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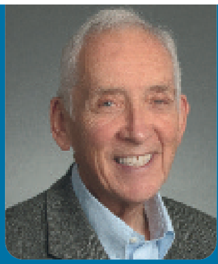
RESERVOIR SEDIMENTATION: CHALLENGES AND MANAGEMENT STRATEGIES

EDITORIAL BY KAMAL EL KADI ABDERREZZAK & ANGELOS N. FINDIKAKIS

This is the third issue of Hydrolink on reservoir sedimentation. The decision to have three issues on this subject was in response to the great interest expressed by many IAHR members and others, which also led to the formation of working research group on reservoir sedimentation, sponsored by the Hydraulic Technical committee of IAHR which will be launched formally during the 38th IAHR World Congress in Panama, September 1-6, 2019. The current issue includes articles on the methods and strategies used in different countries for dealing with the problem of reservoir sedimentation.



Angelos N. Findikakis
Hydrolink Editor

Kamal El Kadi Abderrezzak
Guest Editor

Reservoirs typically trap all the bedload and a percentage of the suspended load that depends on the ratio of the reservoir storage capacity to the river's mean annual flow. Assessing and understanding the risks associated with sediment trapping and management at hydropower facilities is an essential part of developing plans for the sustainable use of their reservoirs. As part of the hydroelectric production activities of Electricité de France (EDF), the risks generated by reservoir sedimentation and management at hydropower facilities have been assessed based on a classification by hazard, which is then broken down by the associated issues and /or sub-issues, and finally by the risks incurred. This methodology is described by Malavoi and El kadi Abderrezzak in the current issue.

The techniques to manage sediment in reservoirs include those that route sediment through or around the reservoir (*e.g*. flushing, sluicing, turbidity current venting, off-channel reservoir, bypass tunnels), those that remove sediment accumulated in the reservoir to regain capacity (*e.g*. mechanical excavation, hydraulic excavation), and those that minimize the sediment arriving to reservoirs from upstream (*e.g*. soil erosion control, check dams "*Sabo*", farm ponds, gully stabilization, revegetation). China has 98,795 reservoirs (as of 31 December 2017) with a total capacity of 941 billion m^3, but also an average annual rate of storage loss of 2.3%, the highest in the world. In this issue, Cao *et al*. describe sediment management strategies applied in China for recovering totally or partially the reservoir storage capacity, providing lessons to help guide planning and design of new dams. A mix of techniques, employed successfully, include check dams, afforestation, grass vegetation and terracing for soil and water conservation, application of the so-called reservoir operation method "store the clear and release the muddy" in many reservoirs, and hydraulic and mechanical desilting techniques to remove sediments, such as a pneumatic pump capable of handling very coarse deposits.

To understand how a reservoir behaves and how to manage it successfully, special investigations are needed to accurately determine the characteristics of sediments and their inflow rate. The sediment yield of the catchment draining in a reservoir depends on several factors, ranging from climate to geologic, topographic, and anthropogenic influences, and is subject to high degree of uncertainty. In the current issue, Francés discusses two methods used for this purpose: the Universal Soil Loss Equation, which calculates the soil erosion, and a spatially distributed, physically based mathematical model incorporating Land Use/Land Cover changes within the catchment. An example of a specific field case is presented in Zamora's article who proposes a simple method for computing the sediment yield of the Samalá river catchment in Guatemala, which has been affecting the El Canadá Hydropower plant. An off-stream regulation pond, which provides daily flow regulation for power peaking, has been losing half of its storage capacity annually due to sedimentation. Monitoring during dredging operations allowed the collection of daily data that were used to back-calculate the sediment yield.

Another specific case is the Camurí Grande basin, which was the theatre of the worst natural disaster in the history of Venezuela. The rainfall event of December 1991 triggered a huge soil mass movement (between 1.3 and 2.2 Mm^3 of sediments), causing thousands of casualties and heavy economic damage. In the current issue Sanchez and Courtel investigate numerically the adequacy of structural counter-measures (retention dams and channelization works) in reducing the consequences of debris flows on the lower parts of the Camurí Grande basin.

