans les zones désertiques ou semi-désertiques. L'irrigation et l'eau potables resteront toutefois parmi les utilisations principales compte tenu des installations importantes dédiées à cet usage. De nombreux petits barrages ont été construits, notamment dans les régions semi-désertiques, l'irrigation, l'alimentation en eau du cheptel, la protection contre les inondations ; la diminution des apports en eau, le caractère plus violent des crues, les apports en sédiments associés sont des facteurs qui peuvent rendre ces petits barrages inopérants. Dans les régions du sud marocain, il y a sans doute lieu de réfléchir à d'autres moyens de mobiliser la ressource : en plus de l'exploitation des nappes, lorsqu'elles sont disponibles, les pistes sont le traitement des eaux saumâtres et la condensation de l'humidité de l'air. Ce contexte difficile est aggravé par l'urbanisation croissante, laquelle s'accompagne de l'augmentation de la consommation ; ainsi, alors que les ressources hydriques diminuent, le besoin en eau et en électricité augmente. La solution de cette équation est apportée par le dessalement associé à l'énergie renouvelable. [AC]

En *Roumanie*, Apele Romane (l'autorité en charge de la gestion de l'eau) opère 125 grands barrages, et l'électricien Hidroelectrica en opère 119. Le rapport

Q108-R10 indique que la demande en eau a décru régulièrement depuis 1990, de 20 km^3/an à environ 8 km^3/an aujourd'hui, en raison d'ajustements structurels de l'économie, en particulier la réduction de l'activité industrielle, la fermeture de certains périmètres irrigués non viables (réduction de 2 millions ha à 0.8 millions ha des périmètres irrigués, et demande en eau correspondante de 8 km^3 à 1 km^3 par an), l'installation de compteurs et d'une redevance pour l'eau potable et la réduction des fuites. Selon ce rapport, l'avenir des barrages est à redéfinir. D'une part, il y a désormais plus d'opportunité pour une fonction de protection contre les inondations, et pour une stratégie d'adaptation au changement climatique, car ce qui est attendu c'est davantage de sécheresses et de crue. Mais la baisse de la consommation en eau génère des diminutions importantes de revenus pour l'opérateur, ce qui limite sa capacité d'action. Q108-R10 mentionne également les effets du transport sédimentaire sur les retenues : certains barrages perdent rapidement leur capacité utile ; et surtout, certains grands barrages subissent de l'érosion au pied aval, avec un risque pour leur sécurité.

En *Slovénie*, le changement climatique se manifeste par des températures moyennes annuelles en hausse (+2°C depuis le XIX^e siècle), des précipitations irrégulières et des phénomènes extrêmes comme des inondations et des sécheresses. En août 2023, des pluies torrentielles, concentrées sur une période de 10 heures, ont saturé les sols et provoqué les plus grandes inondations de l'histoire du pays. Les dégâts ont touché 176 des 212 municipalités, avec des pertes estimées à 9,9 milliards d'euros. Cet événement a mis en lumière la contribution positive de certains aménagements. En 2018, une retenue sèche combinée à une amélioration du chenal d'évacuation des crues avait été construite en amont de Ljubljana ; ce dispositif s'est avéré efficace lors des événements de 2023, évitant des inondations majeures dans la capitale. Sur la rivière Sava, la cascade de cinq barrages (hydroélectriques, et avec également des fonctions écosystémiques) construite entre 1993 et 2017 a limité les inondations, grâce à une gestion adaptée : creux préventif (« pre-emptied ») et remplissage de zones inondables. En revanche, la diminution de la neige hivernale affecte les débits des rivières en été, ce qui exacerbe les pénuries d'eau. Malgré des propositions de nouveaux barrages pour améliorer la capacité de rétention d'eau, une forte opposition publique freine ces projets. [MK].

En *Suisse*, le retrait des glaciers est amorcé. Or les glaciers fonctionnent comme des réservoirs, dont le volume est donc appelé à diminuer. Des projets sont envisagés pour compenser ces effets du retrait glaciaire, en mobilisant des volumes de retenue supplémentaires, de sorte à stocker les eaux de fonte des neige (au printemps) et à les restituer, au long de l'année ou sur une régulation interannuelle (pour pallier les périodes de sécheresse). En particulier, plusieurs projets importants de surélévations sont réalisés ou à l'étude.[AS]. Un exemple majeur, le projet de Gornerli, est présenté par le rapport Q108-R2 [2].

En *Tunisie*, les retenues de barrage sont généralement dimensionnées avec un volume de stockage de l'ordre de deux fois le volume des apports annuels. Ce dimensionnement résulte de calculs d'optimisation du « volume régularisé », dans un climat semi-aride, où l'irrégularité des apports conduit à prévoir un mode de gestion interannuel, les années excédentaires venant soutenir les années plus sèches. Cela présente nécessairement des inconvénients : la quasi-totalité des écoulements est stocké, et donc les sédiments aussi, ce qui conduit à des pertes parfois rapides de la capacité de retenue ; le temps de séjour de l'eau dans les retenues est long, et les pertes par évaporation sont donc fortes (en proportion des apports). La Tunisie n'est pas un pays de superficie très importante ; pourtant, elle connaît des conditions climatiques variables sur son territoire, et il est apparu très utile de développer des interconnexions, pour transférer de l'eau depuis les zones les plus arrosées vers les régions où la ressource est déficitaire. Certaines de ces retenues et interconnexions ont une vocation de sécurité en cas de sécheresse prolongée.

Au *Vietnam*, dans le delta du Mékong, les sécheresses se sont succédé, et l'abaissement des nappes pendant ces périodes (par la combinaison d'effets variés influençant les débits du fleuve, et par le pompage) conduit à des remontées du biseau salé. Une réponse apportée par le gouvernement est l'augmentation du stockage d'eau douce, par exemple par réservoirs hors rivières. [MHTK]

4. PRINCIPES GÉNÉRAUX POUR L'ADAPTATION

4.1. Penser loin, ouvrir les pistes, dialoguer

Les Pays-Bas font partie des pays particulièrement exposés au changement climatique, pour une raison très spécifique : une part importante du pays est située en dessous du niveau de la mer. Les scénarios possibles d'évolution du niveau de la mer ont des conséquences majeures – et même existentielles. Il est intéressant d'évoquer les réflexions en cours, qui permettent de tirer des conclusions générales valables dans de nombreux contexte. Ces réflexions sont présentées dans le rapport "Room for Sea Level Rise" [68]. Le rapport s'intéresse à des horizons de temps long terme, 2100 et 2200, et choisit des scénarios pessimistes d'‘élévation de 2 mètres d'ici 2100 et de 5 mètres d'ici 2200. Le consortium de chercheurs, experts et décideurs propose trois perspectives conceptuelles d'adaptation et dégage des enjeux transversaux. Les trois stratégies d'adaptation sont très différentes les unes des autres :

Accommodate : adaptation progressive de l'usage des terres et des infrastructures pour coexister avec les effets de la montée des eaux. Cela inclut des solutions comme des habitations flottantes, des cultures tolérant le sel, et des infrastructures résistantes aux inondations. Les régions économiques clés, comme le Randstad, seraient protégées aussi longtemps que possible, tandis qu'un déplacement vers des zones plus élevées serait planifiée à long terme.

Protect : renforcement des infrastructures existantes, notamment les digues, barrages et systèmes de pompage. Elle prévoit également l'extension des opérations de recharge en sable pour maintenir la côte. Des stratégies spécifiques incluent la fermeture ou la modification des estuaires avec des barrages, des pompes et des zones de stockage temporaire pour gérer les crues fluviales.

Seaward : construire un très grand lac côtier au large, formé par une digue externe, pour stocker temporairement les débits fluviaux et réduire la salinisation (cf. illustration, Fig. 37). Cette solution réduit les besoins de renforcement des infrastructures à l'intérieur du pays tout en nécessitant des investissements importants pour créer et entretenir ces nouvelles structures.

Les enjeux transversaux sont les suivants : chaque approche nécessite de vastes espaces pour les infrastructures, qu'il faut planifier dès maintenant pour laisser des options ouvertes aux générations futures ; l'approvisionnement en eau douce deviendra plus difficile à cause de l'intrusion saline ; les coûts de mise en œuvre et de maintenance impliquent des investissements majeurs sur plusieurs décennies.

Ce travail met en évidence plusieurs thématiques majeures :

- prendre en compte des horizons éloignés (ici : 2200), avec des scénarios pessimistes, pour laisser des options ouvertes dès maintenant,
- ouvrir largement les pistes de réflexion : la stratégie qui vient d'abord à l'esprit (« Protect » : augmenter progressivement la hauteur des digues) n'est pas nécessairement la bonne car son *adaptabilité* aux conditions futures n'est pas acquise (faisabilité pas acquise au-delà de 3 m d'élévation),
- une réflexion holistique, prenant en compte tous les aspects sociétaux,
- une démarche transparente, et associant les acteurs de la société, pour bâtir des approches partagées.

4.2. Des points clés

4.2.1. *L'adaptation passe par une réduction de la vulnérabilité*

La vulnérabilité est la dépendance de nos sociétés à la disponibilité de la ressource en eau, à la disponibilité de l'électricité, aux effets des crues ou de l'élévation du niveau de la mer.

Il ne suffit pas de mobiliser davantage de moyens de maîtrise (de mobilisation de la ressource, de production d'électricité et de garantie d'électricité, de diminution des débits et hauteurs d'eau dans les zones inondées), il faut également faire l'effort de diminuer la vulnérabilité :

- Sobriété des usages de l'eau (dans les régions où les modèles climatiques indiquent une bassie de la ressource, ou une augmentation des durées des sécheresses),
- Maîtrise de la demande en électricité, et de la demande en pointe,
- Réduction de la vulnérabilité aux crues.

Un sujet central est celui des sécheresses. Le cas du Maroc (§3.4) n'est pas isolé : dans de nombreuses régions, la ressource, en volume annuel, devient insuffisante pour couvrir les besoins. Il est alors tentant de vouloir construire davantage de retenues de stockage – et c'est parfois une demande expresse des populations et des gouvernants – mais ce n'est pas toujours la meilleure option. L'effort, douloureux parfois, de réduction de la demande en eau est souvent nécessaire.

Des régions affectées par les épisodes de sécheresses ont développé des stratégies d'adaptation (par exemple [66]). De manière générale, ces stratégies passent par les axes suivants :

(a) La mesure et l'objectivation :
  - mieux quantifier la ressource ; mieux quantifier (comptabiliser) les usages, par secteurs – en intégrant également les besoins environnementaux ; exercice difficile mais nécessaire,
  - établir des projections d'évolution aux horizons appropriés, par exemple 2050 et 2100 et au-delà pour les projets les plus structurants,
  - en admettant les marges d'incertitudes de cet exercice, que l'on pourra diminuer progressivement, par l'instrumentation et l'acquisition de connaissances.

(b) L'élaboration des règles de partage des eaux :
  - élaboration de la stratégie d'adéquation entre ressources et besoins, dans l'état actuel et futur,
  - mise en place d'une gouvernance permettant la mise en œuvre, le contrôle et l'adaptation du partage des eaux.

(c) Un travail sur la sobriété (réduction de la demande en eau) :
  - lutter contre les gaspillages et les pertes,
  - développer des programmes d'économie d'eau, dans les différents secteurs
  - adapter l'agriculture, en promouvant des changements de pratiques, mieux adaptées aux conditions actuelles et futures.

(d) Un travail sur la mobilisation de la ressource :
  - par exemple par les solutions de stockage développées au §4.3,
  - par l'interconnexion entre des réservoirs, qui permet notamment de mutualiser la ressource entre régions excédentaires et régions déficitaires,
  - en intégrant également les volets de maîtrise de la qualité de l'eau.

(e) La préparation aux crises :
  - développement de scénarios de crise, et des parades à mettre en œuvre,
  - mise en place d'une cellule de gestion de crise.

Ainsi, pour l'adaptation aux enjeux de sécheresse, la mobilisation de la ressource en eau est un axe parmi d'autres. Le travail sur la sobriété permet souvent de dégager des marges d'adaptation sur la mobilisation de la ressource.

Cette conclusion s'applique également aux mesures d'adaptation concernant les crues et l'élévation du niveau de la mer : il doit y avoir un travail sur la diminution de la vulnérabilité en parallèle du travail sur la mobilisation des moyens de protection.

4.2.2. *L'adaptabilité passe par la flexibilité*

Cette section concerne les barrages et réservoirs, et moins les digues de protection.

C'est une évidence : en contexte d'incertitude, l'*Adaptabilité* passe par une certaine flexibilité, c'est-à-dire par la capacité à utiliser au mieux l'ouvrage, ou les ouvrages formant un système, dans des scénarios variés de ressources disponibles et de besoins exprimés.

Flexibilité à l'échelle des systèmes

Electricité

Pour les systèmes électriques, il faut varier les sources d'approvisionnement, et limiter l'exposition à la variabilité du climat. Cela renforce l'intérêt des interconnexions régionales (ce qui peut toutefois avoir des inconvénients en termes de souveraineté énergétique). Cela conduit à considérer qu'il est nécessaire d'évaluer l'impact de sécheresses prolongées – plusieurs semaines à plusieurs années - sur la production hydroélectrique, et de disposer de moyens d'y faire face. Cela conduit à considérer l'impact de périodes à faible ensoleillement et faible vent sur la production solaire et éolienne, et de disposer par exemple de réserves de stockage de sécurité dans des retenues hydroélectriques.

Alimentation en eau

Pour les systèmes d'approvisionnement en eau, la même logique peut être mise en œuvre.

L'interconnexion entre retenues ou entre régions (lorsque c'est possible) augmente les marges d'exploitation. Cela s'est pratiqué dans de nombreux pays et peut par exemple être illustré par le transfert São Francisco mis en service en 2022 au Brésil : objectif de sécurisation de l'alimentation en eau du NordEste (1 milliard de km^2, 28% de la population, 3% des ressources en eau), par deux canaux (260 km et 217 km, débit d'équipement 127 m^3/s). [FM]

Le recours aux interconnexions est utilisé dans de nombreux pays et régions, lorsqu'il y a des écarts de ressource en eau entre les différentes parties du territoire, et que certaines parties du territoire sont affectés par des déficits. C'est par exemple le cas en Algérie (des montagnes vers les zones habitées et les plateaux du centre du pays, 1.5 km^3 par an), en Californie (des rivières du Nord vers les grandes villes du Sud, 3 km^3 par an), en Chine (transfert Sud-Nord, depuis le Yangtze, 5 km^3 en 2022, estimation 15 km^3 par an en 2030), au Maroc (projet de grand transfert du Nord vers le Sud, un peu moins de 1 km^3 par an), en Tunisie (de la cote et du Nord-Ouest vers Tunis, vers les périmètres agricoles de l'Ouest et du Centre).

La redondance des sources d'alimentation offre des marges de sécurité en cas d'indisponibilité d'un ouvrage, pour cause de pollution de la retenue, ou d'incident physique sur le barrage

Des compléments d'alimentation « ne dépendant pas de la pluie » sont dans certains cas utilement mis en œuvre : eaux usées recyclées, nappe, dessalement. C'est par exemple ce qui est développé par la Western Australia Water Corporation, à travers un "Integrated Water Supply Scheme » (IWSS) [65]. Ce système, qui délivre plus de 300 hm^3 chaque année, comporte : de l'eau de mer dessalée, de l'eau souterraine, des réservoirs de surface et de la recharge de nappe à partir d'eau usée traitée.

Flexibilité à l'échelle des ouvrages

Electricité

Pour les centrales hydroélectriques, la « flexibilité » consiste à pouvoir utiliser au mieux la ressource stockée : pouvoir agir avec des pas de temps de variations plus courts, avec des gammes de production plus large ; pouvoir stocker pendant des durées plus longues.

Les besoins sont très importants : l'Agence internationale de l'énergie et l'Agence internationale pour les énergies renouvelables prévoient la nécessité de doubler la capacité hydroélectrique installée dans leurs scénarios pour 2050 afin de soutenir l'intégration des sources renouvelables variables et la décarbonisation du système électrique. Une partie de cette électricité devra provenir des barrages existants, soit en augmentant la capacité des centrales hydroélectriques existantes, soit en ajoutant de la production hydroélectrique à des barrages non équipés. [FLe]. Ce qui a des implications techniques (sur les machines, sur les circuits hydrauliques) et des implications environnementales (effets sur la rivière en aval).

Ce nouveau contexte et les incertitudes qui pèsent sur les évolutions à venir conduisent à changer la vision portée sur les futurs ouvrages.

Les ouvrages de **petite hydroélectricité**, sans retenue de stockage ou avec des petites retenues, doivent être examinés avec soin. Ils sont, en moyenne, plus sensibles aux conséquences du changement climatique, là où ces conséquences augmentent les périodes de sécheresse ou de basses eaux. [MHTK]. On peut également penser que leur empreinte écologique rapportée au MW stocké ou au kWh produit, est généralement plus forte que des projets de plus grande envergure.

Les ouvrages de production d'électricité **au fil de l'eau** (« run-off-river ») perdent et continueront à perdre de l'intérêt dans de nombreux contextes géographiques (mais pas partout), lorsqu'ils ne bénéficient pas d'une régularisation des débits par un réservoir situé en amont et assurant une régularisation annuelle et interannuelle. Sur les rivières non régulées, ces ouvrages ont pour vocation première la production d'électricité de base, sans objectif de garantie ; ils ont historiquement joué un rôle clé de production d'électricité à bon marché, en combinaison avec des centrales thermiques qui assuraient la garantie de fourniture en basses eaux. Désormais, il y a d'autres solutions bon marché (solaire, éolien), et désormais le recours au thermique diminue. L'électricité au fil de l'eau doit alors souvent démontrer une capacité de fourniture garantie, typiquement en accompagnement de l'électricité solaire (régulation jour/nuit), ou démontrer une contribution suffisamment utile en services auxiliaires (réglage de la fréquence, réserve tournante) en accompagnement de l'électricité solaire. Ainsi, la justification économique des centrales au fil de l'eau, sur les rivières non régulées, est souvent plus difficile, et peut-être impossible dès lors que les épisodes de basses eaux limitent substantiellement l'énergie garantie disponible. [PR].

Les ouvrages au fil de l'eau conservent cependant leur intérêt dans plusieurs contextes : dans les régions où l'électricité hydraulique est moins chère que l'électricité éolienne ou solaire ; dans les grands réseaux où ils contribuent à la diversification des sources de production intermittentes ; sur les cours d'eau où un stockage amont (ou des conditions hydrologiques particulières) limite suffisamment la fréquence et la sévérité des épisodes de basses eaux.

A l'inverse, les sites de production électrique **avec réservoir** voient leur intérêt renforcé, par leur capacité à stocker l'énergie, et compenser les intermittences du soleil et du vent. Pour tirer pleinement profit de ces avantages, il faut une capacité installée qui permet la régulation journalière, et par conséquent : un débit d'équipement nettement supérieur au débit moyen de la rivière, sinon aucune régulation n'est possible.

Il faut pouvoir pratiquer la **flexibilité**, avec des variations fréquentes des débits turbinés. Pour les usines hydroélectriques, augmenter la flexibilité nécessite des adaptations des machines (turbines, générateurs, auxiliaires), éventuellement des circuits hydrauliques, et peut bénéficier de l'adjonction de batteries. Il y a beaucoup de progrès et de nouveautés en la matière, qui dépassent le cadre de ce rapport. On pourra par exemple examiner les acquis du projet XFLEX [36].

Pour la rivière, il faut vérifier que les variations de débit imposées à l'aval ne soient pas, ou pas trop, dommageables pour l'environnement (ce qui peut se faire par le recours à du stockage intermédiaire avant restitution à la rivière).

Alimentation en eau

Pour les barrages destinés à l'alimentation en eau (eau potable, eau industrielle, eau pour l'irrigation, eau pour la biodiversité), la flexibilité est la capacité à s'adapter aux scénarios futurs de ressource en eau et de demande en eau.

Le climat futur est souvent synonyme de plus grande irrégularité : crues plus fortes, sécheresses plus fréquentes. Ainsi, en première approximation au moins, plus la **capacité de stockage est importante**, plus grande sont les chances de pouvoir faire aux écarts temporaires entre les débits naturels et la demande en eau. Sous certains climats, il faut cependant porter attention à deux effets induits : une plus grande retenue piège davantage les sédiments (ce qui a des conséquences potentiellement négatives à l'aval) ; une plus grande retenue expose à davantage de pertes par évaporation. Dans ces cas, les options de stockage hors rivière (§5.1) peuvent apporter des réponses adaptées. L'augmentation de la capacité de stockage est traitée au §4.3.

La flexibilité passe également par les conditions d'exploitation. A volume de stockage fixé, il y a des possibilités, parfois importantes, d'optimiser les conditions d'exploitation, en anticipant par des modèles adaptés les apports d'eau dans la retenue et les demandes en eau – notamment agricoles. Il faut pour cela disposer de données et de modèles adaptés (§4.7). Les modèles climatiques permettent, dans une certaine mesure, de prévoir la typologie générale du climat à l'échelle saisonnière (quelques mois). Tant que cela n'a pas d'incidence sur la sécurité des barrages, il pourrait être envisagé d'en tenir compte via une certaine flexibilité dans la gestion des retenues, par exemple en introduisant une possibilité de surremplissage (au-delà du niveau normal) en cas de prévision d'année sèche [TF].

Pour les barrages à vocation écosystémiques (notamment : favorisant la biodiversité), la flexibilité est également une affaire de mesures in-situ (de l'état de écosystèmes) et d'adéquation entre la ressource disponible et les besoins écologiques. Cela a par exemple été illustré dans le cas des sécheresses en Tasmanie, Australie (§3.4).

