RESERVOIR SEDIMENTATION, DAM SAFETY AND HYDROPOWER PRODUCTION: HAZARDS, RISKS AND ISSUES

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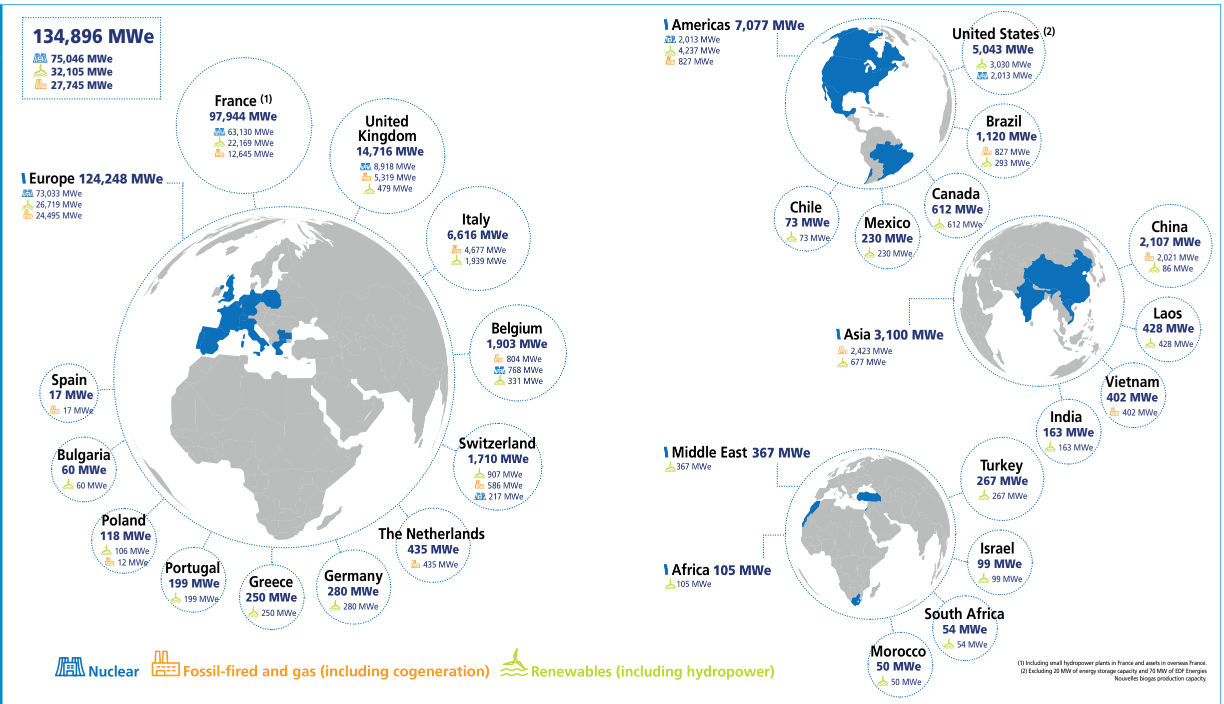
Reservoir dams and hydropower facilities provide a renewable source of electricity. As discussed by Kondolf and Schmitt[1] in the first issue of *Hydrolink* on reservoir sedimentation, silting affects two aspects of energy production: the amount of power produced, which is limited when the active reservoir storage is reduced by the sediment deposits, and maintenance requirements, which increase if the sediment flowing through the turbines results in abrasion of the wet parts (*e.g.* runners, wicket gates). Sediment management of reservoirs used for hydroelectric production is complex and subject to plenty of technical, economic, ecological and societal constraints. Sediment management should be an integral part of the reservoir system for the sustainable use of the resource while safeguarding the river environment. As part of the hydroelectric production activities of Electricité de France (EDF: www.edf.com), the assessment of risks triggered by sediment transport processes and reservoir sediment management is carried out on the basis of a ranking by hazard, which is then broken down by issues (i.e. stakes), and finally by the risks incurred. This methodology is described herein.