Dredging is a common but expensive technique for restoring reservoir storage capacity. The disposal of dredged material is an important issue. In some cases it is possible to discharge the dredged material to the river channel downstream of the dam, but in many cases this is not an option and there are constraints on land disposal. Therefore, it is important to find uses for the removed material. Potential uses of dredged fine sediments include habitat development, agriculture and construction. EDF is exploring different such options. Menu *et al*. describe past and ongoing work investigating the technical conditions and sediment properties required for pre-selected beneficial industrial reuses of the dredged material (*i.e.* roadway bed material; ceramic material, concrete or mortar; Portland cement clinker; agricultural amendment, soil construction and strip mines), without adverse impacts to the environment and public health.

The problems associated with reservoir sedimentation are the subject of ongoing research. For example, the Hydraulic Constructions Platform PL-LCH of the Ecole Polytechnique Fédérale de Lausanne is conducting experimental, numerical and in-situ research on innovative methods to cope with the accumulation of fine sediment in pumped-storage hydropower plants. PL-LCH is working on two solutions: operational reservoir stirring and forced stirring for maintaining fine sediment in suspension for subsequent routing downstream through the hydropower waterways. The first solution uses the inflow and outflow in the reservoir to maintain turbulence levels that prevent fine sediment settling. Forced stirring uses the specially developed SEDMIX water-jet device which has been tested in the laboratory and is now entering the phase of proof-of-concept at a prototype scale. PL-LCH has also proposed new design criteria for dam bottom outlet structures to optimize the efficiency of current turbidity venting operations, as described in the article by De Cesare *et al*.

Despite significant advances in understanding the physical processes, many questions remain. This includes questions on the mechanisms of flow and sediment transport within reservoirs, the migration of delta fronts, which may reach the dam, the formation and movement of turbidity currents, and the creation of dead-water regions, which are propitious areas for sediment deposition. Expanding data collection programs is essential for understanding reservoir sedimentation and assessing strategies for sustainable management. Improved measuring can contribute to developing more reliable estimates of sedimentation rates.

Morphodynamic numerical models are popular tools that are used to estimate sediment transport patterns in reservoirs and to solve related engineering problems. They can be used to simulate long-term reservoir sedimentation, to define operational rules for sediment downstream routing, to quantify the possible amounts of sluiced/flushed sediment under different conditions, and to determine the appropriate location and capacity of bottom outlets. However, still many processes (*e.g*. consolidation of cohesive sediments, mud-sand interactions) are not described well numerically, and are mostly accounted for using empirical relationships. One- or two-dimensional models cannot simulate the complex flow and sediment transport processes near bottom outlets during the initial stage of flushing, sluicing and turbidity current venting operations. This calls for the use of three-dimensional models. ■

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Cover picture: Génissiat Reservoir on the Rhône River in France; the dam was commissioned in 1948; photograph taken by Camille Bezzina during 2012 sediment sluicing operation. (Courtesy Christophe Peteuil, CNR)

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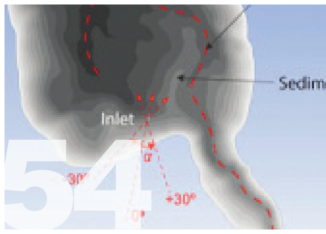
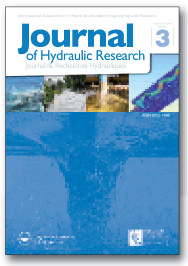


JHR's Impact Factor is now 2.974



The annual Journal Citation Reports released on June 20 show that the impact factor of the Journal of Hydraulic Research (JHR) increased to 2.974. The impact factor of an academic journal is an index that reflects the yearly average number of citations to recent articles published in that journal. It is viewed by many as a proxy for the relative importance of a journal within its field. The steady rise of JHR's impact during the last few years, even though not a goal in itself, is clearly both a reflection and by-product of the focus of its current Editor Mohamed S Ghidaoui and his predecessor Vlad Nikora, as well as the team of the Associate and Assistant Editors, reviewers, and IAHR officers on one single measure: quality! This focus has led to a steady rise in quality manuscripts being submitted which were further enhanced by quality reviews from the JHR team. Our pledge to potential authors is that the focus of JHR will remain quality over everything else.