Protection contre les inondations

Pour les barrages à vocation de protection contre les inondations, la flexibilité consiste à optimiser l'efficacité en fonction des volumes de stockage disponible.

La première option consiste à augmenter le volume de stockage disponible en crue, par exemple en surélevant l'ouvrage (exemple pour le cas du barrage de la Lauch, dans Q108-R6). A volume de retenue inchangé, il y a des options :

- Augmenter le débit de la crue d'aval acceptable, pour ne stocker qu'au-delà d'un débit plus important,
- Adopter une gestion adaptative avant la crue, en opérant des creux préventifs (exemple du Japon, §3.4) et, pendant la crue, en adaptant la gestion du barrage en fonction de la prévision d'évolution de la crue (exemple de Q108-R22, sur le barrage de Stânca-Costeşti). Cela nécessite, dans les deux cas, de disposer de moyens de prévision des crues, quelques heures voire quelques jours à l'avance.

Pour les barrages secs (« dry dams »), la flexibilité exposée ci-dessus peut nécessiter de prévoir des vannes dans les orifices de fond. C'est un facteur de complexité, et également un facteur de risque en cas de mauvaise manipulation des vannes, mais cela offre des gains d'efficacité certains. Pour éviter tout contentieux avec les populations protégées en aval, il est important de disposer de « consignes de crue », qui exposent de manière claire et univoque les conditions de manœuvre des vannes en fonction des paramètres d'entrée (cote, débit).

Réservoirs à usage multiple

Pour les réservoirs à usages multiples, la flexibilité consiste à pouvoir modifier la répartition des usages au cours du temps. Cela peut nécessiter des aménagements des ouvrages (par exemple : surélévation), et cela peut avoir des incidences financières et contractuelles, par exemple s'il s'agit de réduire la production électrique pour optimiser les autres usages (stockage d'énergie, limitation des incidences des sécheresses et des crues, soutien à des fonctions écologiques).

En temps de crise, les réservoirs peuvent jouer un rôle important de résilience pour les sociétés : disponibilité en eau en cas de sécheresse majeure, lutte contre les feux de forêt, zone refuge en cas de vague de chaleur, … Permettre que ce rôle de résilience soit effectivement disponible le jour venu peut nécessiter de limiter exceptionnellement les autres usages, de sorte que la réserve ultime soit bien disponible.

4.3. Stocker l'eau douce

4.3.1. *Etat des lieux*

L'eau douce est rare. On en connaît, avec une part d'incertitude assez large, les principales grandeurs, en termes de stocks et de flux [32][33][34]. L'eau est stockée, sur les continents, sous forme d'eau de surface, dans l'humidité des sols et les tourbières, dans les glaciers montagneux, les pergélisols et glaces souterraines, et dans l'eau douce souterraine. Et en moyenne, il y a 13 km^3 d'eau dans l'atmosphère.

Il faut moduler ces réserves par le temps de séjour moyen : 1500 ans pour les eaux souterraines, 30 ans pour les lacs d'eau douce, 1,8 an pour l'humidité des sols, 17 jours pour les rivières, 9,5 jours pour l'atmosphère. Ainsi, en flux annuel, les chiffres principaux sont les suivants :

Table 1
Inventaire des volumes d'eau douce disponibles, en flux annuel, tableau repris de [33]

COMPARTIMENT	VOLUME (KM^3)	TEMPS DE RÉSIDENCE MOYEN	FLUX ANNUEL (KM^3/AN)
Glace de l'Antarctique	25 millions	10 000 ans	2 600
Glace du Groënland	3 millions	5 000 ans	600
Glaciers de montagne	80 000 à 200 000	100 à 300 ans	800
Pergélisol	22 000		
Eaux souterraines	15 millions (de 7 à 330 millions)	1 500 ans	10 000
Eaux des lacs d'eau douce	176 000	30 ans	5 900
Eau présente dans les sols	122 000	1,8 ans	70 000
Mers intérieures	105 000		
Eau dans l'atmosphère	12 700	9,5 jours	486 000
Eau dans les rivières	1 700	17 jours	36 800
Eau dans les cellules vivantes	1 100	quelques heures	

Il est intéressant de rapporter deux autres chiffres en lien avec ce tableau :

- Chaque année, environ 4 600 km^3 d'eau est consommée (source : [35])
- Le registre mondial de la CIGB indique que le volume brut de stockage des réservoirs est 9000 km^3. Une fraction significative de ce volume a été perdu par sédimentation ; une autre partie n'est pas utilisable (« volume mort »). Le volume utile pourrait être de l'ordre de 5000 km^3, ou un peu plus. Ce n'est qu'une petite fraction du volume des lacs d'eau douce, mais le temps de résidence étant beaucoup plus court, cela représente une grande partie du flux annuel.

4.3.2. *Lorsque c'est possible, stocker davantage*

Il faut augmenter la capacité de stockage, pour augmenter le flux annuel utilisable.

« Il faut », car c'est un instrument majeur de flexibilité (au sens du §0). Cela malgré les nécessaires efforts préalables de réduction de la vulnérabilité (au sens du §4.2.1), et notamment de sobriété, en beaucoup d'endroits du monde, ne suffira pas. Comme le mentionne Felipe Lazaro, pour la Banque Mondiale, « *L'eau et le stockage de l'eau sont des éléments essentiels de l'adaptation au changement climatique, de l'atténuation des émissions et de l'augmentation de la résilience à l'incertitude. Ces considérations sont essentielles à la promotion d'un développement vert, résilient et inclusif et à la réalisation des engagements pris dans le cadre du Plan d'action de la Banque mondiale contre le changement climatique* [. . .] *En tant qu'infrastructures à longue durée de vie, [les barrages et réservoirs] offrent des avantages considérables à la société, en permettant le stockage de l'eau pour l'approvisionnement en eau potable, l'irrigation, la production d'électricité et l'atténuation des inondations.*». [FLa]

Ces affirmations ont par exemple été confirmées par des études quantitatives pour le Sud de l'Europe, c'est-à-dire toute la façade Nord de la mer Méditerranée (case study CS9 de [24]). Il s'agit d'une région qui subit, et va continuer de subir une diminution importante des débits moyens annuels, et une augmentation importante de l'irrégularité des débits. 16 bassins versants majeurs ont été étudiés, pour évaluer l'impact du changement climatique sur la ressource en eau. Il est observé qu'augmenter capacités de stockage atténue la réduction de la ressource en eau et réduit l'incertitude associée aux projections climatiques.

Les rapports nationaux sur le climat et le développement (Country Climate and Development Reports, CCDR) donnent une image des priorités selon les pays. Selon une analyse réalisée en 2024 par la Banque Mondiale, l'augmentation de la capacité de stockage de l'eau pour l'hydroélectricité, l'irrigation et l'eau potable est l'action du secteur de l'eau la plus fréquemment mentionnée dans les 52 CCDR examinés. Les investissements prioritaires varient en fonction du contexte spécifique du pays, avec des interventions telles que l'expansion de l'infrastructure de l'eau et l'investissement dans le stockage de l'eau à usages multiples (Argentine, Irak, Malawi, Kenya), la protection des eaux souterraines et la recharge gérée des aquifères (Bangladesh, Ghana, Maroc), l'investissement dans l'énergie hydroélectrique par pompage (Jordanie), les systèmes de collecte des eaux de pluie (Ghana) et le stockage dans le réseau de distribution d'eau (Jordanie), la révision de l'exploitation des réservoirs pour mieux équilibrer les demandes entre les secteurs (Kazakhstan), la diversification des sources d'eau (Malawi), ainsi que des solutions de stockage basées sur la nature (Kazakhstan, Philippines) et la conservation et la restauration du stockage naturel (Roumanie, Paraguay), parmi d'autres. Tous les CCDR soulignent l'importance d'accroître l'adaptabilité du stockage de l'eau face à des conditions hydroclimatiques plus variables et d'explorer les possibilités de combiner le stockage construit avec des solutions basées sur la nature. [FLa]

Or, comme le mentionne G. Annandale, “*As hydrologic variability increases the reliability will decrease. The only way to deal with this when using rivers to produce power and supply water is to increase reservoir storage. [. . .] The dilemma is that global storage is currently decreasing more rapidly due to reservoir sedimentation than what we are adding due to the construction of new dams*. » [GA]

Ce constat renforce l’idée selon laquelle il y a lieu d’envisager de nouveaux stockages, en de nombreux endroits du monde. Le présent rapport examine les options de stockage dans les réservoirs de surface et, dans une certaine mesure, les options dans les nappes (superficielles, profondes). Il faut cependant constater qu’il y a des limites générales au stockage, limites brièvement exposées dans la section suivante.

4.3.3. *Stocker dans les réservoirs a ses limites*

Limites sociétales du stockage dans les réservoirs de surface

Les sociétés ne sont pas toutes prêtes à accepter la construction de nouveaux ouvrages. Les arguments contre les nouveaux ouvrages sont connus :

- les barrages perturbent les milieux naturels, et dans certains cas ils peuvent avoir des impacts sociaux négatifs par exemple en raison de l’ennoiement des terrains dans les retenues et de la diminution des débits à l’aval,
- les barrages font persister un modèle ancien jugé obsolète et seraient ainsi un obstacle à l’adaptation – par exemple lorsqu’ils ont pour fonction l’irrigation dans des zones soumises à la sécheresse, les opposants réclament d’abord un changement des pratiques agricoles.

Il faut reconnaître le fait que les barrages, digues et réservoirs sont des ouvrages structurants, qui ont des effets importants sur les milieux et les sociétés, et que ces effets doivent être pris en compte. Cela passe notamment par les études d’impacts environnementales et sociales, et par la concertation avec les parties prenantes. Cette nécessité est parfaitement reconnue par la profession, voir par exemple : « *Position Paper on Dams and the Environment* » de ICOLD [23] ou initiative Hydropower Sustainability Standard [38].

Le débat sur ces sujets n’est pas toujours fondé sur des données et des approches scientifiques, et notre profession considère que, parfois, les arguments soulevés par les opposants aux barrages ressortent davantage d’une opposition systématique que d’une analyse objective, au cas par cas. Quoi que l’on en pense, il faut pour l’instant composer avec cette limite sociétale. Il est possible que cela change à l’avenir, avec l’augmentation des besoins de stockage partout dans le monde et avec, du côté de la profession des barrages, la poursuite des progrès dans la prise en compte des sujets environnementaux et sociaux.

Limites environnementales du stockage dans les réservoirs de surface

La construction d'un réservoir de surface se fait nécessairement au détriment de certains pans de la biodiversité (§3.3). Par ailleurs, la construction d'un réservoir destiné à l'alimentation en eau (en particulier l'eau pour l'irrigation) signifie nécessairement que des volumes importants d'eau seront consommés, et ne seront plus disponibles, pour les milieux naturels et les populations. L'exemple de la mer d'Aral est bien connu. La construction d'un réservoir destiné à la production hydroélectrique ne consomme pas d'eau (à l'exception de l'évaporation), mais modifie le régime de la rivière ; il y a des conséquences également pour les milieux naturels et les populations, mais généralement moindres.

Ainsi, tout nouveau réservoir résulte d'une transaction entre des bénéfices (contribution à l'adaptation) et des coûts (impacts négatifs qui pénalisent l'adaptation). Dans certains cas, et du strict point de vue de l'adaptation des sociétés humaines au changement climatique, il vaudra mieux ne pas construire.

Limites physiques du stockage dans les réservoirs de surface

Il est tentant d'augmenter la capacité de stockage des retenues, pour opérer du stockage pluriannuel. L'expérience de certains pays affectés par des conditions hydrologiques déficitaires et surtout irrégulières (par exemple, la Tunisie, §3.4) a été de prévoir des retenues de grand volume, typiquement deux fois le volume des apports annuels. Cela a permis à la Tunisie de disposer de ressources en eau largement fiabilisées par rapport au régime naturel des oueds, et ainsi de répondre à ses besoins. Cependant, cette solution n'est pas nécessairement durable (augmentation du piégeage des sédiments) ni nécessairement adaptable aux conditions climatiques futures (possible insuffisance des ressources hydriques, forte exposition à l'évaporation) : sa fiabilité doit être vérifiée avec soin sous les hypothèses de climat futur, et en tenant compte de la sédimentation.

Le stockage hors rivière et les interconnexions offrent des solutions qui peuvent repousser les limites physiques, en diminuant (voire supprimant) l'exposition à la sédimentation et en diminuant les effets de l'évaporation, cf. §5).

Limites physiques du stockage dans les réservoirs souterrains

Les chiffres du §4.3.1 sont tels qu'il est tentant de vouloir augmenter le stockage en souterrain dans des aquifères exploités. Cela présente au moins un théorie un autre avantage : l'eau stockée en souterrain ne s'évapore pas et elle est protégée des pollutions. Ces considérations ont conduit à développer des technologies de barrages souterrains et de recharge aquifère. Ces ouvrages ont en particulier été envisagés en pays aride.

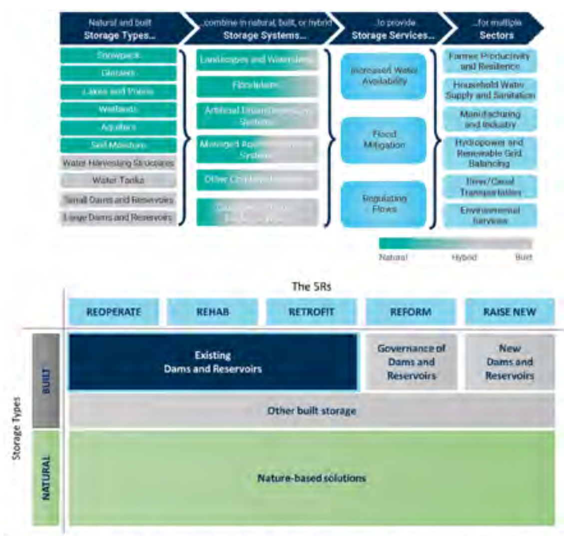
L'examen de ce qui a été expérimenté met cependant en évidence une série de limites physiques ou économiques, décrites au §5.5, qui expliquent que ce développement a été limité. Cependant, les volumes de stockage disponibles dans les sols et les roches sont très importants. Il est toutefois possible que des inventions ou progrès dans la compréhension des mécanismes physiques ouvrent la voie à de nouvelles options de stockage en souterrain.

4.3.4. *Stratégies, pour le stockage*

Multiplier les approches

Considérant les besoins en stockage actuels et futurs, et considérant les différentes limites exposées ci-dessus, il paraît raisonnable de multiplier les approches.

La Banque Mondiale promeut [23] une approche très ouverte, baptisée « 5 Rs », dans laquelle : (a) Les réservoirs des barrages sont une des contributions aux stockages requis et (b) La construction de nouveaux réservoirs est une des options à



« Reoperate »	Modifier l'exploitation (d'un réservoir, d'un groupe de réservoirs), pour améliorer l'efficacité de la réponse à la demande.
« Rehab »	Restauration des réservoirs (artificiels ou naturels), pour retrouver leur capacité ou prolonger leur durée de service
« Retrofit »	Augmentation de la capacité de stockage (par ex : surélévation), ajout de fonctions ou suréquipement (par exemple : prod électrique, PV flottant),
« Reform »	Investir dans les institutions pour mieux gérer le stockage.
« Raise new »	Créer de nouveaux réservoirs, Naturels et construits, En surface et souterrains, De grande et petite échelle, Centralisés et distribués.

Fig. 7
Les " 5Rs" de la Banque Mondiale [29]

explorer, en parallèle des actions sur les ouvrages en service. Cette approche est présentée par les diagrammes ci-dessous.

S'agissant des réservoirs de barrage, le bulletin 200 de la CIGB [23] recommande de prioriser l'amélioration des infrastructures existantes (optimisation de l'exploitation, amélioration de l'efficacité) avant d'envisager des options plus coûteuses telles que la surélévation, la construction de nouveaux barrages, les ouvrages de transfert d'eau ou la végétalisation des bassins versants.

Note spécifique au stockage pour la production hydroélectrique

Il y a encore un potentiel important pour de nouveaux projets hydroélectriques dans de nombreux pays du monde. En particulier, le potentiel hydroélectrique de l'Afrique est exploité à moins de 10%. Parmi ceux-ci, les projets disposant de réservoirs auront une meilleure *adaptabilité* que les projets au fil de l'eau lorsque les projets au fil de l'eau ne sont pas régulés par un réservoir situé en amont.

Il est raisonnable de penser cependant que ces projets seront généralement moins nombreux que les projets éoliens et solaires. Le rapport Q108-R20 illustre par exemple la stratégie de l'Inde :

Table 2
Stratégie de développement des énergies renouvelables en Inde, Q108-R20

	ACTUEL	**2030**	**2047**
Hydroélectricité (hors STEP)	47 GW	55 GW	87 GW
STEP	4 GW	19 GW	116 GW
Solaire		293 GW	1200 GW
Eolien		100 GW	436 GW

Dans certains pays particulièrement favorisés par les conditions naturelles (hydrologie et topographie), l'hydroélectricité jouera un rôle de tout premier plan dans le mix énergétique futur. Dans beaucoup d'autres, il s'agira d'un rôle d'accompagnement. Cela peut amener à recentrer les réservoirs hydroélectriques sur deux fonctions à forte valeur ajoutée sociétale :

- Permettre le déploiement des énergies renouvelables intermittentes, en fournissant des capacités de stockage et les services permettant d'assurer la stabilité des réseaux électriques
- Donner de la place aux autres usages, qui vont offrir aux sociétés une *contribution à l'adaptation* nécessaire.

Comme écrit dans Q108-R20, à propos de l'Inde, « *[. . .] by 2047, India needs to construct around 1000 dams. Apart from meeting requirement of energy transition, these high dams with water storage will provide resilience and address environment vulnerability against droughts, mitigate the risk of flooding and reduce the frequency and extent of inundations and development of artificial wetlands. [. . .]. Increased Dams with reservoir storage capacity will help to tackle hydrologic variability and heightened risk and uncertainty due to climate change*»

4.4. Limiter les inondations

4.4.1. *Approches intégrées*

Limiter les inondations par les cours d'eau peut être réalisé au travers de différentes approches, que l'on peut combiner :

- à la source, favoriser l'infiltration (par la suppression de surfaces imperméabilisées et par le ralentissement des écoulements) et limiter l'érosion par l'aménagement des bassins versants (exemple du Japon qui était complètement déboisé à la fin du XIXème siècle et qui est maintenant très boisé)
- le long du cours d'eau, en favorisant l'inondation de plaines en lit majeur (« ralentissement dynamique »)
- par du stockage dans des réservoirs, éventuellement sec hors période de crue,
- par des digues de protection plus ou moins éloignées du lit mineur de la rivière,
- dans la zone à protéger, par la réduction de la vulnérabilité (diminuer le risque humain et les enjeux économiques dans les zones soumises à l'inondation).

Le stockage dans les réservoirs de barrage et les digues de protection ont fait la preuve de leur utilité dans de très nombreuses circonstances. Il est recommandé également de recourir aux solutions de réduction de la vulnérabilité et d'amélioration de l'infiltration, qui sont des solutions *sans regret*, car elles fonctionnent quelles que soient les crues.

A proximité de la mer, les inondations peuvent provenir des submersions marines et de la courbe de remous dans les estuaires et les fleuves. Limiter les inondations par les submersions marines et la surcote dans les fleuves proches de la mer peut être réalisé au travers de différentes approches, que l'on peut combiner :

- par des digues de protection et des barrières de protection,
- dans la zone à protéger, par la réduction de la vulnérabilité,
- dans la zone à protéger, par des procédés d'abaissement de la ligne d'eau par pompage,

- par du stockage dans des réservoirs pour limiter les débits des fleuves côtiers dans les zones à protéger.

Des généralités sur le stockage des crues dans les réservoirs sont présentées dans la section suivante. Le §5 présente quelques solutions techniques nouvelles pouvant être utilisées pour la limitation des inondations.

4.4.2. *Du stockage additionnel dans les barrages*

Disposer de capacités de stockage est dans de nombreux cas une mesure efficace de limitation des débits de crue. Trois grandes options sont souvent examinées :

- disposer d'une capacité de laminage dans un réservoir (qui peut être destiné à d'autres usages),
- barrages secs (« dry dams ») qui sont parfois préférés pour des raisons environnementales,
- stockage temporaire dans des barrages destinés à d'autres usages (« creux préventifs »).

L'efficacité des barrages et des digues pour la protection contre les crues se mesure au droit des enjeux protégés. Les évaluations correspondantes ne sont pas toujours faciles à mener : lorsque les barrages ne sont pas proches des enjeux, l'efficacité du laminage des crues peut être diminué par les effets de concomitance entre les différents apports intermédiaires, par les affluents à l'aval du barrage (problématique de l' « horloge des crues »).

La conception et l'exploitation des barrages destinés à l'écrêtement des crues nécessite une attention particulière à la question de la progressivité des crues à l'aval du barrage. Il s'agit d'éviter les effets de seuils qui se manifesteraient par le passage, à l'endroit des enjeux protégés, d'une situation de protection très efficace (fort écrêtement des crues) à une situation sans efficacité (peu ou pas d'écrêtement des crues). Dans la mesure du possible,

- les déversoirs, qui régulent la conversion du débit d'entrée maximal en débit de sortie maximal pour des crues de différentes périodes de retour, doivent permettre une augmentation progressive du débit maximal évacué par rapport au débit maximal entrant. Cela maintient une certaine culture des crues auprès des populations aval.
- les débits restitués à l'aval par le barrage sont utilement restitués avec une forme d'hydrogramme progressive ; cela limite l'effet de surprise pour les populations.