Hydropower in the EDF group

EDF is the second largest electricity company in the world in terms of production and distribution (Figures 1 and 2). The company is the world leader for low-carbon energy production: the largest nuclear operator in the world, the biggest producer of renewable energy in Europe, with the largest national power grid in Europe, and the largest electricity supplier in France. In 2017 the electricity production in France was 529.4 TWh (gross), of which 71.6% came from nuclear power plants and 10% from hydropower plants. EDF is well established in Europe, especially France, UK, Italy, and Belgium, as well as in North and South America, and covers all businesses spanning the electricity value chain from production to distribution, including energy transmission and trading activities, to continuously balance supply. The company has a workforce of 152,033 and serves 35.1 million customers (as of 2017).

EDF is Europe's leading producer of renewable energy (water, wind, sun), operating 433 hydroelectric plants in France. The hydropower installed capacity is 20 GW in France (400 MW in Corsica and the French overseas departments), 1,443 MW in other countries in Europe and 1,100 MW in Laos. In France, hydropower

Figure 1. EDF group's net installed capacity worldwide in 2017[2]



represents approximately 10% of EDF's electricity production. The company relies on three main activities to increase hydropower production: rehabilitation (*e.g.* at Romanche-Gavet, France's biggest hydro project), modernisation (*e.g*. at the Rance Tidal Power Station) and development of new projects abroad (*e.g*. Brazil, Cameroon). EDF has set an extremely ambitious goal: doubling of the net installed power in the field of renewable energies to reach over 50 GW in less than 15 years.

Concepts of hazard, risk and issue

A widely accepted definition characterizes "natural risk" as situations whereby natural hazards (*i.e*. meteorological, hydrological, geological, biological, and other phenomena) have the potential to affect humans, their structures or activities (*e.g*. economic, ecological or any similar issues) adversely. This definition is used in this article, but slightly "modified", to identify, within the context of hydroelectric production activities of EDF, the risks associated with reservoir sedimentation and sediment management.

Each hazard is characterised by its location, intensity or magnitude (*e.g*. water level or velocity for floods, magnitude for earthquakes), and frequency or probability of occurrence (*e.g*. flood return period). In the context of sedimentation and hydroelectric reservoirs, a hazard is defined as any sediment-related process (*e.g*. sediment inflow to the reservoir) or artificial intervention (*e.g*. flushing/sluicing, dry excavation or dredging) that may pose a risk to the dam, river or water users. Three categories of hazards are identified in this context:

1. Hazards associated with sediment inflow and sedimentation processes within the reservoir;
2. Hazards associated with sediment management operations; and
3. Hazards associated with the regulation of the river flow regime.

Issues associated with natural hazards are generally related to the presence and vulnerability of humans, infrastructure and activities. In addition, environmental issues (*e.g*. water quality, fauna and flora) are now increasingly of concern. In the context of hydroelectric reservoirs, issues are defined as any activity (industrial, human) or feature (*e.g*. ecosystems) that could be adversely impacted by the hazards associated with sediment transport processes

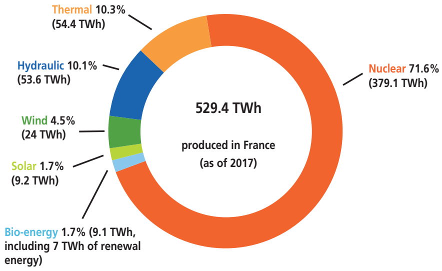


Figure 2. EDF's energy production in France (as of 2017, source: EDF)

or reservoir management operations.
A risk is the product of a hazard and its adverse consequences (*i.e*. issues). In the case of sediments, risks follow the same definition as issues, namely losses or serious damage to activities within the zone potentially impacted by the hazard.
In the present methodology, risks generated by sediment processes and management at hydropower facilities have been assessed on the basis of a classification by a hazard, which is then broken down by an associated issue (and sometimes sub-issue(s)), then by the risks incurred.