RESERVOIR SEDIMENTATION MANAGEMENT IN CHINA

BY WENHONG CAO, CHUNJING LIU & LEILEI GU

Chinese reservoirs face severe sedimentation problems due to the heavy sediment load of the rivers in north China. Long-term management of sediment accumulation for sustainable use of reservoirs has become essential part of the effort to solve water shortage issues. With nearly 70 years of efforts dealing with reservoir sedimentation, especially in the Yellow river region, which has the highest annual sediment transport load in the world, China has got extensive experience upon which to draw lessons. This article summarizes lessons learned on sediment inflow reduction measures, reservoir operation modes and technologies for recovering totally, or partially the reservoir storage capacity. The article is complementary to other articles in this and previous issues of Hydrolink on reservoir sedimentation, such as those by Kondolf and Schmitt, Annandale *et al.*, Kantoush and Sumi, Lyoudi *et al*. Wang and Kuo, who present diverse experiences and policies in managing reservoir sedimentation.

Silting of Chinese dams: facts

There are 98,795 reservoirs (as of 31 December 2017) with a total capacity of 941 billion m^3 in China. These reservoirs not only supply water to 22% of the world's population, but also play an irreplaceable role in mitigating floods and droughts, maintaining ecological balance, as well as ensuring power generation, water supply for irrigation, and navigation. In China, the global storage capacity of reservoirs is diminishing because of sedimentation with the average annual rate of storage loss being 2.3%[1], the highest in the world, and many large reservoirs in China having already passed their half-life[2].

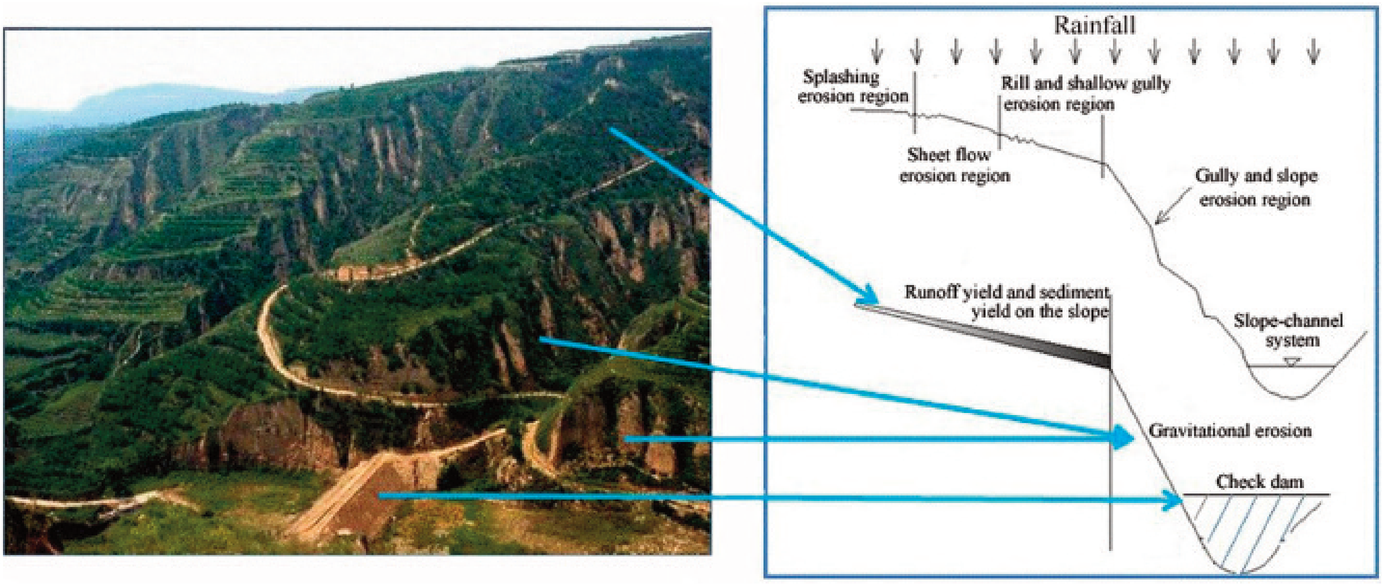
Sedimentation directly affects the benefits derived from the reservoirs, as already mentioned in several of the articles published in the two previous issues of Hydrolink on this subject. In addition, clear water released from the reservoir results in erosion of downstream river channels, which in turn gives rise to riverbank erosion and embankment/dike safety issues. Drought and flood disasters are getting more and more acute in China, exacerbated by global climate change, resulting therefore in a growing demand for long-term maintenance, sustainable use of the storage capacity of existing reservoirs and for the recovery of storage capacity loss due to sedimentation. In China, the concerned water authorities along with academia have always attached great importance to the study of reservoirs silting. They have gradually established a systematic strategy for combating reservoir sedimentation, mainly by using the following three techniques:

- reducing incoming sediment yield into reservoirs through soil and water management and conservation in watersheds;
- managing sediment within reservoirs through suitable dam operating modes (*e.g*. flushing, sluicing, turbidity venting) or bypassing part of the incoming sediment-laden waters around the reservoir to downstream reaches; and
- removing deposited sediment from reservoirs by mechanical techniques (*e.g*. dredging, dry excavation or hydrosuction).