Pour les barrages dont la destination principale est la protection contre les inondations, il est utile d'examiner les possibilités de conception de barrage tolérant à la surverse (pouvant être surversé sans risque de rupture). Il s'agit de garantir, par des mesures adéquates de protection de la crête, du parement aval et de la restitution en pied de barrage, la résistance du barrage à une surverse modérée. Cela permet d'envisager la situation d'une cote de retenue qui dépasse la cote de la crête, avec deux avantages importants :

- cela peut éviter, dans certains cas, de devoir ouvrir trop rapidement des vannes de crue pour protéger le barrage : cela peut améliorer la progressivité de l'hydrogramme restitué,
- cela offre un gain de sécurité ultime, appréciable pour tous les barrages compte-tenu des incertitudes hydrologiques, mais particulièrement intéressant pour les barrages de protection contre les inondations en raison de leurs spécificités (forts enjeux aval et, souvent, débitance des évacuateurs de crue sensiblement inférieure au débit de pointe des crues).

Cette thématique, techniquement délicate dans le cas des barrages en remblai, est un sujet de recherche à faire progresser.

4.4.3. *Garder à l'esprit les limites du stockage des crues*

Les barrages ne permettent pas de supprimer les effets des crues à l'aval ; en revanche, ils permettent d'en atténuer les effets. Il y a donc régulièrement des événements d'inondations importantes, alors même qu'il y a des barrages dans le bassin versant. Cela a conduit dans certains cas à des procès, dont il est possible de tirer quelques leçons [PM] :

- La fiabilité des données sur les inondations en amont pendant un événement est cruciale.
- Des protocoles de communication clairs et une confiance mutuelle entre les parties prenantes sont extrêmement précieux.
- Plans de gestion des inondations : il y a lieu de :
  - Définir clairement les objectifs, les rôles et les processus pour les actions opérationnelles.
  - Consulter les parties prenantes et communiquer clairement le plan ainsi que ses limites.
  - Fournir des déclarations explicites sur l'utilisation et les limites des prévisions.
- Si une marge de manœuvre peut être utilisée, elle doit être explicitement mentionnée dans le plan ; sinon, il faut s'en tenir strictement au plan.
- Ne pas « sur-vendre » les bénéfices apportés par les barrages lors des événements d'inondation ; communiquer sur les risques résiduels d'inondation, pour limiter l'effet de surprise en crue.
- Une attention particulière doit être portée aux exigences d'atténuation des inondations, afin d'éviter des attentes ou exigences irréalisables.
- Les attentes du public évoluent dans un contexte en constante mutation.

4.5. Promouvoir la biodiversité

Par leur présence même, les lacs de retenues peuvent avoir des contributions positives. Par exemple, 54% des retenues en Slovénie sont considérés comme des sites où des mesures de protections ont été mises en œuvre, en raison de leur importance écologique [MK]. De nombreux lacs artificiels sont classés comme site d'importance Ramsar. L'IPBES souligne également les contributions positives (§3.3).

Par ailleurs, les modes d'exploitation ont leur importance. Une exploitation adaptée des barrages et de la rivière peut avoir des effets bénéfiques importants, ce que montrent des exemples dans différents pays. Notamment :

- En maintenant un apport en eau en situation de sécheresse. Par exemple, en Australie, une attention particulière a été portée aux besoins écologiques pendant la gestion de la sécheresse de 2015-16 (§3.4).
- En travaillant sur la continuité écologique (poissons, sédiments). Par exemple, au Japon, des interventions de gestion sédimentaire ont un impact sur la biodiversité en permettant le développement d'habitats diversifiés et favorables [TS].
- En tentant de progresser sur la qualité de l'eau relâchée à l'aval. En effet, les lâchers d'eau provenant du fond du réservoir ont des incidences négatives : dégazage du méthane en aval, températures d'eau non naturelles, eau de mauvaise qualité biochimique [AH]. Les solutions de prises d'eau étagées, ou de prises d'eau de surface permettent une amélioration de la qualité de l'eau relâchée [TS].

Promouvoir ou soutenir la biodiversité, c'est certainement contribuer à l'adaptation. C'est un sujet important, qui fait l'objet de travaux de recherche et d'expérimentations, et qui n'est pas développé dans le présent rapport.

4.6. Gouvernance : prendre les bonnes décisions

4.6.1. *Une question de méthode*

Le contexte de la Prise de décision

Des projets de construction neuve, de réhabilitation ou de modification d'ouvrages sont discutés et envisagés partout dans le monde. Une question centrale est de savoir comment les décisions sont prises, sur l'opportunité des travaux et sur leur conception générale. [EH]

La prise de décision doit être établie sur la base d'objectifs clairs prédéfinis : répondre à des besoins (en eau, en électricité, en protection), améliorer la résilience aux situation exceptionnelles, améliorer les conditions environnementales, etc ... Dans le cas des barrages et des digues, compte-tenu de leur aspect structurant, la *Contribution à l'adaptation* devrait toujours être un objectif central. La *Contribution à l'atténuation* est également souvent un objectif majeur. La prise de décision doit intégrer l'ensemble des contraintes. Parmi ces contraintes, il y a lieu d'intégrer l'*Adaptabilité*, et la *Soutenabilité*.

Cela soulève des questions de gouvernance et de méthode : comment et par quels organes sont définis ces objectifs et les contraintes ; comment la prise en compte de ces objectifs et contraintes est-elle menée ?

Définition des objectifs et des contraintes

La définition des objectifs et des contraintes est du ressort de la puissance publique.

L'expérience montre qu'il y a consensus sur la nécessité de prendre en compte les objectifs et contraintes mentionnées au § précédent, consensus reflété notamment dans les positions de la CIGB. L'expérience montre cependant que ce consensus est difficilement traduit dans les faits car, lorsqu'un projet est développé, les considérations économiques, financières et sociales de court terme prennent une place prépondérante.

En réalité, pour que ces objectifs et contraintes soient pris en compte, ils doivent être imposés, de manière explicite et contraignante, par la puissance publique. Comme l'exprime Eric Halpin : *« Laws and regulations which specify long term requirements for items like sustainability and climate change move these important topics outside the cost effectiveness of decision making, which is likely a must »* [EH].

Méthodes de travail

Depuis quelques décennies déjà, l'approche par la seule maximisation d'un bénéfice unique (minimisation du coût de l'électricité produite, minimisation du coût du mètre cube d'eau régularisé) est abandonnée. Les analyses multicritères ont été souvent mises en œuvre, mais elles sont exposées à des critiques, pour au moins deux raisons : (1) leur caractère souvent subjectif qui les expose à des biais de jugement et (2) le fait qu'elles sont mal adaptées à la prise en compte de scénarios (de climat futur). Les démarches recommandées aujourd'hui sont la combinaison :

- De démarches quantitatives : approche par les risques (« risk informed decision making ») et analyses en cycle de vie (« LCA » et « LCSA »).
- D'approches holistiques : études environnementales et sociales, concertation avec les parties prenantes et notamment les populations affectées.

Ce sont des démarches potentiellement lourdes et il convient de les proportionner à l'importance de la décision à prendre. Ce sont des démarches qui restent soumises à une part (importante) de subjectivité, en particulier lorsqu'il s'agit de prendre en compte des coûts et bénéfices indirects et des externalités non monétisables. Quelques-uns de ces éléments de méthode sont détaillés dans les sections qui suivent.

4.6.2. *Penser « soutenabilité »*

Evaluer la soutenabilité

Le développement de nouveaux ouvrages ou la transformation des ouvrages existants doit être conduite en intégrant la soutenabilité, c'est-à-dire la minimisation des impacts environnementaux et sociaux. Le présent rapport n'examine pas ces objectifs. Il importe cependant de rappeler que, à services rendus équivalents, les projets peuvent avoir une empreinte environnementale et sociale plus ou moins grande.

Des analyses en cycle de vie permettent de comparer les différentes options, et de privilégier les options qui, entre autres thématiques, minimisent les émissions de GES provoquées par la construction des ouvrages et de la mise en eau des retenues. Les émissions de GES ne sont pas le seul paramètre à prendre en compte pour juger de la soutenabilité d'un projet et, à la suite d'initiatives telles que celle de l'Hydropower Sustainability Alliance, des travaux en cours de la CIGB viendront fournir des outils permettant de préciser cette question.

Allonger la durée de service

Généralités

Un paramètre central de la soutenabilité est la durée de service. En première analyse, doubler la durée de service d'un réservoir (durée de service 2D au lieu de D), c'est diviser par deux le coût environnemental de la construction. En effet, sur la durée globale de service, 2D, on ne construit alors qu'un ouvrage, plutôt que deux.

Ce calcul est un peu simpliste et doit être modulé : il vaut mieux émettre 1 tonne de CO2 dans 100 ans qu'émettre 1 tonne de CO2 aujourd'hui ; il vaut mieux mettre en œuvre une mesure favorisant la biodiversité aujourd'hui plutôt que dans 100 ans. Il y a donc, comme pour les approches monétaires, une forme de taux d'actualisation à considérer pour indiquer qu'il y a une « préférence pour le présent » : faire les efforts aujourd'hui (pour le changement climatique, pour la biodiversité) est plus efficace que faire les efforts demain.

Cette modulation ne modifie pas l'affirmation principale : doubler la durée de service d'un réservoir, ce n'est pas exactement diviser par deux le coût environnemental de la construction, mais c'est certainement le diminuer de manière très importante.

Des réservoirs de barrage sont en service depuis des centaines d'années. D'autres sont hors service au bout de quelques années ou quelques décennies. Il y a donc des marges de manœuvre.

Durabilité des réservoirs : Sédimentation

La prise en compte de la sédimentation dans la conception et l'exploitation des barrages est un sujet majeur, à tous égards : *Soutenabilité, Adaptabilité, Contribution à l'adaptation*. La gestion sédimentaire doit être une composante majeure des projets avec une vision de long terme, 100 ans, 200 ans et pourquoi pas davantage. Malheureusement, il est encore constaté de nos jours que certains projets se contentent d'un horizon de 20 ou 30 ans, horizon compatible avec la durée de retour sur investissement d'un aménagement hydroélectrique privé. Par ailleurs, le changement climatique devrait conduire à une augmentation du transport sédimentaire.

La gestion sédimentaire est une thématique difficile, mais pour laquelle des progrès sont réalisés, et dont il faut tenir compte dans la conception des projets, et dans l'exploitation des barrages :

- L'amélioration des moyens d'étude (simulation de transport sédimentaire ; intégration des indications de pollution des sédiments dans les analyses) permet d'affiner les modes d'exploitation des ouvrages.
- Pour les ouvrages neufs, et sous réserve des conditions locales, l'expérience accumulée montre l'utilité de prévoir des organes de fond dimensionnés pour la crue de 50 ans environ ; cela permet de mettre en œuvre des opérations de gestion sédimentaire efficaces. [AS]
- Pour les ouvrages en cascade, l'expérience montre l'utilité de prévoir des opérations de gestion sédimentaire coordonnée le long des ouvrages de la cascade.
- Il y a, dans de nombreuses régions, une utilité certaine à lutter contre l'érosion à la source. Les mesures de conservation des sols ont le double avantage de maintenir la richesse des sols (et donc leur biodiversité, leur productivité) et de limiter l'alluvionnement. Il s'agit de travaux de longue haleine, qui ont été parfois couronnés de succès avec des bénéfices à court terme et à long terme.

La thématique de la gestion sédimentaire est traitée par plusieurs bulletins de la CIGB (bulletins 140, 147, 182, 193) et n'est pas développée dans ce rapport.

Durabilité des structures : Conception générale et Matériaux de construction

Il ne paraît pas impossible, et sans doute souhaitable, de vouloir construire des barrages conçus pour durer bien plus de 100 ans. La durée de vie d'un barrage dépend de sa conception (les facteurs de vieillissement sont-ils identifiés et la maintenance est-elle possible ?) et de la nature des matériaux de construction (sont-ils sensibles au vieillissement ?). Elle dépend également de sa capacité à résister aux événements extrêmes qu'il peut subir. Cet objectif est de plus en bonne synergie avec la problématique de la sécurité des barrages.

La discussion sur ces thématiques sort du cadre du présent rapport.

Faut-il accélérer et simplifier les procédures d'autorisation environnementale ?

Q108-R20 indique que le rythme de développement des projets hydro (y compris STEP) doit être au moins trois fois plus rapide que le rythme actuellement constaté. Pour y parvenir, Q108-R20 recommande des mesures d'incitation financière et une simplification des démarches d'autorisation environnementale.

Les mesures d'incitation financières sont certainement justifiées, en raison des services non monétisés rendus par les réservoirs, et en raison de la grande durée de vie de ces ouvrages (grande durée de vie mal prise en compte par le mécanisme des taux d'intérêt et taux d'actualisation). La simplification des démarches d'autorisation environnementale fait davantage débat : reconnaissant les impacts importants des grands réservoirs, à la fois positifs et négatifs, il peut paraître justifié de prendre le temps d'un examen approfondi, pour aboutir au meilleur projet : de nos jours, la composante technique des projets de barrages est de mieux en mieux maîtrisée ; la composante environnementale demeure un défi.

Bien entendu, la profondeur et l'étendue des investigations et justifications environnementales doit être proportionnée aux enjeux environnementaux du projet. En particulier, beaucoup des retenues hors rivière (et notamment les réservoirs des STEP en circuit fermé) ont des enjeux environnementaux modérés. L'urgence du déploiement des énergies renouvelables et la nécessité de prévoir en parallèle des moyens de stockage justifie probablement une accélération des procédures pour ces ouvrages.

4.6.3. *Consentir au surcoût de l'adaptation, le prendre en charge*

Recourir à des solutions mieux adaptées a un coût : l'investissement initial peut-être plus élevé que celui à consentir pour une solution de court terme, qui répond à des besoins immédiats et ne se soucie pas de l'adaptation à long terme. Il paraît nécessaire de consentir à ce coût immédiat : c'est n'est pas aux générations futures de supporter le coût de solutions mal-adaptées.

Taux d'actualisation

Cela soulève la question du « taux d'actualisation » utilisé pour les études économiques lorsque l'on évalue des ouvrages ayant une importance pour le changement climatique. Il s'agit d'un sujet central, que l'on peut illustrer ainsi : le tableau ci-dessous indique le montant des dommages évités dans 100 ans nécessaires pout rentabiliser un investissement de 1000 € aujourd'hui.

TAUX D'ACTUALI-SATION	**COMMENTAIRE**	**MONTANT DES DOMMAGES ÉVITÉS DANS 100 ANS**
1,4%	Taux proposé par Nicholas Stern (dont composante « préférence pour le présent » 0%).	4 000 €
4%	Taux utilisé dans de nombreux projets d'infrastructure	50 000 €
6%	Taux utilisé dans de nombreux projets d'infrastructure	340 000 €

Pour Nicholas Stern, économiste en chef de la Banque mondiale de 2000 à 2003, et également pour les économistes du GIEC, il ne faut pas accorder de « préférence pour le présent », et donc utiliser un taux d'actualisation bas. Pour d'autres écoles d'économistes, il y a une « préférence pour le présent » visible dans les taux d'intérêt du marché ; il faut en tenir compte, et cela conduit à des taux d'actualisation plus élevés. Il ne s'agit pas, dans ce rapport, de fixer un taux d'actualisation à utiliser. On souligne simplement que :

- l'emploi d'un taux de 4% ou de 6%, conduit nécessairement à projeter des ouvrages sans beaucoup se préoccuper des incidences à long et très long terme,
- l'emploi d'un taux de 10%, parfois observé, peut être considéré comme un non-sens pour les projets structurants de barrages et réservoirs amenés à rendre des services pendant 100 ans et plus,
- depuis 2006 (rapport Stern), il paraît légitime d'utiliser des taux sensiblement plus bas.

Les débats sur le taux d'actualisation à retenir sont complexes ; on note que, dans de nombreux pays, depuis 2003, il y a une tendance à mieux prendre en compte la question du très long terme (« Social discounting »), avec des taux d'actualisation plus bas, et décroissant avec le temps. Une discussion de synthèse sur ce sujet est disponible dans [45].

Ces débats, en revanche, ne semblent pas tenir compte d'une autre composante de la comptabilité de long terme : certaines actions sont plus efficaces si elles sont entreprises tôt, comme l'expose le §0 ci-dessus. Ainsi, il y a lieu d'affecter également un « taux d'actualisation » à certaines des externalités, et pas seulement aux coûts monétaires, pour donner plus de poids aux actions immédiates.

Pays en développement : Partage des coûts

Les pays en développement n’ont pas toujours les moyens de supporter le coût d’ouvrages structurants pour garantir leur adaptation au climat futur, ou le surcoût à consentir pour qu’un ouvrage remplissant un besoin de court terme soit également bien adapté pour le long et le très long terme. Il paraît légitime que les pays plus riches participent à ce coût d’investissement, voire prennent en charge le surcoût, pour au moins les trois raisons suivantes :

- Ce sont ces pays « plus riches » qui ont le plus contribué aux émissions de GES, et cela très largement.
- La soutenabilité des ouvrages, leur contribution à l’atténuation et leur contribution à l’adaptation ont des composantes qui bénéficie à l’humanité tout entière : minimisation des émissions de GES, support à la biodiversité. Cela justifie une prise en charge au moins partiellement mutualisée.
- C’est le seul moyen de progresser rapidement vers les objectifs de développement durable de l’ONU (comme l’exprime Adama Nombre : « *il s’agit de d’adapter aux changements climatiques global et aussi de chercher les solutions pour leur atténuation tout en élevant les conditions de vie de millions d’hommes et de femmes et d’enfant qui sont indignes et qui se trouvent dans les pays non développés* »).

4.6.4. *Partager l’eau*

Généralités

En contexte de rareté, il va falloir partager l’eau, ou re-définir le partage de l’eau, dans de nombreuses régions du monde. Les modalités de partage ne sont pas évidentes, car :

- Les usages sont multiples et souvent contradictoires.
- Certains usages « payent » et d’autres non : la production d’électricité, l’eau industrielle et dans certains cas l’eau agricole (« cash crops »), peuvent financer, ou partiellement financer, la construction et l’exploitation ; ce n’est généralement pas le cas de l’eau pour les communautés villageoises, l’eau pour le soutien d’étiage, l’eau pour le stockage de sécurité en cas de sécheresse.

Un exemple est donné par le projet de barrage Fomi/Moussako, sur le fleuve Niger, en Guinée. Ce projet est justifié notamment par le souhait de produire de l’hydroélectricité, énergie renouvelable, pilotable et peu chère et de soutenir les grands périmètres irrigués du Mali. Cependant, les conséquences sur le delta intérieur du Niger où la crue annuelle du fleuve joue un rôle majeur sur les ressources agropastorales et est à la base des conditions de vie et des structures sociétales pour des populations nombreuses, peuvent être catastrophiques. Il y a donc lieu de trouver un partage, dans la gestion du futur réservoir, entre l'optimisation de la production électrique et de l'agriculture irriguée et le maintien du régime naturel du fleuve [ADB] [74].

La question se donc pose des outils disponibles pour débattre de ce partage.

Un outil : Les approches économiques

Cadre général : internaliser les externalités

Les approches économiques modernes ne se contentent pas de chiffrer les coûts d'investissement, les coûts d'exploitation et de mesurer la production issue de la vente de l'eau et de l'électricité. La notion d'externalité est devenue centrale. *« L'externalité caractérise le fait qu'un agent économique crée, par son activité, un effet externe en procurant à autrui, sans contrepartie monétaire, une utilité ou un avantage de façon gratuite, ou au contraire une nuisance, un dommage sans compensation »* (wikipedia). Prendre en compte les externalités, c'est bien faire le tour complet de la justification des projets.

En matière de retenues de barrages, les externalités, positives et négatives, pèsent beaucoup. Elles demeurent difficiles à quantifier (puis à affecter) et sont de ce fait sous-valorisées dans la mise au point des projets. Les externalités négatives sont les impacts sociaux et environnementaux négatifs liés à l'ennoiement de la retenue et aux modifications de la rivière à l'aval. Elles sont, en toute première approximation, proportionnelles au volume stocké, aux volumes prélevés dans la rivière, et à la superficie ennoyée. Les externalités positives sont liées à l'usage fait de la ressource : retombées indirectes liées à la production d'électricité (développement économique et social), à la production d'électricité garantie, aux services réseau (report d'investissements sur le réseau) et d'électricité renouvelable (mitigation du changement climatique), diminution des zones inondées en crue, soutien des étiages, et éventuellement soutien à certains compartiments de biodiversité.

La balance bénéfices / coûts d'un projet se mesure alors par le quotient :

$$\frac{B}{C} = \frac{\text{bénéficeséconomiquesmonétisables} + \text{externalitéspositives}}{\text{coûtsmonétisables} + \text{externalitésnégatives}}$$

Si on ne s'intéresse qu'au numérateur (les bénéfices), l'inventaire de tout ce qui a une « valeur » est déjà très important :

- la production d'électricité, dont la valeur (par kWh) dépend du niveau de garantie
- le stockage (en kW) utilisable pour compenser l'intermittence du solaire et du vent, et les services au réseau, dont la valeur dépend de la disponibilité et de

ce qu'elle permet comme développement solaire et éolien (ou évite comme déploiement de batteries),

- la fourniture d'eau « commerciale », c'est-à-dire pour lesquelles les utilisateurs payent : eau potable, eau industrielle, agriculture commerciale ; dont la valeur est peut-être proche du prix de vente – lorsque l'eau n'est pas subventionnée,
- la fourniture d'eau pour la subsistance : irrigation et élevage non marchands ; dont la valeur est du même ordre de grandeur que la fourniture d'eau « commerciale », même si le prix est 0 ou proche de 0,
- l'écrêtement des débits de crue, dont la valeur dépend des dommages évités pour les différentes périodes de retour des crues,
- le soutien des étiages, pour les besoins humaines (assainissement, pêche, mode de vie),
- le soutien des étiages, pour la biodiversité, dont la valeur rejoint la notion des services écosystémiques, c'est -à-dire de tous les services assurés gratuitement par la nature au profit des humains, et que l'on est souvent bien en peine de comptabiliser,
- les réserves stratégiques en cas de sécheresse, volumes d'eau sanctuarisés pour les épisodes de sécheresse grave et prolongés ; il s'agit d'une forme d'assurance : l'eau n'est pas utilisée sauf circonstances exceptionnelles ; la valeur est donc très forte, mais à multiplier par une probabilité d'occurrence faible,
- l'agrément et le tourisme, les paysages.