Hazards associated with sediment inflow into hydroelectric reservoirs

Hazards associated with sediment inflow are related to the sediment yield of the catchment, resulting in sedimentation processes within the reservoir. Seven issues are identified: (i) active reservoir capacity; (ii) reservoir operation, (iii) safety; (iv) water uses around the reservoir, (v) status of water body within the reservoir, as defined by the European Water Framework Directive (WFD)[3]; (vi) status of watercourses downstream of the dam, as defined by the WFD; and (vii) status of coastal areas in the vicinity of the mouth of the river impacted by the reservoir.

Issue 1: Active reservoir capacity
The gross annual volume loss in dam reservoirs worldwide is approximately 1%, according

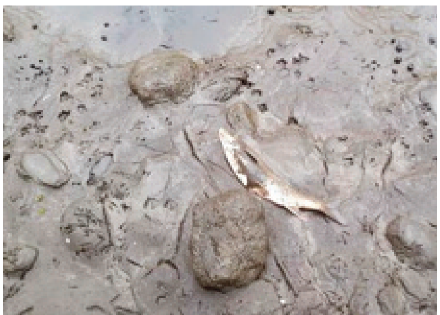


Figure 3. Fish mortality following a drawdown operation in an Italian reservoir. (Courtesy: S. Bastasi)

to ICOLD. For reservoirs operated by EDF, the gross annual loss is 0.1%. The need, or not to preserve the active volume of the reservoir is related to the following sub-issues[4]:

- *Hydropower production*: this is a major sub-issue, particularly for reservoirs storing water partially for use during the main season of hydropower generation. The associated risk is less hydropower production capacity available for sale, due to loss in the reservoir active capacity. This is notably the case for reservoirs used for hydro peaking demands;
- *Re-regulation*: some reservoirs serve to regulate the hydropeaking flows from hydropower plants located further upstream. The associated risk is loss of the reservoir regulation capability;
- *Desilting*: Some reservoirs serve as upstream sediment trapping systems, decreasing the sediment inflow to downstream hydropower units. The associated risk is the loss of desilting efficiency of the reservoir; and
- *Other purposes of the reservoir*: EDF operates multi-purpose dam reservoirs (*e.g*. water supply, irrigation and hydropower). Loss of the reservoir active volume due to sedimentation can generate the risk of not maintaining water supplies for domestic use, irrigation and industry.

Issue 2: Dam operation
Silting can present different risks for the dam operation, whereby blocking the intake structures, the outlet structures ensuring a minimum "ecological" flow in the downstream river channels, and the fish bypass structures.

Issue 3: Safety
This issue can be broken down into two sub-issues:

- *Safety of the dam itself*: sediment trapped behind the dam may impair functions and/or render useless the dam infrastructure, posing therefore safety hazards; and
- *Hydraulic safety upstream of the reservoir*: the sedimentary delta developing upward in the upstream sections of certain reservoirs may lead to reduced conveyance capacity, increased flooding, and increased ground water table elevations.

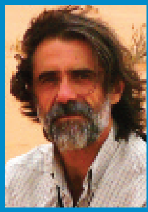
Issue 4: Water uses of reservoirs
Water for domestic supply and recreational activities are the main water uses of many reservoirs. The risks attributed to sedimentation are, among others, bathing ban, disappearance of beaches, reduced water depths

interfering with, or preventing operation of boat marinas, decreasing fish stock, as well as unpleasant odors.

Issue 5: WFD status of water bodies
This European legislation aims to achieve so-called “good ecological status” in groundwater and surface water, including reservoirs. The associated risk is the failure to achieve this requirement due to the presence of excessive amounts of fine and/or contaminated sediments that may have a negative effect on the aquatic ecosystem (*i.e.* habitat, water quality).