Reducing sediment inflows

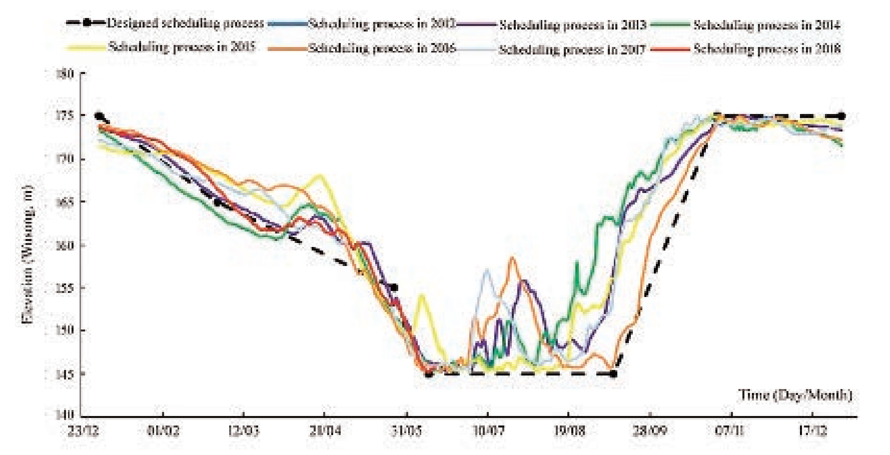
Sediment inflows into reservoirs originate from soil erosion in the watershed of the reservoir, which can ultimately be reduced through soil

Figure 1. Check dams and slope-gully system



and water management, as well as through protection and restoration of natural vegetation. China has been interested in developing integrated solutions for watershed management, treating small watersheds as individual units (dozens of square kilometers) accounting for local conditions and aiming at optimal allocation of engineering, biological and tillage measures as well as comprehensive management of the mountain, water, field, forest, road and rural environment. As the result of such strategies, soil erosion has decreased, while the utilization and productivity of land resources has improved.