Définir des valeurs pour chacun de ces services est délicat, et contient nécessairement une part de subjectivité. Pourtant, il faut le faire : mettre des chiffres permet de renforcer l'attention portée aux externalités. Cette approche, lorsqu'on l'applique à des cas réels, fournit deux enseignements.

- La « valeur » associée aux différents services économiques, sociaux et environnementaux sont dans les mêmes ordres de grandeur. Pour augmenter la valeur d'un aménagement, il faut travailler tous les aspects. Ce résultat corrobore les approches plus qualitatives développées par certains acteurs (par exemple, WWF, [44]).
- Un m^3 stocké peut compter plusieurs fois, par exemple s'il est turbiné au meilleur moment pour offrir de la garantie de puissance, s'il contribue de plus au soutien des étiages grâce à un bassin de compensation à l'aval, et enfin si, sensiblement plus loin à l'aval, il vient alimenter des périmètres irrigués. Le multiusage augmente la valeur d'un aménagement.

Il faut admettre l'idée selon laquelle la valeur économique n'est pas égale à la valeur commerciale ou financière. L'eau pour le soutien d'étiage, la résilience en cas de sécheresse ou pour l'agriculture de subsistance n'a pas de grande valeur commerciale, mais elle peut avoir dans certains cas une valeur économique globale (c'est-à-dire incluant les externalités) qui dépasse la valeur économique de l'hydroélectricité.

Coopération internationale

De nombreux bassins versants sont partagés entre pays voisins. Il faut encourager le renforcement de la collaboration régionale dans les bassins versants partagés, en particulier dans le cadre des études hydrologiques, de la recherche climatique, de la révision éventuelle des lignes directrices existantes pour l'exploitation des réservoirs, ainsi que de la gestion de la sécurité des barrages [AB]. Cela paraît particulièrement nécessaire pour limiter les tensions qui vont naître de l'augmentation des irrégularités des ressources en eau.

4.6.5. *Partager et valoriser l'espace*

Un des enjeux de la soutenabilité est l'artificialisation des terres. Il est utile d'envisager les solutions qui limitent l'emprise au sol nécessaire pour les activités humaines. Cela peut conduire à rechercher des solutions de barrages qui minimisent l'emprise des réservoirs à services rendus constant. Surtout, cela amène à réfléchir aux utilisations qui peuvent être faites pour valoriser les surfaces occupées par les réservoirs. Le solaire flottant, l'aquaculture, la pisciculture, le tourisme sont des moyens de valorisation de ces surfaces. Il y a peut-être d'autres idées ...

Pourrions-nous imaginer d'autres utilisations qui pourraient être installées dans les réservoirs, sur le barrage lui-même ou en utilisant la même infrastructure ? L'énergie éolienne flottante sur le réservoir, des électrolyseurs flottants pour produire de l'hydrogène, des « jardins » flottants pour l'agriculture, des habitations flottantes, ou d'autres idées audacieuses ? [AH]

4.7. Recherche, ingénierie : les besoins en études

4.7.1. *Des données !*

Il y a besoin d'acquérir de la connaissance, et donc de la donnée, en particulier pour faire les bons choix en matière de *Soutenabilité* et pour optimiser *Adaptabilité et Contribution à l'adaptation* [JS] [JPT]. Les données à compléter sont par exemple les suivantes.

- Densification des données hydrométriques (débit des cours d'eau) et hydrogéologiques (niveaux de nappe), de sorte à pouvoir mieux mesurer les ressources actuelles, mesurer les tendances, procéder à l'élaboration des projections hydroclimatiques ([23]) et définir les stratégies d'adaptation.
- Densification des données caractérisant les ressources en eau, les consommations en eau (et l'humidité des sols) en temps réel ; cela permet d'adapter l'exploitation des retenues à la réalité des conditions du moment ;

cela permet aussi d'élaborer des prévisions et, en cas de crise, de faire des choix éclairés.

- Amélioration des prévisions météorologiques et hydrologiques pour aider aux décisions d'exploitation en temps de crue, avec par exemple la possibilité d'opérer des creux préventifs.
- Densification des mesures de qualité de l'eau (paramètres physiques, chimiques et biologiques) dans les retenues de barrage, de sorte à mieux comprendre et modéliser le comportement des retenues (cycles physiques, chimiques et biologiques), et agir au mieux pour restituer à l'aval des eaux dont la qualité est compatible avec les besoins des milieux.
- Densification des mesures biologiques (par méthodes traditionnelles et e-DNA) dans et à l'aval de retenues représentatives, de sorte à mieux comprendre les effets des retenues sur la dynamique de biodiversité, et infléchir les règles de gestion des ouvrages en conséquence : soutiens d'étiage, crues artificielles, modulation en fonction de la qualité de l'eau et des saisons, ...

4.7.2. *Les modèles et scénarios de référence : une nécessité*

Les questions d'adaptation nécessitent l'élaboration de modèles et de scénarios de référence, à l'échelle du pays ou de la région, pour :

- D'une part définir les besoins en termes de trajectoire d'atténuation : production d'électricité renouvelable et de stockage,
- D'autre part définir les besoins en termes de trajectoire d'adaptation : objectifs de *Contribution à l'adaptation* et contraintes pour l'*Adaptabilité*.

A l'échelle d'un pays, c'est un travail long, complexe, coûteux.

Cadre général : Bulletin 169 de la CIGB et guide IHA

Le Bulletin 169 [24] recommande les approches à retenir pour évaluer l'adaptabilité d'un projet de barrage en contexte de changement climatique. Le bulletin recommande d'utiliser les méthodes de l'IPCC pour développer les scénarios de climat futur ; l'incertitude est intégrée en comparant une série de scénarios climatiques probables.

Le guide IHA [31] recommande également d'évaluer les performances d'un projet sous différents scénarios de climat futur, de sorte à prendre des options de conception résilientes, et à évaluer l'amplitude des risques associés au climat.

Approches évoquées par les rapports de la question 108

Un seul rapport expose les résultats d'une étude d'adaptabilité au changement climatique. Le rapport Q108-R22 illustre le cas d'un réservoir de barrage en Roumanie. Les auteurs examinent l'exploitation future du barrage de Paltinu, en tenant compte d'une part de l'évolution de la ressource (à partir d'une projection du scénario RCP 8.5) et de l'évolution de la demande en eau, sous trois hypothèses (minimale, moyenne, maximale). Le barrage est à usage multiple : eau potable, eau industrielle et soutien écologique. Le calcul est fait à horizon 2050, et il est utilisé pour déterminer quelle est la tranche de la retenue qui restera disponible pour assurer de l'écrêtement des crues.

Le rapport Q108-R14, rédigé par des chercheurs du National Research Council, au Canada est plus général. Il tente de dresser un panorama général des méthodes de modélisation des conditions futures pour les réservoirs de barrages, prenant en compte des résultats ou conclusions extraits de 165 références bibliographiques. Il aborde successivement la question de la modélisation de la ressource en eau, de la demande en eau, de l'optimisation de l'exploitation des barrages, de l'adaptation structurelle des barrages et liste les lacunes à combler par la recherche. Les principales recommandations sont les suivantes :

- utilisation de modèles avancés pour simuler les ressources en eau disponibles à l'avenir,
- le développement de modèles intégrés simulant les évolutions sociétales (démographie, agriculture énergie, ...) pour pouvoir optimiser l'allocation de la ressource, par exemple par des modèles de programmation dynamique ou d'optimisation stochastique,
- optimisation l'exploitation multi-usage des barrages, en intégrant la fourniture d'eau, la production d'électricité et l'action sur les crues ; là également des algorithme d'optimisation avancée.

Les conclusions de Q108-R14 soulignent à juste titre le fait que les barrages devront s'adapter non seulement à l'évolution de la ressource, mais aussi à l'évolution de la demande. Il est également probable que des outils d'optimisation avancée puissent, lorsque les données sont disponibles, permettre de mieux tirer parti des volumes stockés dans les réservoirs (meilleure allocation de la ressource, meilleures performances en amortissement des crues). Cependant, il semble important que, au moins dans l'état actuel des techniques, le recours aux algorithmes avancés reste raisonnable : les principes fondamentaux de l'exploitation des barrages (courbes d'objectifs de gestion, consignes de manœuvre des vannes en crue) devraient être mis au point par des approches simples, et rester aisément compréhensibles et interprétables par l'homme, les algorithmes avancés ne venant qu'en optimisation de second ordre.

Elaboration d'un cadre de référence, exemple de le France

A l'échelle d'un pays, il peut être utile d'élaborer un cadre général anticipant les besoins et demandes futures. Ce cadre général est alors utilisable pour tous les porteurs de projet, grands et petits. L'exemple de la France est pris ici, pour illustrer cette approche, et l'ampleur des efforts à consentir pour parvenir à un corpus de documentation suffisant.

Elaboration des scénarios : futurs énergétiques 2050 : les scénarios de mix de production à l'étude permettant d'atteindre la neutralité carbone à l'horizon 2050. Un travail de modélisation et de synthèse de grande ampleur, qui a été nécessaire pour dégager les scénarios. Deux ans de travail, des dizaines de spécialistes impliqués.

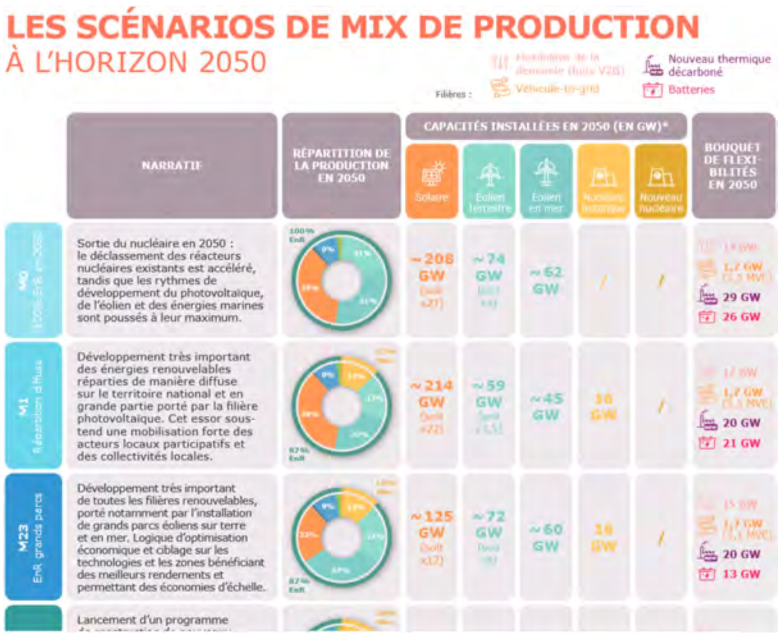


Fig. 8
Scénarios de mix de production, exemple de la France, source [60]

Simulation hydro-climatique Explore2 : ce travail a regroupé plusieurs instituts de recherche, pendant quatre ans (2021-2024). Le rapport Q108-R6 décrit la méthode, et certains des résultats. Il a consisté à élaborer des projections climatiques à l'échelle du territoire français, à partir des scénarios d'émission de GES. Trois scénarios d'émission sont retenus par le projet (RCP2.6, RCP4.5 et RCP8.5), RCP8.5 étant le scénario « extrême » décrivant un futur sans politique de régulation du climat. Ces scénarios sont traduits en *projections climatiques* : modèles de circulation générale (GCM) simulant le climat de la Terre, puis modèles climatiques régionaux, baptisés RCM, puis modèles hydrologiques (jusqu'à 9 selon le territoire). Le résultat est la mise à disposition des données hydro-climatiques sur tout le territoire français, pour l'ensemble des acteurs, ce qui permet de télécharger l'ensemble des variables et indicateurs hydrologiques, pour les horizons de temps jusqu'à 2100, à une échelle très détaillée. Cela fournit le cadre dans lequel l'adaptation (adaptabilité, contribution à l'adaptation) peut être évaluée.

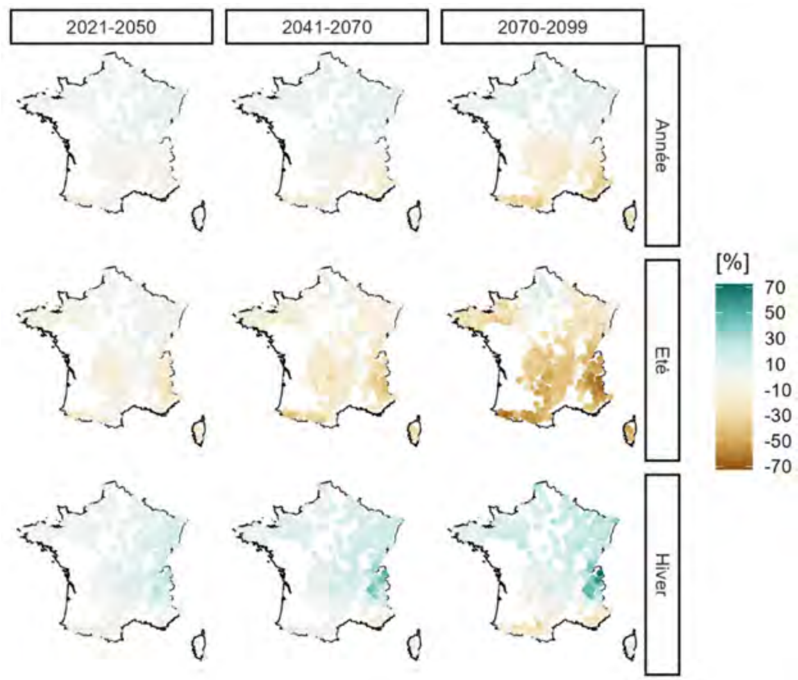


Fig. 9
France, cartes des évolutions de débits (scénario RCP8.5, moyenne de 17 RCM, source [6]

Cela fournit également des projections pour l'impact du changement climatique sur la production hydroélectrique.

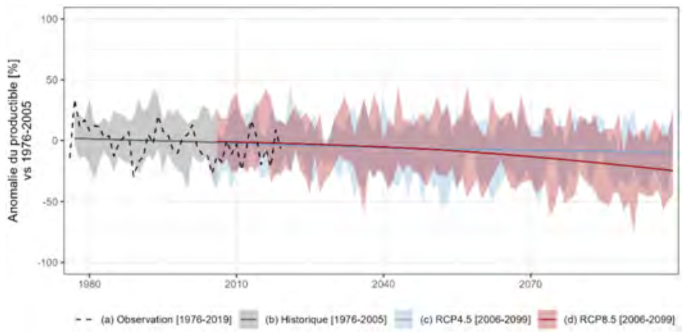


Fig. 10
Évolution du productible hydro-électrique pour les deux scénarios RCP4.5 et RCP8.5, source [6]

Evaluation des besoins futurs en eau : travail réalisé par une équipe de chercheurs, en 18 mois [61]. Le résultat est la mise à disposition, par bassin versant, des perspectives d'évolution de la demande en eau. En distinguant les prélèvements (les volumes d'eau prélevés, mais qui peuvent être immédiatement restitués : c'est le cas par exemple de la production hydroélectrique) et les consommations (les volumes d'eau qui sont prélevés mais qui ne sont pas restitués au milieu naturel – en particulier l'eau d'irrigation). Par croisement avec l'évolution des ressources en eau, cela permet d'élaborer des politiques d'adaptation locales (par bassin versant) quantitatives.

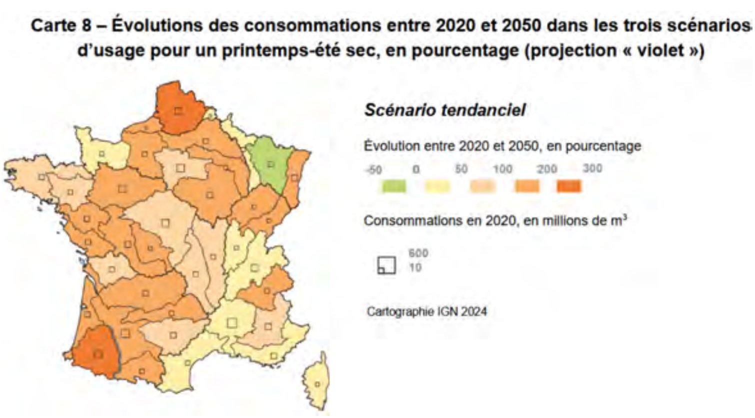


Fig. 11
Évolution des consommations futures en eau, exemple de la France, Source [61].

Plan National pour s'adapter au changement climatique : « Préparer une France à +2,7° en 2050, + 4° en 2100 ». Au sein de ce plan national, un « Plan Eau », avec 53 mesures pour : organiser la sobriété des usages, optimiser la disponibilité de la ressource, préserver la qualité de l'eau.

D'autres pays ont conduit de telles études. Ces études sont toujours axées sur leurs enjeux spécifiques. On peut citer par exemple, les Pays-Bas sur le sujet de l'adaptation à l'élévation du niveau de la mer [67].

5. SOLUTIONS TECHNIQUES

5.1. Stockage hors-rivière

5.1.1. *Présentation, principes et intérêt*

Généralités

Le stockage hors-rivière consiste à associer : une prise d'eau en rivière et un bassin de stockage, construit en dehors de l'emprise de la rivière. Le bassin de stockage est alimenté par la prise d'eau, par gravité ou par pompage.

Il s'agit d'une solution largement pratiquée depuis des décennies, avec des réservoirs de petite ou grande capacité. Les réservoirs hors-rivière ont été construits pour des usages variés : constitution de réserves pour l'alimentation en eau, protection contre les inondations, stockage de l'énergie. Les principaux avantages sont les suivants :

- Empreinte écologique minimisée : la prise d'eau en rivière est un ouvrage relativement modeste, ne formant pas de réservoir : elle ne crée pas d'obstacle à la continuité écologique. Le réservoir peut être implanté dans un secteur de moindre enjeu social et environnemental.
- Moindre exposition à la sédimentation : la conception du système peut permettre de limiter la sédimentation du réservoir ; en laissant passer les crues les plus chargée en sédiment ; et/ou en assurant une décantation dans la retenue du barrage de prise, qui peut aisément faire l'objet d'opérations de chasses,
- Moindre exposition aux crues : il est possible de prévoir une conception de barrage de prise qui s'efface en crue. Il n'y a alors pas besoin d'évacuateur coûteux, et la sécurité en cas de crue extrême est plus facilement garantie.

- Moindre évaporation : il est possible, pour les bassins petits et moyens, de prévoir une conception avec une profondeur moyenne plus grande que pour un barrage standard (pour une retenue classique, la profondeur moyenne est de l'ordre de 25 à 50% de la profondeur maximale ; pour un bassin hors-rivière, le ratio peut être bien meilleur).

Les principaux inconvénients sont les suivants :

- Les eaux de crue ne sont que partiellement captées par le réservoir. Cela peut constituer une perte en capacité de mobilisation de la ressource en eau. Cela peut également diminuer les performances de protection contre les inondations.
- Le réservoir est implanté en dehors du lit majeur. Souvent hors nappe, il est plus exposé aux fuites, et doit parfois être entièrement revêtu par une étanchéité.

Ce type d'ouvrage est plus facile à implémenter en terrain peu accidenté, en particulier en plaine. Cependant, des bassins hors rivière ont également été construits en zone montagneuse, notamment pour le stockage d'énergie.