Issue 6: WFD status of downstream water-courses
The water downstream of the dam is sometimes referred to as “sediment hungry” water due to the reservoir capturing fine and coarse sediment. The associated risk is the non-achievement of “good ecological status” in the downstream watercourses deprived from nutrients (*i.e.* fine sediment) and aquatic habitat (*e.g.* gravel for spawning, or as habitat for aquatic invertebrates).

Issue 7: Coastal water bodies
Reservoir sedimentation reduces the amount of sediment discharging into estuaries and oceans from rivers, resulting in erosion of coast and beaches can deteriorate. Three sub-issues raise:
- *WFD* requirement of good ecological *status* for *coastal* and *estuarial water bodies*. The risk of non-achievement of this requirement is linked to the trapping of fine sediment and particulate organic matter into reservoirs, interrupting therefore food and nutrient flows essential for estuarial and costal ecosystems;
- *Functionality of river deltas*: this sub-issue is probably not common in France, with the exception of the Rhone River Delta. It is, however, widely associated with many large hydropower plants throughout the world, where the trapping of fine sediment has impacted many deltas (*e.g.* the Mekong and the Ganges deltas). The risks are erosion of deltas (*i.e.* loss of land), salt water intrusion (*e.g.* water quality), and social implications for populations living around the river deltas; and
- *Status of the coast*: where the amount of sediment discharging into oceans from rivers is reduced because of reservoir sedimentation, the risk of coastal erosion and loss of mangroves increases. This issue is not common in France.



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Hazards associated with dam or sediment management operations
This second category of sediment-related hazards can generate risks due to -operation actions (*e.g.* reservoir emptying), proactive dam operations (*e.g.* sluicing, flushing) or sediment removal (*e.g.* dry excavation, dredging)[5].

Hazard associated with reservoir emptying or similar operations
Reservoirs are generally drawn down for inspection or maintenance of the dam. Water flushing during the emptying of the reservoir releases high sediment loads with limited water volume. Two issues arising from these operations are the impact on the status of the downstream watercourses and on water uses downstream of the dam.

Issue 1: Status of downstream watercourses
Two sub-issues are outlined:
- *WFD status*: a poorly implemented drawdown operation can result in significant suspended sediment discharges into the downstream river channels. The associated risks are fish mortality (Figure 3) and degradation of habitats (*e.g.* pollution if contaminated sediment[6] is released, silting over gravel bars, surface and interstitial clogging); and.
- *Sanitary*: where the sediments in the reservoir are contaminated, an inadequately controlled drawdown operation can lead to the release of pollutants, impacting the water uses (*e.g.* domestic supply, recreational activities)[7].

Issue 2: Water uses downstream of the dam
Downstream of the dam, the main risks due to reservoir emptying are the deterioration of the quality of water for municipal or other users (*e.g.* industry, bathing, and irrigation), accumulation of sediment in heat exchangers that draw cooling water from the river, and deposition of fine sediment on the river banks reducing the quality of their recreational use.

Hazard associated with flushing and sluicing operations
Four main issues are identified:
- *Issue 1 - Status of downstream water-courses*: the associated risks are the same as those related to reservoir emptying (*e.g.* failure to achieve the WFD status, *sanitary* concerns);
- *Issue 2 - Power production*: flushing and sluicing techniques involve lowering the reservoir water levels in advance of high stream flows. The reservoir level is raised later to fill storage for sustaining releases during the low-flow season. There is therefore a direct risk in the form of less hydropower production during the flushing and sluicing operations;
- *Issue 3 - Dam operation*: evacuation of sediment from the reservoir by flushing or sluicing requires a priori organisation. The risk is the absence of qualified staff for supervising the dam operation; and
- *Issue 4 - Water uses downstream of the dam*: risks are the same as those related to reservoir emptying (*e.g.* quality of water, reduced recreational quality).