Note sur la sédimentation

Des réservoirs hors-rivière ont, depuis longtemps, été construits pour limiter la problématique de l'alluvionnement des retenues. L'alluvionnement a d'autres incidences, et génère d'autres motivations pour envisager des alternatives utilisant des réservoirs hors rivière. Par exemple, pour les grandes retenues de l'Afrique de l'Ouest et Centrale, le volume de sédiments peut être marginal par rapport au volume d'eau contrôlé ; il n'y a pas alors de raisons de transférer ou stocker ce flux de matières en dehors de la retenue. Mais, au Bénin, le trait de côte est stabilisé par les sédiments qui proviennent de la dérive littorale c'est-à-dire par le mouvement d'Est en Ouest des matériaux sableux par le biais des houles. Une partie des sédiments provient des fleuves côtiers. Le volume annuel qui transite le long des côtes béninoises est de 600 000 m^3 environ. L'Ouémé, grand fleuve qui traverse le pays, transporte quelques centaines de milliers de m^3 par an c'est à dire une proportion significative comparée à la dérive littorale. Des projets de barrages envisagés sur ce fleuve pourraient bloquer le transit de volumes de sédiments d'un ordre de grandeur équivalent à celui de la dérive littorale, et cela produira un déséquilibre. Des alternatives qui n'auraient pas d'impact sur le transport solide devraient être possibles (typiquement : STEP + solaire) et à comparer aux bénéfices apportés par les réservoirs classiques implantés sur le fleuve. [ADB]

5.1.2. *Quelques exemples récents*

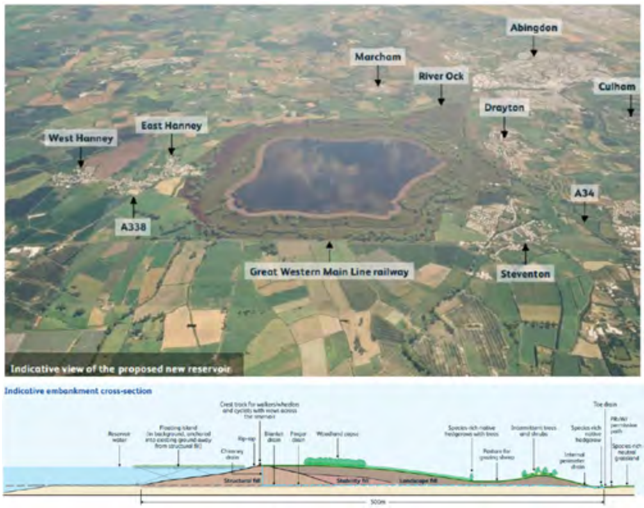


Fig. 12
South-East Strategic Reservoir project, UK, [70], figure communiquée par [JW]

Volume utile : 75 - 100 hm^3	Remplissage par : gravité et pompage	Fonction : alimentation en eau, soutien en période de sécheresse
Notes : ce projet de réservoir fait partie du plan d'adaptation au changement climatique de l'Angleterre (§3.4), et en particulier à la constitution de réserves stratégiques pour les cas de sécheresses. D'autres réservoirs de ce type sont également envisagés. Un point d'attention a été la période de retour des sécheresses à considérer pour le dimensionnement de ces réservoirs. Il a été considéré qu'une période de retour 1% (sécheresse de probabilité d'occurrence 1% chaque année) n'était pas suffisamment prudente, car cela correspond à une probabilité d'occurrence 26% en 30 ans. [JW]		

Fig. 13
Le réservoir de Kenh Lap, Vietnam. Le réservoir est constitué par un bras naturel du Mékong, fermé à ses deux extrémités par un barrage en remblai, et un ouvrage de régulation amont. Photo communicated by [MHTK]

Volume utile : 1 hm^3 (longueur 4.6 km ; largeur 50 à 100 m ; profondeur 2 à 3 m)	Remplissage par : gravité et pompage	Fonction : alimentation en eau
Notes : ce réservoir fait partie des initiatives récentes, en réaction à des périodes de sécheresses plus fréquentes dans le delta du Mékong (par effet du changement climatique ?). C'est une solution adaptée au contexte (pays plat, pas d'emprise foncière). Avec une efficacité limitée par l'amplitude du marnage (2 à 3 seulement) et par l'évaporation. [MHTK]		

Fig. 14
Synoptique du canal Seine Nord Europe et de son système d'alimentation en eau, France, ; photomontage : illustration d'une écluse, avec ses bassins d'épargne et la station de pompage intégrée, Q108-R9 [9].

Volume utile (bassin de Louette) : 14 hm^3	Remplissage par : pompage	Fonction : sécurisation de l'alimentation en eau du canal en cas de sécheresse
Notes : la conception du Canal Seine Nord Europe est choisie de sorte à minimiser les prélèvements d'eau sur le milieu naturel. Aucun prélèvement dans la nappe. Remplissage par pompage dans la rivière Oise, lorsque son débit est suffisant ; Stockage hors rivière (bassin de Louette) pour les périodes d'étiage de la rivière Oise ; Economie et recyclage d'eau aux écluses : par bassins d'épargne et station de pompage. Ainsi, les seules consommations sont les fuites et l'évaporation.		

Fig. 15
Réservoir hors-rivière de Olifantspoort, République d'Afrique du Sud, Q108-R13 [13][9].

Volume utile : environ 2 hm^3	Remplissage par: pompage	Fonction : sécurisation de l'alimentation en eau de la ville de Polokwane et de ses environs (un million d'habitants)
Notes : la ville de Polokwane est alimentée par différentes sources, dont un prélèvement par pompage depuis un bassin versant adjacent (Olifantspoort). Le transport solide important a réduit la fiabilité de cet approvisionnement par pompage. Le projet de réservoir hors rivière comporte trois composantes : un nouveau seuil de prise en rivière avec des capacités d'auto-curage, une station de pompage, un réservoir hors rivière, qui assure une fonction de volume tampon et de décantation des sédiments (le réservoir fera l'objet d'opérations de curage). Le rapport Q108-R13 détaille les éléments de conception de l'ouvrage de prise (en fonction des problématiques de transport sédimentaire), et les particularités originales des barrages de fermeture du réservoir, barrages à voûtes multiples en béton cyclopéen (« rubble masonry concrete »).		

Fig. 16
Bassin inférieur de la STEP de Kokhav Hayarden, Israël, Q108-R5 et Q108-R17

Volume utile : environ 3 hm^3	Réservoir inférieur d'une station de pompage turbi-nage	Fonction : stock-age d'électricité
A fin 2023, Israël avait développé environ 6 GW d'électricité solaire, et le solaire représentait 13% de la production électrique. Pour le reste, la production électrique est assurée par des centrales thermiques, essentiellement gaz. Le développement du solaire devrait se poursuivre, et il est accompagné d'un programme de construction de stations de pompage-turbinage. La station de pompage-turbinage de Kokhav Hayarden a une puissance équipée de 344 MW.		

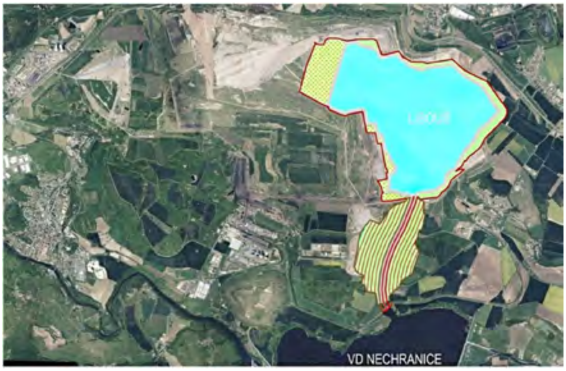


Fig. 17
Projet de raccordement par un canal entre Nechranice Reservoir (en bas de l'image) et la mine à ciel ouvert de Libouš (en bleu-ciel), Rép. Tchèque, Q108-R21[9].

Réservoir de Libous (remplissage de la mine) : 106 hm^3 Réservoir de Nechranice : 288 hm^3	Remplissage par : gravité	Fonction : augmentation des performances de la retenue initial pour la protection contre les inondations et pour la fourniture d'eau.
Dans ce cas particulier, la retenue hors rivière (la mine qui sera remplie) est directement reliée par un canal au réservoir principal.		

5.1.3. *La question de l'étanchéité*

Le plus souvent, lorsque des réservoirs hors rivières sont envisagés, une étanchéité artificielle est mise en œuvre sur toute l'étendue du réservoir. C'est par exemple le cas de beaucoup des bassins des stations de pompage turbinage, lorsque ces bassins sont déconnectés du milieu naturel. C'est également le cas des différents réservoirs du Canal Seine-Nord Europe.

Cependant, ce n'est pas systématique, et il est utile d'explorer des solutions sans étanchéités rapportées en particulier pour les grandes retenues. On note par exemple que :

- Le bassin supérieur de la STEP de Hatta, bien qu'en milieu aride, n'est pas revêtu ; l'effort de limitation des fuites se traduit par des injections sous les barrages de fermeture
- Le réservoir de Khen Lap, illustré par la Fig. 13, n'est pas revêtu : il profite d'une étanchéité, au moins relative, apportée par les sédiments fins,

- Les grands réservoirs hors rivière construits en amont de la ville de Paris, pour la protection contre les inondations et pour le soutien d'étiage, ne sont pas revêtus – ils profitent de conditions de sol à dominante argileuse.

Dans le cas du barrage Olifantspoort (Q108-R13), le rocher sur lequel est installé le réservoir hors rivière est très perméable. Il n'a pas été prévu de le couvrir d'une étanchéité artificielle ; en revanche, des travaux importants d'injection ont été réalisés sous les barrages. Notons cependant, dans ce cas particulier que : (1) l'eau pompée depuis la rivière est chargée en sédiments fins, ce qui pourrait avoir un effet positif sur l'étanchéité globale et (2) le réservoir hors rivière est un bassin tampon, dans lequel le temps de résidence de l'eau est court : le volume des fuites, en proportion des volumes transférés, est plus faible que pour un barrage de stockage saisonnier.

Les réservoirs hors rivière peuvent être simplement fermés par des remblais au-dessus du terrain naturel, ou par une technique mixte, associant excavations dans le réservoir et remblaiements pour former la ceinture. Cela présente l'avantage d'équilibrer les volumes de déblais et de remblai. Le rapport Q108-R15 illustre un tel cas, pour le bassin inférieur de la STEP de Kokhav Hayarden, en Israël. La profondeur d'excavation du bassin est 20 m environ sous le terrain naturel, avec un remblai de ceinture de hauteur 5 à 10 m ; les excavations sont pour partie sous nappe, dans des argiles et limons argileux : il y a lieu d'aborder avec vigilance les conditions de stabilité des talus. Dans ce cas précis, la nappe a été rabattue au moyen de puits de décompression, et la maîtrise de la stabilité des talus a imposé un terrassement phasé, avec des tranches de 3 m.

Dans ce type de configuration, les conditions de stabilité des talus à long terme, en cas de nappe haute et réservoir bas doivent être examinées avec soin. Il s'agit en particulier de garantir la pérennité du drainage et de l'éventuel dispositif de rabattement de nappe (surveillance des débits et pressions ; conception du drainage permettant la maintenance), et/ou de vérifier la stabilité dans des cas accidentels de défaillance du drainage.

Il y a également des spécificités liées à l'étanchement des bassins de STEP ; ces spécificités sont traitées au §5.2.

5.1.4. *Le « trop-plein » : un outil économique pour la sécurité ultime*

Les réservoirs hors-rivière sont pour l'essentiel à l'abri des crues de la rivière principale (à partir de laquelle ils sont alimentés). Cependant, cela ne signifie pas qu'ils sont à l'abri des crues, naturelles ou artificielles. Ils peuvent être soumis aux crues de leur bassin versant propre (en plus de la pluie directe sur le bassin et ses talus d'excavation) ; ils peuvent recevoir des excédents d'eau en cas de défaillance du système d'alimentation (rupture du barrage de Taum Sauk), que ce soit par gravité ou par pompage.

Il est généralement admis que la sécurité en crue d'un grand barrage en remblai doive être assurée pour des périodes de retour très élevées, par exemple 10 000 ans (probabilité de dépassement inférieure à 10^{-4} par an). Il est parfois difficile de garantir contre tout dysfonctionnement dangereux du système d'alimentation, par gravité ou par pompage, avec une probabilité de défaillance inférieure à 10^{-4} par an. Dans ce cas, un dispositif d'évacuation des eaux excédentaires, par un seuil passif placé en dessous de la crête du barrage en remblai, augmente substantiellement la sécurité du barrage.

5.2. Stations de pompage turbinage

Ce rapport traite des volets d'infrastructures (génie-civil, géotechnique) et hydraulique (les retenues, les chemins d'eau). Il ne traite pas des questions relatives aux équipements électriques et électromécaniques.

5.2.1. *Rôle, principes généraux*

Un développement majeur dans les années à venir

Les STEP ont initialement été construites en accompagnement des centrales nucléaires, qui n'avaient qu'une faible flexibilité.

Dans le contexte mondial actuel, où tous les pays s'orientent vers la décarbonation et où le secteur de l'énergie fait de gros efforts pour intégrer de plus en plus de sources d'énergie renouvelables propres mais intermittentes (principalement le solaire et l'éolien), la demande pour des services de stockage d'énergie et d'équilibrage augmente de manière spectaculaire. L'hydroélectricité par pompage-turbinage reste la source de stockage d'énergie la plus efficace à l'échelle mondiale et peut contribuer à atténuer les effets du réchauffement climatique en réduisant les émissions de gaz à effet de serre [LC].

Pour cette raison, les IFI (Institutions Financières Internationales) et les BMD (Banques Multilatérales de Développement) offrent de nombreuses opportunités de financement de projets ou de composantes de projets de STEP, lorsque ces projets répondent aux exigences d'adaptation au changement climatique [LC].

De nombreux pays inscrivent les STEP dans leurs stratégies de développement énergétique. Le cas de l'Inde est par exemple présenté par Q108-R20 :

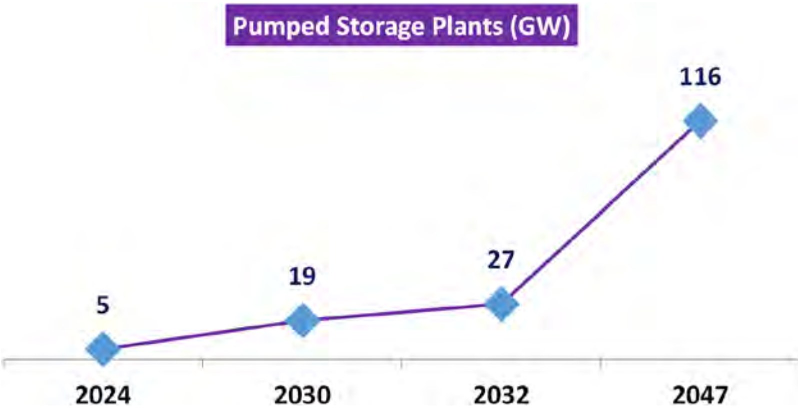


Fig. 18
Prévisions de futurs systèmes de pompage-turbinage en Inde, Q108-R20

Durée (et volume) de stockage

Les STEP offrent une capacité de stockage (énergie, puissance) bien adapté à la compensation de l'intermittence du solaire – et dans une moindre mesure de l'éolien -, avec des volumes de stockage de quelques heures à quelques dizaines d'heures.

A puissance donnée, la sélection du volume de stockage est un sujet central, et délicat. Il dépend de plusieurs facteurs, parmi lesquels la nature des sources d'électricité intermittentes du réseau, leur foisonnement (c'est-à-dire l'effet de lissage de l'intermittence pouvant être provoqué par le nombre, la variété et l'éloignement géographique des diverses sources intermittentes), les conditions climatiques locales, . . . Des études en Australie ont mis en évidence l'intérêt de stockages avec des volume de stockage en dizaines d'heures, pour au moins une partie des STEP du réseau [63]. La sélection de la profondeur du stockage dépend également du coût marginal d'augmentation du volume. Dans certains cas, il est relativement aisé de prévoir un volume de stockage de quelques dizaines d'heure, et alors il ne faut pas s'en priver. Le projet Snowy 2.0, en Australie, qui raccorde deux retenues existantes, dispose ainsi d'une réserve de 175 heures à pleine puissance.

Les réseaux électriques ont également besoin de capacités de stockage de plus longue durée, une ou plusieurs semaines ou plusieurs mois. Cela ne peut souvent pas être économiquement fourni par les STEP. Les compléments de stockage sont apportés par les réservoirs hydroélectriques lorsqu'ils sont en mesure de le faire, ou par des capacités thermiques, par exemple le gaz. Ainsi, la Suisse envisage la construction d'un nouveau réservoir de grande ampleur, dont une des vocations est d'augmenter la sécurité de l'approvisionnement énergétique de la Suisse en hiver (Q108-R2) avec une capacité de stockage de 650 GWh. Ce projet de stockage saisonnier complète l'équipement hydroélectrique du pays, qui dispose déjà de plusieurs STEP.

Par ailleurs, la transition énergétique conduit à renoncer à la production d'électricité d'origine thermique (charbon, gaz). Il paraît judicieux de conserver les capacités installées, ou au moins une partie d'entre elles, pour assurer une production de secours en cas d'épuisement des réserves hydrauliques.

Circuit ouvert / Circuit fermé

Les STEP en circuit ouvert ont au moins une retenue connectée au milieu naturel. Les STEP en circuit fermé ont les deux retenues déconnectées du milieu naturel ; elles ne prélèvent de l'eau sur le milieu naturel que pour le remplissage initial et la compensation des pertes (fuites, évaporation). Ces deux options ont des avantages et des inconvénients [LC] [DBB] :

AVANTAGES DE LA SOLUTION « CIRCUIT OUVERT »	**AVANTAGES DE LA SOLUTION « CIRCUIT FERMÉ »**
Permet de tirer profit de retenues existantes, pour le bassin haut et/ou le bassin bas, ce qui permet de : 1/ limiter les coûts d'investissement 2/ prévoir, dans le cadre du projet, des travaux d'amélioration sur les ouvrages existants	Déconnecte les retenues du milieu naturel, ce qui limite les impacts sur l'environnement.
Permet, dans le cadre d'un projet de STEP, de prévoir des retenues qui remplissent d'autres fonctions : 1/ nouvelles retenues multi-usages 2/ augmentation de la capacité de retenues déjà existantes, pour améliorer leur vocation multi-usages.	Déconnecte les retenues du milieu naturel, ce qui limite le risque d'un défaut de remplissage des retenues par manque d'eau.(le « circuit ouvert » peut être mis en défaut lorsque les retenues amont ou aval remplissent d'autres usages, hydroélectricité, approvisionnement en eau, limitation des crues, et sont amenées à connaître des variations de niveau en raison de ces autres usages).
	Offre davantage d'opportunités de localisation pour une nouvelle STEP, ce qui permet d'optimiser les impacts, et les facteurs topographiques (chute, longueur des circuits hydrauliques)

Comme l'indique Luciano Canale de la BEI : « *Private sector developers with a narrow focus on the energy sector and strong commercial drivers may push for the climate-safer option of closed-loop but for public sector developers reusing/adapting existing reservoir for PSP may also provide opportunities to optimize and modernize public sector assets and improve their long-term sustainability. Dam heightening to create additional water volume for the PS scheme or sediment removal to gain active storage for the hydro-battery may be a win-win decision to satisfy the electricity storage demand and make the life of dams longer at the same time.* »

5.2.2. *Quelques exemples récents*

Fig. 19
La STEP de Kidston dans le Queensland, Australie [63], Crédit : Genex Power Limited

Puissance : 250 MW	Stockage : 8h (2 GWh) à pleine puissance	Chute : 181m – 218m
Le projet utilise deux carrières d'or à ciel ouvert. C'est la première STEP à être construite en Australie depuis des décennies. Sur le site, une centrale solaire et une centrale éolienne sont également prévues. Un barrage en enrochements ceinture le réservoir supérieur.		

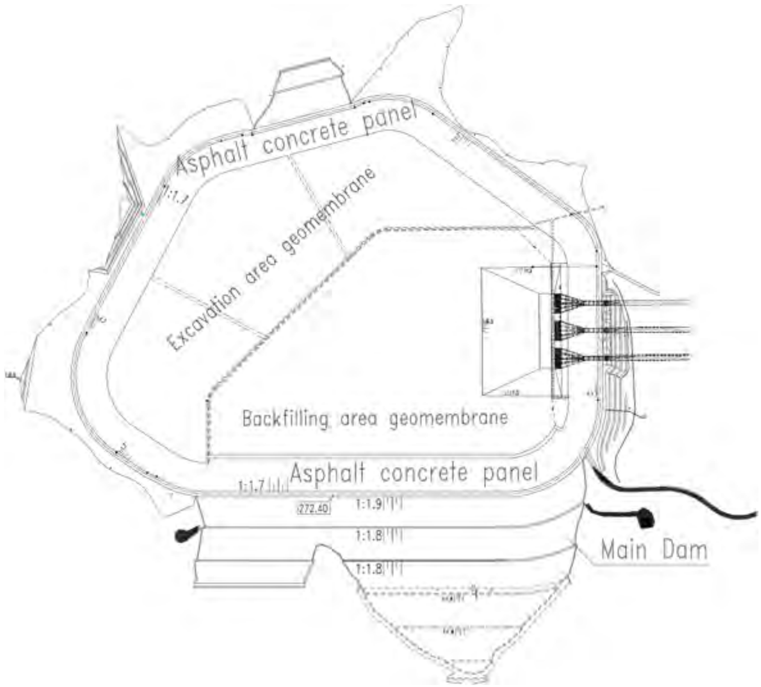


Fig. 20
La STEP de Jurong, Jiangsu, Chine, Q108-R17

Puissance : 6*225 MW		
Notes : conditions géologiques difficiles pour l'étanchéité des bassins : rocher karstique ; bassin supérieur fermé par un barrage AFRD, hauteur maximale 182 m (record du monde) ;		

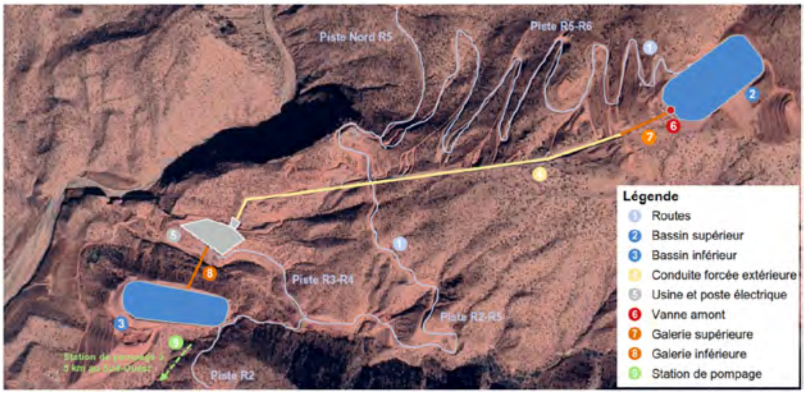


Fig. 21
STEP d'Abdelmoumen, Maroc, Q108-R8

Puissance : 350 MW	Stockage : 5 heures à pleine puissance	Chute : environ 550 m
Notes : La mise en service de la STEP d'Abdelmoumen en 2024 suit celle de la STEP d'Afourer en exploitation depuis 2004. L'aménagement vise notamment à équilibrer les intermittences de la production éolienne ; il a été dimensionné de manière à pouvoir basculer rapidement d'un mode pompage à un mode turbinage, et à réaliser jusqu'à 20 cycles de démarrage/arrêt par jour. En contexte de rareté des ressources en eau au Maroc, le fonctionnement en circuit fermé réduit l'impact de l'aménagement sur l'environnement et sur les ressources en eau.		

5.2.3. *Optimiser les coûts et le rythme de construction : exemple de la politique de construction de STEP en Chine*

La Chine offre un exemple important d'une politique industrielle de développement de STEP. 179 GW sont en construction, ce qui conduit à rechercher une rationalisation et une optimisation des process de construction. A l'heure actuelle, le coût d'investissement (CAPEX) de ces STEP est de l'ordre de 700 à 1000 USD/kW. Des gains de l'ordre de 15% sont espérés. Les leviers sont les suivants [58] :

- Mise en place d'une politique incitative : amélioration des mécanismes de rémunération, support au financement des investissement, incitation à l'ouverture du capital.
- Utilisation d'outils automatisés de recherche de sites favorables (topographie, hydrologie, conditions climatiques, optimisation du placement du stockage sur le résau)

- Utilisation d'outils automatisés de prédimensionnement des ouvrages : barrages, réservoirs, cavernes et ouvrages souterrains, permettant une forme d'optimisation et de standardisation,
- Utilisation des moyens modernes de contrôle de mise en œuvre et de compactage pour les barrages en remblai et en BCR : digitalisation des chantiers
- Optimisation de certaines technologies : dispositifs d'étanchéité des réservoirs (cf. §5.2.6) ; dispositifs de soutènement pour les travaux souterrains ; tunneliers y compris pour certains puits inclinés ou verticaux (shaft boring machine), raise boring pour les puits verticaux et inclinés ; revêtements pour les galeries haute pression ; turbines et pompes de forte capacité et sous forte charge.

5.2.4. *Explorer les STEP à faible dénivelée (et fort débit)*

Problématique

- Les stations de pompage-turbinage traditionnelles utilisent des dénivelées de plusieurs centaines de mètres. Mais il y a également des besoins dans des pays et des régions ou de telles hauteurs de chute ne sont pas disponibles. Ce n'est pas un obstacle insurmontable :
- A Alqueva, la station de pompage-turbinage de 4*128 MW fonctionne sous des hauteurs de 45 à 73 m, avec des débits d'équipement de l'ordre de 190 m^3/s pour chaque turbine.
- A La Rance, l'usine marémotrice (240 MW) fonctionne en mode turbine et pompe sous des hauteurs inférieures à 10 m.
- Plusieurs stations de pompage-turbinage ont été construites ou sont en projet, pour des hauteurs de moins de 50 m. Par exemple, trois groupes hydroélectriques réversibles (3 MW en pompage, 2.65 MW en turbinage) ont été installés en 1998 sur le barrage existant de Naussac, France, avec une hauteur de chute variant de 32 à 57 m. Des pompes-turbines Deriaz ont été sélectionnées, en raison de leur capacité à fonctionner sur une large gamme de débits, en mode pompe et en mode turbine.
- Des initiatives ont été lancées pour concevoir des projets adaptés aux pays plats, avec des dénivelées très modestes, par exemple de 2 à 30 m pour des pays plats du Nord de l'Europe [42].

  Il s'agit certainement d'une démarche prometteuse, à poursuivre.

Ainsi, le rapport Q108-R11 évoque le cas du Rwanda, où le secteur hydroélectrique a connu un très fort développement. Ce rapport de RWANCOLD mentionne l'intérêt pour tirer profit d'une configuration particulière, avec deux lacs volcaniques (Burera et Ruhondo), très proches l'un de l'autre, avec une dénivelée de 100 m.

Twin Dams

Les « twin dams » consistent à associer deux barrages successifs, partageant une même retenue. Une usine, accolée au barrage amont peut turbiner ou pomper sous quelques mètres ou dizaines de mètres de charge des volumes d’eau considérable en peu de temps.

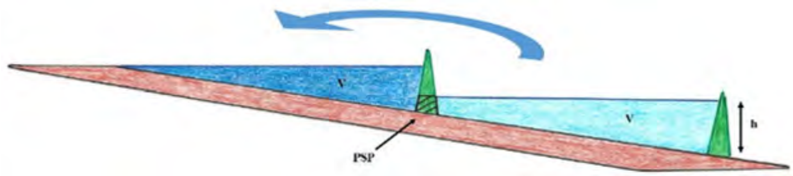


Fig. 22
Twin dams, [55]

Ces deux barrages peuvent être nouveaux ou résulter de l’adaptation d’un ou deux barrages existants. Le projet de Bassieri au Burkina Faso est un exemple pour un barrage neuf.

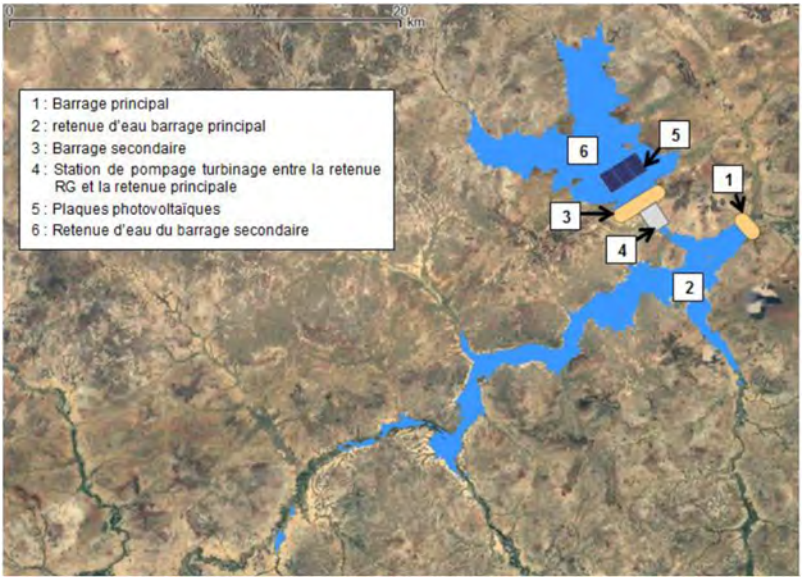


Fig. 23
Le projet « Twin dams » de Bassieri

Puissance : 350 MWp solar, 120 MW pompage, 85 MW turbinage	Stockage : 8h en pompage, 16h en turbinage	Chute moyenne : un peu moins de 15 m
Notes : Le projet de Bassiéri est un projet multi-usages (réservoir de 660 hm^3), à vocations principales irrigation, production d'électricité, alimentation en eau potable, pêche et pisciculture. La très faible chute disponible, en contexte de topographie plate, limite fortement l'intérêt d'une centrale hydroélectrique classique adossée au barrage. L'option « twin dams » permet de multiplier par 20 la capacité de production électrique associée au réservoir, et permet une garantie de puissance en toute saison, ce qui n'est pas le cas de la centrale classique. Le débit d'équipement en pompage est un peu supérieur à 1000 m^3/s.		

De manière conceptuelle, cette option a été examinée pour de grands réservoirs existants, comme Assouan et Kariba, qui seraient alors divisés en deux parties par un nouveau barrage associé à une usine de pompage et turbinage. La puissance et la production des centrales électriques hydro-solaires ainsi créées seraient très nettement supérieures à la puissance et la production de centrales hydroélectriques existantes, et elles libèreraient de la ressource en eau pour d'autres usages.

5.2.5. *Utilisation de l'eau de mer*

Lorsque l'eau douce vient à manquer, il peut être envisagé d'utiliser l'eau de mer. Deux options ont été envisagées, et mises en œuvre : l'utilisation de l'eau de mer dans les circuits hydrauliques, ou le dessalement.

A Okinawa au Japon, une STEP a été mise en service avec utilisation de l'eau de mer dans le circuit hydraulique. La puissance est de 30 MW, la chute environ 150 m, le volume de stockage de l'ordre de 0.5 hm^3, la mise en service date de 1999. L'exploitation a été arrêtée en 2016, pour des raisons non techniques. Il y a un intérêt réel à développer cette technologie, pour les pays avec des façades maritimes, et en particulier pour les îles. Les questions de corrosion et de biofouling trouvent des solutions techniques, inspirées par exemple de ce qui se pratique dans d'autres industries, cf. par exemple [46]. L'usine marémotrice de la Rance a tous ses ouvrages en milieu salin, elle est exploitée depuis 60 ans, et le retour d'expérience de son fonctionnement a fait l'objet de nombreuses publications. Des projets sont en cours de développement dans plusieurs pays.

La STEP de Salto de Chira (200 MW), sur l'île de Gran Canaria (Espagne), est alimentée par une prise d'eau en mer et un circuit de dessalement dédiée, qui contribuent au remplissage des retenues existantes de Soria et Chira, de sorte à ne pas amputer les volumes réservés à l'irrigation. C'est également l'option retenue pour le projet de 20 MW (Santiago PSP) au Cap Vert. [LC]

5.2.6. *Quelques points-techniques clé*

L'étanchéité

Les éléments qui suivent viennent en complément de ceux, plus généraux, développés au §5.1.3.

Le rapport Q108-R5 explore la question de l'étanchéité des barrages et réservoirs des STEP. A cet effet, il dresse un retour d'expérience d'une dizaine de projets. Trois catégories d'étanchéité sont ainsi passées en revue : le masque amont rigide (béton de ciment, béton bitumineux, ou plus rarement brai-vinyle), le BCR à bonne ouvrabilité, les géomembranes. Le rapport Q108-R17 ajoute un type d'étanchéité supplémentaire : le tapis d'argile.

Trois références de bassins de STEP, exploités depuis 50 ans par EDF (Q108-R5), démontrent l'efficacité des solutions de masque rigide ; les difficultés se concentrent pour l'essentiel sur les zones singulières : zones de tassements différentiels, zones de jonction ou de raccordement. Dans ce contexte, la capacité et la pérennité du drainage sont essentielles, et ce rapport recommande donc d'intégrer dans la conception du drainage : une capacité de drainage supérieure, la possibilité de visiter le drainage sur sa totalité, et un dispositif de surveillance de la pression en plus du débit dans le drainage. Un des barrages est équipé d'une double étanchéité. Cette option est jugée très efficace pour les projets où les enjeux des fuites sont particulièrement importants.

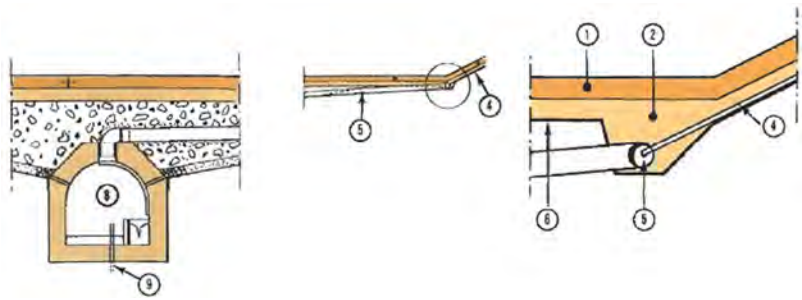


Fig. 24
Barrage de la Coche, Q108-R5, (1) Etanchéité primaire (dalles de béton armé), (2) drainage (béton poreux), (6) étanchéité secondaire (géomembrane PVC-P armée) – cf Q108-R5 pour une légende plus complète

Le rapport Q108-R5 présente le cas d'une étanchéité assurée par un BCR moderne, pour le barrage de fermeture d'un réservoir de STEP en milieu aride. Le mix retenu (indice Vebe modifié de 12 à 20s, optimisation des granulats pour limiter l'indice des vides, teneur en liants élevés y compris matériaux pouzzolaniques pour obtenir à la fois une proportion de pâte excédentaire et un BCR peu sujet au retrait endogène et au fluage au jeune âge) a permis d'atteindre les critères de performance demandés pour un barrage de STEP étanche dans la masse, avec une bonne résistance et un retrait net final à long terme faible, ce qui a permis d'espacer les joints de retrait. Les joints de retrait sont équipés de doubles lames d'étanchéité de type waterstop enrobés de GERCC. [Q108-R5]

Le rapport Q108-R5 rappelle que, jusqu'au milieu des années 2010, il n'y avait qu'un seul cas de réservoir de STEP étanché par géomembrane : le barrage en BCR d'Olivenhain. Plusieurs références récentes sont décrites, avec à chaque fois une solution par géomembrane exposée : Pico da Urze sur l'île de Madère au Portugal (barrage en enrochements), Kokhav Hayarden en Israël (remblais en terre compactée, également présenté par Q108-R17), Abdelmoumen au Maroc (remblais en petits enrochements, également présenté par Q108-R8), Pinnapuram en Inde (remblais en grands enrochements). Dans ces différents ouvrages, la géomembrane retenue est en PVC, en raison de ses propriétés mécaniques et de sa durabilité. Le rapport décrit les solutions retenues pour assurer de bonnes conditions de couche support et pour assurer la résistance au soulèvement des membranes exposées.

Fig. 25
STEP de Kokhav Hayardn (gauche) et d'Abdelmoumen (droite), Q108-R5, principe d'étanchement par géomembrane exposée, avec lanières (anchor strips), bandes d'ancrages, puis pose de la géomembrane

Le rapport Q108-R8 complète la description des dispositions prises à Abdelmoumen pour assurer la stabilité de la géomembrane au soulèvement par le vent : des évents connectés au drainage sous membrane qui permettent de générer une dépression sous la membrane, et un lestage par blocs de béton ancrés en tête de talus dans les secteurs les plus exposés au vent.

Fig. 26
STEP d'Abdelmoumen, Maroc, Q108-R8, évents d'extraction d'air (gauche) et lests en béton (droite), pour assurer la stabilité de la géomembrane en cas de tempête.

Le rapport Q108-R17 indique que, dans le cas de la STEP de Jurong (charge d'eau maximale 180 m), l'étanchéité du fond du bassin supérieur a utilisé d'autres types de géomembranes : PEHD et TPO ; les talus de ce bassin ont, eux, été étanchés par un masque en béton bitumineux, et le raccordement entre la géomembrane et le masque en béton bitumineux a fait l'objet d'une attention particulière.

Les étanchéités minces des barrages hors rivière, et en particulier des bassins de STEP sont des solution pratiques et performantes. Deux points de vigilance méritent cependant d'être rappelés :

- Les étanchéités par tapis d'argile peuvent subir des pathologies importantes, par l'effet de l'érosion interne, car les gradients à travers l'épaisseur du tapis sont très élevés (nettement plus qu'à travers un noyau de barrage, par exemple). La mise en œuvre de filtres et transitions sûres est alors une composante majeure de ces projets, en particulier lorsque le tapis est installé dans un contexte de rocher présenter des cavités.
- Les étanchéités par géomembrane exposée disposent d'un retour d'expérience favorable pour l'étanchéité des remblais d'enrochements. Il n'est pas possible d'exclure complètement le risque de percement des géomembranes pendant la vie des ouvrages, mais dans le cas des remblais d'enrochements, la seule conséquence est une augmentation des fuites, tant que la géomembrane n'est pas réparée. La configuration est un peu différente pour les géomembranes sur remblais peu perméables, avec couche de drainage immédiatement sous la géomembrane, comme par exemple à Kokhav Hayarden (Q108-R17). C'est plus délicat pour deux raisons : (1) le drainage sous membrane est plus difficile à entretenir dans la durée et (2) en cas de déchirure importante de la membrane, il peut y avoir saturation du réseau de drainage. Par exemple, dans le cas du projet CSNE (Q108-R9), les remblais sont en limons et en craie, peu perméables ; compte-tenu du risque significatif de percement de la membrane,

par les bateaux circulant sur le canal, il a été jugé préférable de ne pas prévoir de drainage immédiatement sous la membrane : le contrôle des percolations est reporté à l'axe du barrage, sous la forme d'une cheminée de filtration-drainage.

Les circuits hydrauliques

Le rapport Q108-R7 tire des leçons d'un projet de STEP, en contexte de pays aride, pour une hauteur de chute de 150 m et une puissance de 2x125 MW. Deux objectifs particuliers étaient recherchés : l'étanchéité du chemin d'eau (avec un objectif strict, en contexte de pays aride : pertes limitées à 150 l/min pour les 1200 m de tunnel), la minimisation des pertes de charge aux prises d'eau, la minimisation du volume mort des retenues hautes et basses. Les solutions retenues ont été les suivantes : revêtement en béton armé précontraint avec membrane étanche pour la galerie au rocher, triple modélisation des prises d'eau : calculs analytiques, simulations numériques et modèles physiques. Le rapport présente en détail ces solutions techniques.

La flexibilité

Les besoins en flexibilité sont accrus avec la pénétration des énergies renouvelables intermittentes (vent, soleil). Le cas de la station de pompage d'Abdelmoumen (Q108-R8) en est une bonne illustration : elle est conçue pour supporter des variations fréquentes, jusqu'à 20 démarrages-arrêts par jour. Le rapport expose les enjeux particuliers pour les équipements électro-mécaniques, en particulier les turbines, et pour le contrôle-commande, conçu pour optimiser les durées des séquences d'arrêt et démarrage.

5.2.7. *Intérêt des CMD pour les barrages de réservoir de STEP [ML].*

Le bassin supérieur d'une STEP et parfois également son bassin inférieur dans le cas de STEP en circuit fermé, est constitué par un barrage de grande longueur fermé sur lui-même entourant le réservoir. La solution la plus fréquemment retenue est un barrage en enrochements ou en remblai étanché sur sa face amont. Les barrages poids en remblais durs (Hardfill, CSG) présentent un certain nombre de caractéristiques favorables qui encouragent de les envisager pour ce type de projet :

- Ils ont une emprise au sol réduite favorable pour un réservoir fermé (bon rapport volume stocké sur volume du barrage).
- Ils sont tolérants aux fondations variées et localement médiocres que l'on rencontre dans ce type de configuration.
- Ils sont insensibles aux sous-pressions et bien adaptés aux remplissages-vidanges fréquents et de façon générale présentent un haut degré de sécurité.

- Ils peuvent facilement intégrer les matériaux de la cuvette pour la fabrication du remblai dur.
- L'intégration des fonctions hydrauliques est plus aisée que pour un barrage en remblai.
- Ils sont insensibles à la submersion en cas de sur remplissage accidentel (cf. la rupture du barrage de Taum Sauk déjà évoqué).
- La cadence de construction du remblai dur (Hardfill) peut être très élevée.

Cette solution a été envisagée pour le projet de STEP de Gandi Sagar en Inde ainsi que pour deux grands projets de stockage étudiés à un stade préliminaire en Afrique du Sud.

5.2.8. *Ré-orientation de la production hydroélectrique traditionnelle pour le stockage de l'énergie*

Les stations de pompage-turbinage ne sont pas les seules à compenser la pénétration des énergies intermittentes. Les centrales hydroélectriques traditionnelles sont de plus en plus sollicitées à cet effet.

C'est le cas de la centrale hydroélectrique de Poatina en Tasmanie, qui est reliée à Great Lake [64]. Cette centrale devenant davantage une centrale de pointe, un barrage de re-régulation a été construit en aval. Ainsi, dans le cadre de la stratégie d'atténuation du changement climatique, avec la transition vers les énergies renouvelables, le régime d'exploitation de certaines centrales hydroélectriques traditionnelles va changer, avec des opérations de pointe, il sera nécessaire de réguler les débits sortants de la centrale avec un barrage de régulation en aval.

Fig. 27
Bassin de régularisation, Poatina, Tasmanie, Australie [64], Crédit : Hydro Tasmania

Volume utile : 1.5 hm^3		Fonction : bassin de régulation
Notes : ce bassin de régulation a été ajouté en aval de la centrale de Poatina, dont le mode d'exploitation est modifié, pour réguler les effets de l'introduction de fermes éoliennes en Tasmanie. Les arrêts et démarrages à la centrale de Poatina sont plus fréquents, cela a des impacts écologiques négatifs sur la rivière à l'aval. Le bassin de 1.5 hm^3 a été construits pour éviter ces impacts ; il est dimensionné pour lisser 60% des fluctuations de débit engendrées par l'exploitation de la centrale.[JW]		

5.3. Association hydro-solaire

5.3.1. *Présentation, principes et intérêt*

<u>Généralités</u>

Le principe de l'association hydro-solaire consiste à combiner les avantages du solaire (énergie abondante, devenue peu chère, et facile à développer) et de l'hydroélectricité (énergie stockable & pilotable, peu chère, et fournissant des services au réseau). Cette piste recouvre en réalité plusieurs idées :

- FPV (Floating PhotoVoltaic) : Utilisation de réservoirs de barrages pour implanter des panneaux flottants

- VPP (Virtual Power Plant): Une centrale virtuelle est formée par l'exploitation conjointe de retenues hydroélectriques et de centrales solaires, opérées par un exploitant unique, et injectées sur le réseau de manière optimisée.
- ShSH et HhSH (Slightly hybridized Solar Hydro et Highly hybridized Solar Hydro) : hybridation hydro-solaire sur un barrage hydroélectrique existant. Un parc solaire est installé à proximité ou sur un réservoir hydroélectrique ; un EMS (Energy Management System) assure l'hybridation. On distingue ShSH et HhSH en fonction du ratio de puissance entre la ferme solaire et la centrale hydroélectrique : plus ce ratio est élevé, puis l'hybridation est forte, et plus les moyens techniques à mettre en œuvre pour la réaliser sont importants. On peut envisager, sur un site donné, de procéder en deux phases : d'abord ShSH puis, après quelques années de retour d'expérience, HhSH.
- FSH (Full Solar Hydro) et Twindams : Centrale hydro-solaire, dans laquelle l'électricité est (essentiellement) apportée par le solaire et la régulation par l'hydro. Peut s'envisager sur barrage hydroélectrique ou barrage destiné à l'alimentation en eau.