Hazard associated with dry excavation/dredging operations
Mechanical removal (dry excavation, dredging) is currently the most frequently used technique in EDF reservoirs for restoring all or part of the effective reservoir capacity (Figure 4), clearing the water intake structures, the dam outlets (*e.g.* drainage gates, spillways) and the upstream face of the dam for inspection purposes, or for preparing a drawdown operation by mechanically removing part of the accumulated fine material. Dry excavation can be classified into three categories:
- Dry excavation and dilution: the removed fine material is diluted and re-injected either into the intake structure and hydropower equipment, or bypassed through a channel around the storage reservoir;
- Dry extraction and storage of materials according to their properties (*e.g.* fine, coarse, contaminated or not) in temporary or

Figure 4. Cleaning operation at the Longefan reservoir, France. (Courtesy: EDF)

final disposal areas; and

- Dry extraction and sediment re-injection in the downstream river channel. Sediment re-injection is advantageous in that it sustains the sediment continuity, particularly for the coarse material.

Issues relating to dilution are not discussed here as they are similar to those attributed to dam operations and to those of sediment routing through the hydropower generation units. The principal risks associated with the excavation of sediment include the relatively high cost of the operation and of moving the sediment from reservoirs to areas where they would be commercially used, the need to use specific and more expensive disposal sites to store contaminated sediments, and the scarcity of sites suitable for the disposal of large volumes of excavated sediment. Because the excavation operations often involve partial drawdown of the reservoir pool, or even the shut-down of the hydropower units, there is also a risk of reduction in power supply.

Hazard associated with sediment routing through the generation units

The transport of fine and median sediments containing high levels of hard minerals (*e.g.* quartz, feldspar, tourmaline) through the hydropower generation units can cause severe abrasion of turbine parts (*e.g.* runners, wicket gates) (Figure 5), leading to inefficiencies in power generation and costly repairs.
The hydro-abrasive resistance of generation units and their penstocks with the aid of coatings is an important property requirement for the EDF hydropower plants. The selection of sustainable coating systems requires the characterization of the coating performance, which can be achieved by performing laboratory tests[8]. At EDF, for waterways not equipped with sand traps, the method for dealing with the abrasion of runners in the past was doing welding repairs. This solution was abandoned and replaced first by stellite coating, and then by High-Velocity Oxygen Fuel (HVOF) coating of the runners for both Pelton and Francis turbines.

Hazards associated with flow regulation

We have not considered any sub-type of hydrological hazard, although a distinction could possibly be made between "average" and "flood" hydrological regulations. Two main issues are exposed hereafter.

Issue 1: Hydraulic safety downstream of the installation

The reduction in flooding frequency creates two sediment-related risks:

- Excess sediment deposition at certain river channel confluences, increasing the flood risk in the surrounding areas; and
- Decrease in submersion frequency of gravel bars downstream of the dam and intense development of riparian vegetation on the bars, resulting in flood risk increases due to the reduction of the flow conveyance of the river.

Figure 5. Abrasion on Pelton runner (source: EDF)

Issue 2: Status of river channels downstream of the installation

The regulation of both average flows and floods may deteriorate the aquatic and riparian habitats downstream of the hydropower installation, due to:

- Excess sediment accumulation over some reaches, smothering invertebrate habitat and fish spawning sites; and
- Failure to achieve a good ecological status due to too much fine sediment clogging the coarse alluvial habitats.

Conclusions

Most large hydropower companies are increasingly considering reservoir sedimentation related issues and recognize the need for sustainable, economically, socially and environmentally acceptable reservoir management strategies. However, sediment management, at the dam scale, and more broadly at the watershed scale, still requires scientific knowledge of physical processes, field monitoring and numerical modelling of sediment transport from different parts of the watershed to the river reaches downstream of the dam. The relationship between sediment transport processes (erosion, transport, sedimentation, consolidation) and the functioning of aquatic ecosystems and associated riparian habitats must be well understood and taken into account in dealing with reservoir sedimentation issues.

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