L'intérêt de la combinaison entre hydro et solaire, et plus généralement, de l'hybridation est désormais bien reconnue [CG]. Cette approche offre deux manières nouvelles de considérer les projets :

- Avec l'hydro-solaire HhSH, l'exploitation des retenues de barrage peut se concentrer sur les services non énergétiques ; l'hydro-solaire apportant la composante énergétique nécessaire pour la justification commerciale.
- Avec l'hydro-solaire FSH et TwinDams, il s'agit d'un nouveau type de centrale de production d'électricité, essentiellement renouvelable, qui ne consomme pas d'eau, qui est entièrement pilotable et qui n'est pas limité en puissance installée. Les centrales FSH et TwinDams peuvent ainsi, partout dans le monde, remplacer les centrales thermiques.

Ainsi, l'hydrosolaire peut jouer un rôle majeur dans l'adaptation au changement climatique. En version FSH, elle fournit des sources d'électricité renouvelable, pilotable, ne dépendant pas des ressources en eau, et pouvant être développées dans de très nombreuses régions du monde, en particulier les régions ensoleillées. En versions HhSH et FSH, elle permet de diminuer la pression sur la ressource en eau, sans perte de production électrique.

Développement du PV flottant

Le PV flottant est une technologie qui a d'abord été développée sur des plans d'eau statique (sans marnage) et de faible profondeur. Cette technologie a connu un essor rapide.

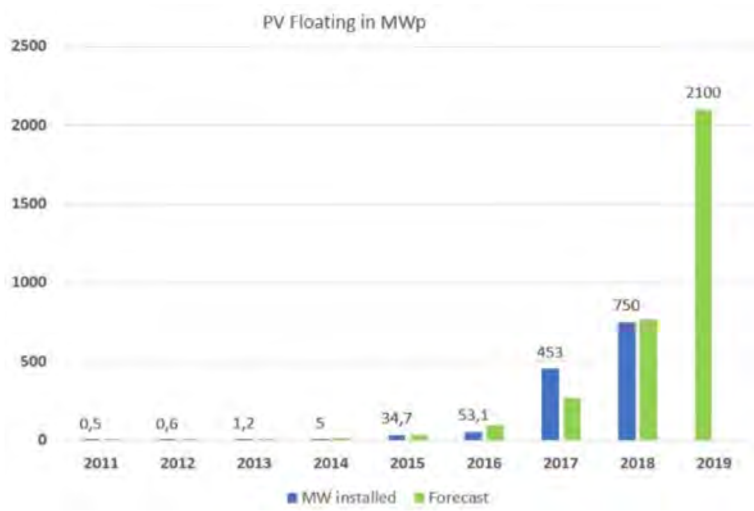


Fig. 28
Illustration extraite des rapports de World Bank et SERIS illustrant la croissance rapide du PV flottant [51]

Le PV flottant sur les réservoirs de barrage offre un très grand potentiel d'expansion de cette technique. Cependant, il pose des problèmes techniques nouveaux : sur de plus grands réservoirs, les vagues sont plus hautes et plus fréquentes ; les plus grandes profondeurs et le marnage compliquent les solutions d'ancrage et d'amarrage ; la présence du barrage oblige à renforcer les études de sécurité de ces installations.

Aujourd'hui, seules quelques installations de PV flottants sur des réservoirs de barrage ont été réalisées. Un des pays dans lequel cette technologie se développe rapidement est l'Inde : Ramagundam 100 MW en 2022, Kayamkulam 92 MW en 2022, Simhadri 25 MW en 2021, Rihand Dam 150 MW en cours d'installation, Omkareshwar 600 MW en cours d'installation [BD]. Le projet de Cirata (Q108-R19) en Indonésie est un exemple important de ce type de réalisation.

On trouvera une synthèse rédigée sur le sujet du PV flottant dans [51] ainsi qu'une revue des particularités techniques du PV flottant sur les retenues de barrages dans [52].

Développement de l’hybridation

L’hybridation de type VPP est déjà pratique par des opérateurs de production d’électricité, qui combinent leurs différentes sources de production pour optimiser le placement de l’électricité. Les réservoirs hydroélectriques sont utilisés pour lisser la variabilité infra-horaire et infra-journalière de la production intermittente fatale.

L’hybridation FSH trouve des applications importantes, avec par exemple la centrale intégrée de Pinnapuram en Inde (Greenko Group, 1 GW de solaire, 550 MW d’éolien, 1.2 GW de STEP avec une capacité de stockage de 9 heures). Des projets variés d’hybridation ShSH et HhSH sont à l’étude.

On trouvera un essai de synthèse sur la question de l’hybridation dans [53].

5.3.2. *Des technologies qui doivent encore mûrir*

Le solaire flottant est une technologie relativement récente, avec un développement qui date du début des années 2010 environ. Cette technologie a été développée pour des plans d’eau de faible profondeur, généralement de faible étendue, sans marnage (ou avec un marnage réduit), et sans barrage pour fermer le réservoir.

Ainsi, le solaire flottant sur les retenues de barrage est une technologie différente à plusieurs égards. Les solutions d’ancrage, d’amarrage et de flotteurs qui ont été développés depuis 2010 ne sont pas nécessairement adaptées aux conditions spécifiques des lacs de barrage, et en particulier des lacs de grands barrages :

- Les profondeurs peuvent être nettement plus grandes, et il faut composer avec le marnage de la retenue
- Les hauteurs de vagues, qui dépendent du fetch, peuvent être sensiblement plus grandes,
- Les grands réservoirs sont également plus fréquemment agités de vagues de différentes fréquence et hauteur, ce qui engendre une fatigue des connecteurs
- Les conséquences d’un accident (d’une perte des ancrages par exemple) peuvent être plus graves.

Deux rapports dressent un retour d’expérience : Q108-R12, à propos d’un projet pilote en Europe, et Q108-R19, qui décrit quelques uns des aspects du projet de Cirata (145 MWp) en Indonésie. Le rapport Q108-R12 précise que l’objectif du projet pilote de 2 MWp était de démontrer la viabilité technique et commerciale d’une technologie spécifique. Le projet est constitué de 4 unités de 500 kWp, installées sur une membrane étanche (polymère renforcé ou caoutchouc) formant l’îlot flottant. Le projet avait été contractualisé par le biais d’un PPA (Power Purchase Agreement) sur 15 ans. Ce projet pilote met en évidence les nombreux facteurs qui peuvent altérer les performances d’un tel projet : action des vagues, humidité, poussière, salissures, …). Le rapport Q108-R19 décrit les conditions de site particulières de la retenue Cirata : profondeur de 100 m, marnage de 20 m, dépôt de sédiments sur plusieurs mètres d'épaisseur en fond de retenue, avec parfois des pentes dépassant 20 degrés. Dans ce contexte, la solution technique retenue utilise un amarrage via des corps morts en béton équipés de clés de cisaillement métalliques ; le positionnement de ces blocs d'amarrages est vérifié par un système de suivi de position sous-marin (« Ultra-Short BaseLine », USBL) ; la surveillance en exploitation s'effectue notamment via un suivi en continu de la position des îlots flottants, par balises GPS, qui permettent un suivi de la dérive (« drift ») des îlots.

D'autres projets ont été réalisés ou sont en cours, avec des technologies d'amarrage et d'ancrage qui peuvent différer de celles exposées par ces deux rapports. Citons par exemple les projets suivants :

- A Alqueva au Portugal, une technologie innovante d'amarrage par des câbles avec une forte capacité de déformation élastique (Seaflex) a été développée pour s'adapter au contexte de fort marnage ; ce projet a été conduit dans le cadre d'un programme d'innovation européen.
- A Dau-Tieng au Vietnam, les berges de la retenue sont douces, et il y a une vaste surface qui est noyée une partie de l'année seulement, en période de hautes eaux. Le projet a consisté à prévoir des panneaux installés sur pilotis, dans une zone de faible profondeur d'eau. Les panneaux sont conçus pour pouvoir être noyés en cas de hautes eaux.
- Sur le projet du Cheylas, en cours de développement en France, pour une retenue de barrage de profondeur limitée mais avec fort marnage (bassin de STEP), le principe classiquement utilisé de nombreux ancrages par blocs est remplacé par un nombre réduit d'ancrages de grande capacité, avec deux avantages : meilleure maîtrise de la répartition des efforts, meilleure adaptation au marnage.

Le rapport Q108-R19 et ces approches différentes mettent bien en évidence certaines des difficultés associées à l'amarrage et à l'ancrage des îlots de PV flottant. La répartition des efforts d'amarrage dépend de la position précise des blocs d'ancrage, et varie en fonction des conditions combinées de cote de retenue et d'orientation du vent.

Il y a lieu de continuer à apprendre de ces projets innovants, pour progressivement mettre au point des technologies éprouvées, adaptées aux conditions des grands réservoirs de barrages. C'est ce que souligne Q108-R12, qui met en avant le fait qu'il y a lieu de mettre en place des « écosystèmes d'innovation », pour faire émerger et qualifier les technologies adaptées.

5.3.3. *Des risques nouveaux pour les barrages ?*

Les panneaux solaires flottants sur les retenues peuvent engendrer des risques nouveaux pour les barrages. En effet, la solidité des îlots de FPV (des ancrages, des amarrages ou des connecteurs) est mise à rude épreuve par les vents et les vagues lors des tempêtes, et il y a eu plusieurs accidents de rupture de ces îlots, puis de dérive des îlots sur les retenues.

Cela peut avoir des conséquences sur la sécurité des barrages. Le plus grand risque est celui du blocage de l'évacuateur de crues par les modules de PV flottants à la dérive. Il y a également d'autres risques : les efforts supplémentaires qui peuvent être transmis aux structures (par exemple les tours de prise) si un îlot vient s'y échouer ; les conséquences d'un incendie si l'îlot à la dérive prend feu ; la rupture d'une étanchéité mince si un îlot à la dérive vient la percuter.

Dans ce contexte, il y a des initiatives pour tenter d'offrir des éléments de cadrage pour le développement des projets de FPV sur les retenues de barrage. Deux initiatives, parmi d'autres, sont en cours et devraient donner lieu à la parution de documents d'orientation : le Comité T de la CIGB élabore un bulletin et le Comité Français prépare des Recommandations professionnelles. Le rapport Q108-R4 décrit les travaux en cours par le Comité Français, ce qui permet de dresser la liste des principaux points de vigilance lors du développement de projets de PV flottants sur les retenues de barrage :

- La définition des reconnaissances initiales nécessaires pour apprécier les conditions de site (géotechnique, vent et vagues) ;
- La définition des critères de dimensionnement, en particulier sur les paramètres de vent et de vagues à considérer, et l'élaboration de la note d'hypothèse ;
- La définition des moyens de surveillance, d'auscultation et de maintenance des ouvrages en service, et en particulier des ancrages ;
- La clarification du partage de responsabilités entre l'exploitant du barrage et l'exploitant de la centrale solaire flottante (et la vérification de la cohérence entre les consignes d'exploitation appliquées par ces deux entités) ;
- Les moyens de contrôle de la sécurité dans les phases délicates d'installation.

Ce rapport conclut sur la nécessité de procéder à des analyses de risques spécifiques préalablement à l'autorisation de centrales solaires sur les barrages.

5.3.4. *Hybridation*

Au-delà du simple partage de la surface du réservoir et des lignes de transmission, l'hybridation hydro-solaire peut amener des projets nouveaux de production d'électricité renouvelable, abondante et garantie. L'hybridation solaire-hydro repose sur l'intégration d'un parc solaire à une infrastructure hydroélectrique, permettant une production d'électricité optimisée sur plusieurs échelles de temps.

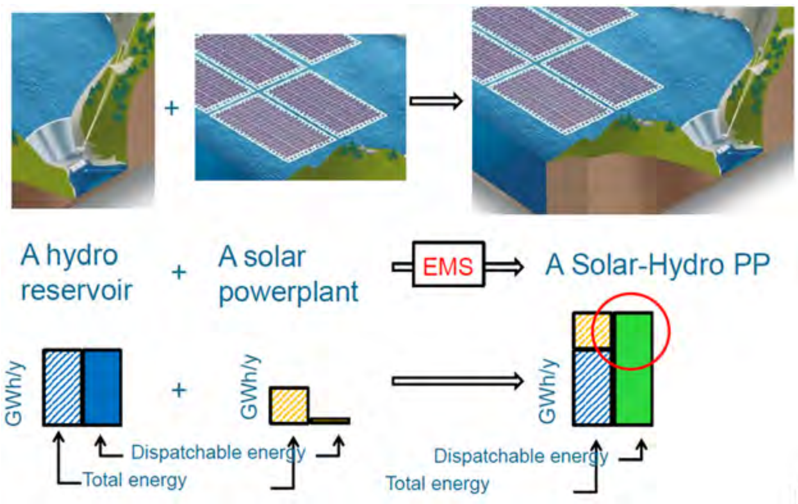


Fig. 29
Principe générique de l'hybridation Solar-Hydro [51]

L'hybridation se décline en plusieurs configurations :

- Hybridation avec un réservoir hydroélectrique : ShSH et HhSH
  - ShSH (Slightly Hybridized Solar-Hydro) : La puissance installée de la ferme solaire est limitée ; l'hydroélectricité compense la variabilité de la production solaire due aux passages nuageux, sans nécessiter d'importantes modifications des infrastructures hydrauliques. C'est ce qui a été réalisé avec le projet pilote d'Alqueva (Portugal).
  - HhSH (Highly Hybridized Solar-Hydro) : La puissance installée de la ferme solaire est plus importante ; l'hybridation impose des variations plus rapides et plus profondes de la production hydroélectrique ; cela nécessite des ajustements techniques sur les turbines et le réseau. C'est ce qui est à l'étude pour le projet de Manantali (Mali).
- Hybridation avec stockage hydraulique dédié : FSH
  - FSH Type 1 : Association d'un parc solaire à une station de pompage (pumped-storage). Cette configuration permet un stockage d'énergie sur quelques heures et est adaptée aux grandes centrales. C'est ce qui est réalisé à Pinnapuram (Inde).

- FSH Type 2 : Intégration d'un parc solaire, d'une station de pompage et d'un barrage réservoir, permettant un stockage sur des échelles journalières ou saisonnières. C'est ce qui est à l'étude pour le projet de Bassiéri (Burkina Faso).

Le système hybridé est, dans tous les cas, piloté par un système de gestion énergétique (EMS). L'EMS coordonne la production des différentes composantes du système hybride. Il doit en particulier gérer les fluctuations de la production solaire occasionnées par le passage des nuages : sous de nombreux climats, la couverture nuageuse peut entraîner une perte d'ensoleillement de 80 % en quelques minutes. Il adapte pour cela la production hydroélectrique pour absorber les fluctuations de l'énergie solaire, en tenant compte des questions techniques et environnementales, qui limitent notamment les gradients de variations des débits turbinés.

L'EMS repose sur une combinaison de techniques : en ShSH, optimisation de la répartition de puissance entre solaire, hydro et éventuellement batteries ; en HhSH, ajouts de fonction de prévisions météorologiques d'ensoleillement ultra-courtes (5-15 min) pour lisser les gradients, et recours au « curtailment » solaire (réduction volontaire de la production solaire en journée d'ensoleillement instable) afin de limiter les variations brutales.

L'hybridation solaire-hydro est naturellement envisagée pour les échelles de temps infra-journalière et journalière. Elle peut également être envisagée pour le stockage saisonnier. L'intégration d'un stockage hydraulique de longue durée permet d'adapter la production à la variabilité saisonnière du solaire. Il est ainsi démontré qu'un stockage hydraulique correspondant à 20 jours de production solaire permet de complètement lisser la production solaire à Aswan (Egypte). Qu'il suffit d'un stockage de 6 jours à Brasilia (Brésil), et qu'il faut 90 jours à Paris (France), en raison de la forte baisse de l'ensoleillement en hiver [53].

La figure ci-dessous illustre le projet hybride de Xiangbilin : « "hydro-wind-solar-storage-agriculture hybrid clean energy base », développé en China [58].

Fig. 30
Xiangbiling “Hydro-Wind-Solar-Agricultural” Hybrid Clean Energy Base

5.4. D’autres solutions par pompage

5.4.1. *Pour lutter contre les inondations*

Le pompage peut être une solution pour limiter les inondations dans les rivières de plaine et les estuaires. Dans le cas des estuaires, cela a été développé par exemple aux Pays-Bas et à la Nouvelle-Orléans, ce qui est présenté au chapitre des « barrages en mer », §5.6.

Cette solution peut également être explorée pour les rivières de plaine, loin de la mer, lorsque la pente de la rivière est suffisamment faible (typiquement moins de 20 ou 30 cm par km). Elle a été examinée pour la Seine à Paris et en région francilienne, avec des modalités différentes des barrages de fermeture d’estuaires :

- Option (a) : Station de pompage et barrage vanné assurant une fermeture
- Option (b) : Matrice d’hydroliennes fonctionnant en mode « hélice » pour accélérer les écoulements.

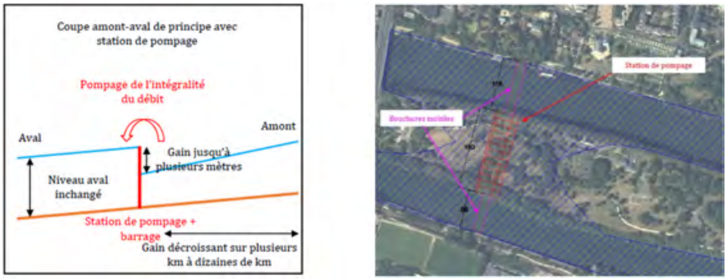


Fig. 31
Projet DANCE « Dispositif d’Abaissement du Niveau des Crues Exceptionnelles », option (a) : par la méthode Station de pompage [56]

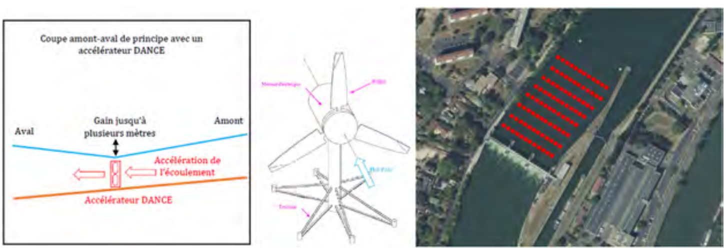


Fig. 32
Projet DANCE « Dispositif d’Abaissement du Niveau des Crues Exceptionnelles », option (b) : par la méthode Matrice d’hélices accélératrices

Ces pistes sont toujours au stade exploratoire.

5.4.2. *Pour constituer des réserves saisonnières*

Ces dernières décennies ont connu deux évolutions importantes, amenées à se prolonger :

- avec l’introduction des énergies renouvelables intermittentes, le coût de l’électricité est parfois très faible,
- avec l’augmentation de l’irrégularité des ressources en eau, la valeur économique et sociale de l’eau stockée augmente.

Chacune de ces deux raisons conduit à renforcer l'intérêt du pompage, comme mode d'alimentation de retenues existantes ou de nouveaux stockages. Il peut s'agir d'un pompage continu, à faible débit ; ou d'un pompage plus concentré à certains moments de l'année (en fonction de l'hydraulicité de la rivière et des coûts de l'électricité). Le pompage peut par exemple être envisagé :

- avec un débit faible et régulier, en aval de barrages hydroélectriques exploités avec de fortes variations de débit turbiné, pour remplir le réservoir hydroélectrique,
- avec un débit concentré en saison pluvieuse, par pompage depuis un cours d'eau voisin qui dispose de débits importants pendant cette saison, pour remplir un grand réservoir.

5.5. Stockage en nappe aquifère et barrages souterrains

5.5.1. *Présentation, Principe et intérêt*

Les nappes aquifères sont largement utilisées comme ressource en eau dans le monde. Elles sont surexploitées dans de nombreux endroits. Pour limiter ces effets, les méthodes privilégiées sont : favoriser l'infiltration et limiter les prélèvements. En plus de ces approches, il y a eu de nombreux essais et projets de recharge de nappe.

La *recharge de nappe aquifère* consiste à artificiellement augmenter les volumes d'eau dans un aquifère, qu'il soit de surface (alluvions) ou profond. Il s'agit d'un concept qui présente, au moins en théorie, des avantages importants, en particulier sous climat aride ou semi-aride : pas d'évaporation, pas de perte de volume par sédimentation, et généralement pas d'évacuateur de crue. Ce concept a souvent été exploré, pour tenter de contrer les effets de la surexploitation, et pour maintenir une réserve d'eau accessible en saison sèche [57]. Il est également envisagé pour reconstituer des réserves de long et très long terme, en favorisant l'infiltration des eaux excédentaires certains années (par exemple : Californie, moyens mis en œuvre pour optimiser l'infiltration des eaux excédentaires de l'hiver 2022-23).

Les barrages sont parfois utilisés à cet effet :

- Des *barrages de recharge* sont parfois utilisés pour favoriser la recharge de nappe.
- Des barrages ont également été édifiés pour former de nouvelles nappes aquifères, les *sand dams*. De nombreux ouvrages – plutôt petits – ont été construits, par exemple au Kenya.

- Les *barrages souterrains* ont une fonction différente : ils ne visent pas à augmenter les volumes d'eau infiltrés, mais à relever le niveau de la nappe. Ceux qui ont été construits l'ont en majorité été pour réaliser un stockage en nappe aquifère. Il y a quelques autres exemples, pour lesquels la fonction a été de réaliser une barrière contre l'intrusion d'eau salée près des cotes (« salt barrier »), voire d'eau polluée, pour protéger une nappe d'eau douce.

Les paragraphes qui suivent distinguent les barrages de subsurface (et le stockage en aquifère de surface) et les barrages visant les aquifères profonds.

Il est globalement constaté que les projets sont relativement peu nombreux, et qu'il y a eu des échecs. Or, le Tableau 1 met en évidence le volume conséquent des ressources souterraines et donc, au moins en théorie, l'intérêt qu'il y aurait à améliorer la recharge des nappes et le stockage en souterrain. Comme l'écrit Anton Schleiss « *Les barrages de recharge des aquifères vont certainement avoir plus d'intérêt à l'avenir mais leur mise en œuvre est délicate et nécessite plus de R&D* » [AS].

5.5.2. *Stockage en nappe de surface,*

Le stockage en nappe de surface consiste à stocker l'eau dans des alluvions, par l'intermédiaire d'un barrage qui assure une coupure des écoulements souterrains, et maintient une différence de niveau entre l'amont et l'aval. Les schémas ci-dessous, élaborés par INOWAS [48], illustrent quelques-uns des concepts utilisés.

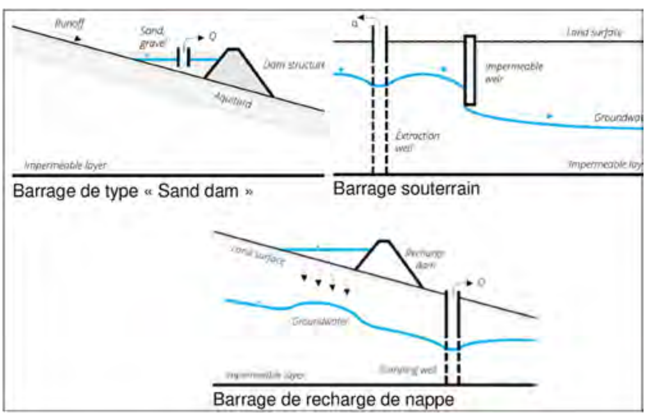


Fig. 33
Différents types de barrages pour augmenter le stockage en nappe aquifère de surface [48]

Petits barrages : assurer un certain volume d'eau en saison sèche, pour la subsistance

Il y a de très nombreux petits barrages qui fonctionnent en « sand dam » dans les zones semi-aride de l'Afrique sahélienne, que les barrages aient été conçus de cette manière, ou simplement par conséquences des conditions climatiques : les retenues se vident une partie de l'année, mais une nappe perchée persiste dans les alluvions de la retenue. [RS].

Le rapport Q108-R1 explore l'intérêt des « sand dams » comme solution de stockage d'eau pour les régions arides. Les auteurs constatent qu'il y a un grand nombre de ces projets, déployés par des ONG qui constatent que ces barrages souterrains offrent une réserve d'eau utile aux populations, en particulier en cas de sécheresse ; le fait que l'eau souterraine n'attire pas les moustiques est également un avantage important. Cependant, il y a un nombre important d'échecs, de l'ordre de 50%, la plupart du temps parce que les sédiments qui se sont déposés dans la retenue sont trop fins. Q108-R1 suggère une coopération accrue entre les ONG, qui développent ces projets, et la profession des barrages, qui peut apporter une expertise utile pour limiter le taux d'échecs. L'expertise requise couvre les thématiques de la géologie, de l'hydrologie et du transport sédimentaire (la retenue doit être suffisamment petite pour que les sédiments fins ne soient pas piégés, et que seul les sédiments grossiers soient stockés en arrière du barrage). L'exemple pratique d'un barrage au Kenya illustre ce propos [1].

Une variante des « sand dams » est le principe des « sponge riverbeds », développé en Chine. Il s'agit de remplacer les alluvions du lit de la rivière par des matériaux granulaires (sable, gravier) ; le lit retient ainsi une fraction d'eau bien plus importante (jusqu'à 450 kg/m3), ce qui augmente les réserves abritées de l'évaporation, et ce qui présente également l'intérêt d'améliorer les écoulements de surface. Cette variante est pour l'instant expérimentale. Elle illustre en tous cas l'intérêt renouvelé du stockage en aquifère de surface. [JJ]

Grands aquifères : mobiliser des ressources en eau plus importantes

Cependant, les ressources tirées de ces petits barrages restent limitées. Seuls certains projets permettent une mobilisation plus importante. Il s'agit de projets de type Barrage souterrain ou Barrage de recharge.

Barrages souterrains - Un inventaire des projets, fait en 2016, ne recense qu'un petit nombre de projets pour lesquels le volume d'eau mobilisé dépasse 10 000 m^3/jour, soit donc 100 l/s ou 3 hm^3 par an.

Fukusato, Sunagawa, Minafuku (Okinawa, Japon)	Trois barrages souterrains construits sur la même vallée.Aquifère : horizon calcaire Ryuku très perméable (3.5 10^{-3} m/s), épaisseur 10 à 70 m, porosité 10% Hauteur de la coupure étanche : 16.5 à 50 m Production annuelle : 7 et 8 hm^3/an pour Sunagawa et Fukusato (Minakafu, plus petit, avait été construit à titre expérimental) Capacité des réservoirs : 10.5 – 9.5 et 0.7 hm^3
Nakhara (Okinawa, Japon)	Barrage souterrain Aquifère : horizon calcaire Ryuku très perméable Production annuelle : 9 hm^3/anCapacité du réservoir : 2 hm^3
Komesu (Okinawa, Japon)	Barrage souterrain assurant une barrière anti-sel. Hauteur importante (69 m) Aquifère : horizon calcaire Ryuku très perméable Production annuelle : 1.8 hm^3/an Capacité du réservoir : 2 hm^3
Tadjemout (Algérie)	Barrage souterrain Aquifère : sables et galets, au contact d'une formation de grès ; perméabilité des alluvions : 10^{-3} m/s Production annuelle : de l'ordre de 6 hm^3/an La nappe des alluvions est alimentée par une source dans les grès.
Ssangcheon (S. Korea)	Aquifère : Alluvions grossières Production annuelle : de l'ordre de 12 hm^3/an La nappe des alluvions est alimentée par l'écoulement de surface (infiltration)

Plusieurs de ces projets ont été développés sur l'île d'Okinawa au Japon, en raison de la configuration topographique (relief accidenté) et géologique spécifique (formation très perméable de quelques dizaines de mètres surmontant un substratum étanche). Cela offre un retour d'expérience très utile pour des conditions similaires [47]. De manière générale, quatre conditions sont nécessaires pour qu'un barrage souterrain soit en mesure de mobiliser des ressources en eau significatives :

- Un réservoir souterrain :
  - constitué d'alluvions grossières ou de rocher très perméable ; typiquement une perméabilité de plus de 10^{-4} m/s
  - et de capacité suffisante : volume topographique disponible au-dessus de la nappe naturelle, multiplié par la porosité accessible
- Une fermeture hydraulique :
  - A la base et sur les rives du réservoir, des formations géologiques de faible perméabilité (typiquement un contraste de perméabilité d'un facteur 100), ou un niveau de nappe suffisamment eau sur les rives
  - Un verrou sur lequel il est possible d'installer une coupure étanche à une profondeur raisonnable ; cela a été fait jusqu'à 70 m de profondeur
- Une alimentation en eau du réservoir en quantité suffisante :
  - Idéalement, directement par l'écoulement souterrain, comme à Okinawa
  - Sinon, par infiltration depuis l'eau de surface, mais cela expose à la problématique du colmatage.
  - Dans tous les cas, en vérifiant le volume annuel de l'écoulement souterrain
- La vérification des impacts : en particulier l'impact à l'aval de l'abaissement de la nappe (en cote et flux annuel) sur les puits et forages qui sont exploités

Barrages de recharge

Les barrages de recharge forment des réservoirs de stockage classiques, associés à des dispositifs favorisant l'infiltration de l'eau. Il existe ainsi :

- Des réservoirs installés au-dessus de la nappe, sur des horizons perméables, et l'eau stockée en période pluvieuse s'infiltre dans la nappe.
- Des réservoirs classiques, à partir desquels des lâchures sont opérées et dirigées vers des champs d'infiltration, naturels ou renforcés par des puits d'infiltration.

Il serait utile de réaliser le retour d'expérience de grands barrages ayant la recharge de nappe comme fonction principale. A la connaissance de l'auteur, un tel travail de retour d'expérience n'est pas disponible. On peut souligner le fait que de nombreux barrages assurent une fonction de recharge de nappe, en raison des « fuites » par les berges de la retenue.

Barrage pour le Stockage en aquifère profond

Il n'a pas été trouvé, pour la rédaction de ce rapport, d'exemple significatif de barrage (au sens de coupure étanche) pour le stockage en aquifère profond. Le stockage artificiel en aquifère profond (« Aquifer Storage and Recovery », ASR), qui consiste à injecter de l'eau douce dans des aquifères en profondeur, est une technologie peu déployée, mais pour laquelle il existe quelques cas d'application majeurs, notamment aux Etats-Unis :

Table 3
Exemples de Stockage en aquifère profonds, Etats-Unis.

	VOLUME DE STOCKAGE, HM^3	CAPACITÉ DE PRODUCTION JOURNALIÈRE, M^3/JOUR
Las Vegas, Nevada	400	750 000
San Antonio, Texas	85	225 000
Calleguas, California	40	150 000

Selon certaines publications [49], le coût de cette forme de stockage serait du même ordre de grandeur que le coût du stockage en surface par les barrages. Cela reste à confirmer.

5.5.3. *Assurer le renouvellement des nappes par le stockage de surface*

Une manière d'assurer la recharge des nappes est de limiter les prélèvements. Les projets de nouveaux réservoirs en Angleterre (cf. §3.4) ont notamment pour fonction d'éviter les pompages dans la nappe de la craie, pour permettre à cette nappe de se maintenir, y compris en saison sèche, et ainsi d'assurer naturellement ses fonctions écologiques d'alimentation des petits cours d'eau et des zones humides.

5.6. Barrages en mer

5.6.1. *Présentation, Principe et intérêt*

Par « barrages en mer », on entend les ouvrages qui retiennent l'eau de la mer. Ces barrages peuvent avoir différentes fonctions :

- La protection côtière, par exemple la barrière « Delta Works » aux Pays-Bas
- La production d'électricité marémotrice, par exemple le barrage de la Rance, en France
- Le stockage d'énergie, en formant un réservoir off-shore pour un dispositif de pompage turbinage utilisant l'eau de mer. Il n'existe pas de tel ouvrage aujourd'hui, mais il y a eu de premières expérimentations de STEP utilisant l'eau de la mer, par exemple la STEP d'Okinawa au Japon.

Fig. 34
Delta Works, Pays-Bas

Fig. 35
Barrage de La Rance

Fig. 36
Barrage de Sihwa, By Arne Müseler / www.arne-mueseler.com

Le principe général consiste à construire un ouvrage de fermeture en mer, éventuellement complété par des ouvrages de régulation (vannes, turbines, écluses, ...).

L'intérêt de la protection côtière est évident dans les zones de faibles altitude, soumises à l'élévation du niveau de la mer, lorsque les options de repli ne sont pas favorables. Aux Pays-Bas, les digues ont été dimensionnées pour des événements de période de retour jusqu'à 10 000 ans (combinaison de cote de marée et de tempête), et elles protègent un quart de la population.

L'intérêt des barrages pour la production d'électricité marémotrice a été démontré historiquement pour les cotes où la hauteur de marée dépasse 4 m. L'électricité marémotrice est une électricité renouvelable et prédictible, et suffisamment économique. Il y a des réalisations notamment en France (La Rance, 240 MW) et en Corée du Sud (Sihwa, 254 MW). Des projets sont à l'étude au Royaume-Uni (Swansea Bay, Mersey river), pour plusieurs centaines de MW. Une étude d'opportunité a été conduite en France [39][40], démontrant l'intérêt de cette technologie, et montrant que, sous certaines conditions, elle pouvait utiliser des hauteurs de marée plus faibles (cf. « maréliennes », ci-dessous).

Le stockage d'énergie en mer a les mêmes fonctions que le stockage d'énergie par des STEP sur le continent. Pour des raisons qui tiennent à la dynamique d'évolution des cotes, il y a de grands linéaires de falaises côtières le long desquelles des bassins peuvent être construits, avec des remblais qui repose sur un fond marin peu profond (issu du recul progressif de la cote). Les bassins à la mer permettent d'envisager des STEP à fort débit d'équipement, très courte distance entre bassin haut et bassin bas, et éventuellement volume de stockage de plusieurs jours dans le bassin haut.

Les questions environnementales relatives à la construction de barrages en mer sont délicates : les milieux littoraux sont souvent des écosystèmes riches. Deux raisons laissent penser que des projets sont possibles, et éventuellement souhaitables. D'abord, certaines zones côtières doivent être protégées, et vont devoir être demain encore davantage protégées contre les submersions marines – et pas seulement aux Pays-Bas. Ainsi, des endiguements sont inévitables, et il est utile d'envisager les autres services que ces endiguements pourraient rendre (production ou stockage d'énergie par exemple). Ensuite, certaines zones côtières sont déjà fortement anthropisées ou polluées, par exemple le long de zones industrielles, ports, ou à proximité de centrales thermiques ou nucléaires. Notons par exemple que le projet marémoteur de Swansea Bay avait reçu un accueil favorable d'ONG.

5.6.2. *Protections à la cote, quelques exemples et idées*

L'élévation du niveau de la mer pose des questions difficiles pour les populations vivant près des cotes. Les mesures envisagées sont variées et à choisir au cas par cas : accepter le recul et déplacer les populations ; protéger contre les tempêtes en luttant contre l'érosion et en confortant les ouvrages de protection (ouvrages naturels ou artificiels, en soulignant le recours de plus en plus fréquent à l'écoconception et aux solutions fondées sur la nature) contre le franchissement par les vagues ; réhaussement des niveaux de protection.

Ce rapport n'a pas pour ambition de traiter ce sujet dans son ensemble. Il se limite à présenter des cas où la solution retenue a consisté à installer des ouvrages de grande ampleur, véritables « barrages » contre les très hautes eaux et tempêtes.

Les Pays-Bas sont abrités derrière les digues de protection du plan Delta (1953-1985). Plus de 100 km de digues artificielles ont été érigées, pour fermer des estuaires ou protéger des zones spécifiques. Des barrières mobiles anti-tempêtes gèrent l'ouverture ou la fermeture de la connexion entre les fleuves et la mer. En 1993 et 1995, les crues centennales de la Meuse et du Rhin ont conduit à des inondations importantes, et ont motivé le programme « Room for Rivers », qui augmente les plaines inondables disponibles, pour amortir les élévations du niveau d'eau en crue. Des stations de pompage sont nécessaires pour renvoyer les eaux excédentaires en mer. L'une d'entre elles, Afsluitdijk, a été récemment rénovée, et sa puissance portée à 275 m^3/s pour une dénivelée de 3,40 m.

La poursuite de l'élévation du niveau de la mer conduit les Pays-Bas à envisager des modifications du système de protection. Une des options envisagées (« seaward ») consiste à construire un grand barrage en mer, combiné à des stations de pompage de forte capacité.

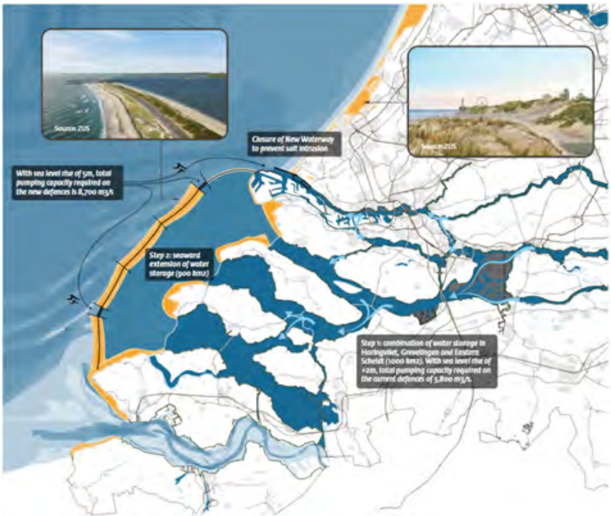


Fig. 37
Stratégies d'adaptation à une élévation de la mer de +4 ou +5m, option « seaward », Pays-Bas [67]

Aux Etats-Unis, le désastre de l'ouragan Katrina a conduit à des travaux importants de protection contre les submersions marines, dans le delta du Mississipi. Il faut à la fois permettre l'écoulement du fleuve, et pouvoir protéger les zones intérieures des tempêtes en mer (combinaison d'une élévation du niveau moyen et des hauteurs de vagues). Un des ouvrages assurant cette fonction est le West Closure Complex, réalisé par l'USACE, et illustré ci-dessous. Comme aux Pays-Bas, cela combine : des murs ou digues de fermeture, une très grande barrière mobile, ouverte en temps normal et fermée en cas de tempête, et une station de pompage, qui transfère l'intégralité des débits de la rivière lorsque la barrière est fermée.

Fig. 38
Le système « West Closure Complex » : illustration du système (gauche) [69] ; système en fonctionnement pendant l'ouragan Isaac (droite) Photo by: PAO, USACE, New Orleans District

5.6.3. *Energie marémotrice : le concept de marélienne*

L'énergie marémotrice connaît un regain d'intérêt depuis quelques années, pour deux raisons : il s'agit d'une électricité renouvelable, qui a l'avantage d'être prédictible ; l'élévation du niveau de la mer génère des besoins de protection côtière qui peuvent être combinés avec de la production ou du stockage d'électricité.

Un des inconvénients de l'énergie marémotrice est le fait que les solutions classiques nécessitent des marées importantes pour être rentables. Une solution alternative a été proposée, sous le nom de « maréliennes » [41]. Les « maréliennes » résultent de la combinaison d'un bassin marémoteur et de chenaux équipés d'hydroliennes. Le principe des maréliennes est de relier des bassins de centaines de kilomètres carrés à la mer par des chenaux de plusieurs kilomètres où sont placées des rangées d'hydroliennes. [FLe]

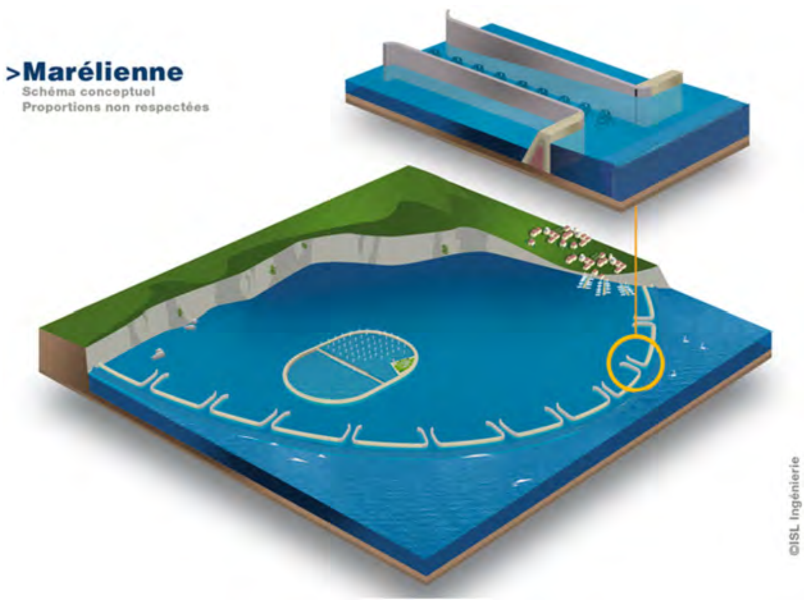


Fig. 39.
Le concept de maréliennes, © ISL ingénierie

Il s’agit à ce stade d’un principe de développement conceptuel, qui présente les avantages suivants :

- Il est efficace sous des hauteurs de marée plus faibles qu’une usine marémotrice classique (plus faible charge, plus forts débits)
- Le principe des chenaux augmente la liaisons hydraulique entre le bassin et la mer, ce qui diminue donc l’artificialisation du bassin.

Selon les évaluations préliminaires, cette solution est attractive dans des pays de faible amplitude des marées, c’est-à-dire dans une quinzaine de pays au total, pour un potentiel mondial de l’ordre de 1 000 TWh/an. La France est un des pays les plus prometteurs avec la possibilité de plus de 50 TWh/an.

6. ACRONYMES

GHG : Green House Gas

IPCC : International Panel on Climate Change

RCP : Representative Concentration Pathway : les quatre scénarios globaux considérés par IPCC. RCP8.5 ; RCP6.0 ; RCP4.5 ; RCP2.6, les chiffres représentent le forçage radiatif (en W/m^2 à l’horizon 2100), c’est-à-dire l’écart avec le bilan radiatif d’avant la période industrielle.

GLOF : Glacial Lake Outburst Flood

GCM : Global Climate Model, voir par exemple le bulletin 200 pour une définition

RCM : Regional Climate Model, voir par exemple le bulletin 200 pour une définition

LCSA : Life Cycle Sustainability Analysis

ESAI : Environmental and Social Impact Assessment

IPBES : International Panel on Biodiversity and Ecosystemic Services

ShSH : Slightly Hybridized Solar Hydro (a solar farm and a hydropower plant, with the solar farm AC peak power around 20% to 40% of the hydropower installed capacity)

HhSH : Highly Hybridized Solar Hydro (a solar farm and a hydropower plant, with the solar farm AC peak power around 30% to 70% of the hydropower installed capacity)

FSH : Full Solar Hydro (a solar farm + a dedicated pumped storage)

STEP : Station de Transfert d'Energie par Pompage

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7.2. Contributions personnelles

La liste des contributeurs personnels est donnée ci-dessous. Ces contributions ont alimenté la réflexion générale. Par ailleurs, quand un développement dans le texte reprend explicitement et entièrement une idée développée par l'un des contributeurs, cela est référencé par les initiales, selon la codification ci-dessous.

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