Figure 2. Seasonal pool operation at the Three Gorges Reservoir



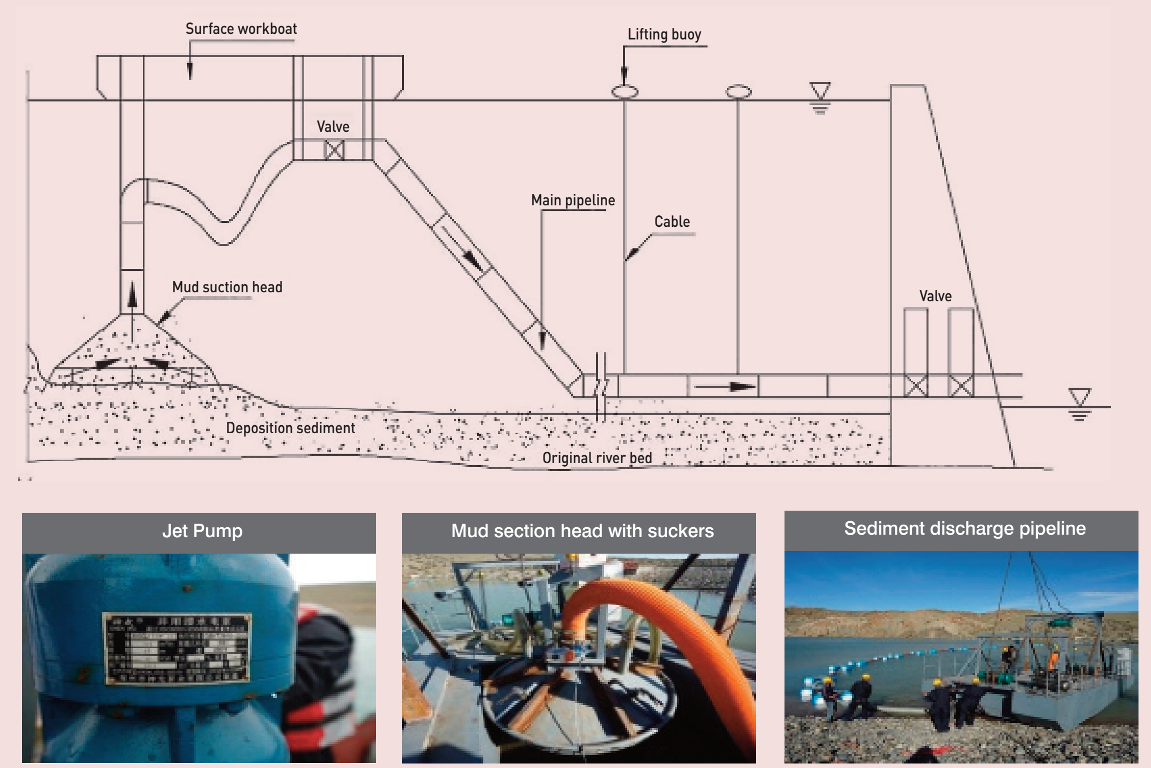
In the Loess Plateau (640,000 km^2), check dams, forest, grass vegetation and terracing are the three major measures for soil and water conservation (Figure 1). When the vegetation coverage is below 50%, the effect of increasing vegetation coverage on sediment reduction is noticeable. When the vegetation coverage exceeds 60%, the effect of further increase in vegetation cover on sediment reduction tends to be small[3]. More than 100,000 check dams have been built since 1950s in the Loess Plateau, intercepting 21 billion m^3 of sediments[4], reducing the slope of the gully channel systems to diminish their transport sediment capacity and forming fertile farmland terracing in the areas between dams. These terraced fields are basic agricultural farmlands in hilly areas, very important for improving the lives of local people. Farmland terracing changes the sloping fields into flat lands, reducing therefore the amount of soil and water losses. Leveled terraced fields not only significantly reduce their sediment yield, but also intercept sediment from the upper reaches and reduce the sediment yield in the gullies downstream by inhibiting slope runoff generation[5].

Soil and water conservation has been one of the most important mitigating strategies for reservoir sedimentation since the construction of the Sanmenxia dam in 1950s. Although it is difficult to determine the direct benefits of such strategy, it is clear that after sixty years of soil and water conservation efforts, the annual sediment load carried by the Yellow River has dropped down from 1.6 billion tons in 1950s to 0.15 billion tons since 2000, reducing therefore the sediment inflow into the Xiaolangdi reservoir as well as other small reservoirs in the Yellow river basin.

Optimizing reservoir operation modes

China's Water Conservancy science and technology staff has explored and put forward the application of the reservoir operation

Figure 3. Schematic diagram of self-suction sediment discharge piping system



method described as “store the clear and release the muddy”, which has successfully solved the problems of sediment deposition in many reservoirs and played a very important role in achieving sustainable use of many reservoirs, such as the Xiaolangdi, Three Gorges, Xiangjiaba and Sanmenxia reservoirs. The operational mode of “store the clear and release the muddy” consists of keeping a low water level in the flood season with high sediment content to maximize flow velocity and sustain sediment transport through the reservoir (i.e. sluicing). The reservoir level is raised later in the season to ensure that only the water with lower sediment concentration be stored in the reservoir. Figure 2 shows the operation mode at the Three Gorges Reservoir, where 115 million tonnes of sediment have been retained each year since 2003[6]. According to the preliminary design, the flood control level is at elevation145 m during the annual flood season between mid of June and end of September, in which period about 90% annual sediment transported each year[6]. After the beginning of October, the reservoir water level gradually rises to reach the normal pool level at elevation 175 m to satisfy the power generation and shipping requirements. The water level is drawn down again to elevation 145 m in early June to create conditions favoring sediment flushing and sluicing. In addition, storing clear and releasing muddy depends on the reservoir, and the effectiveness of this operation depends also on the upstream runoff and sediment inflow, the gate elevation and opening, as well as the downstream discharge flow.

The strategy of storing clear water and discharging muddy flow must take into account many other factors such as flood control, water supply, power generation, shipping, ecological benefits, and the impact of the reservoir water uses on upstream and downstream . This requires continuously predicting and evaluating the effects and benefits of the actual operation mode, and exploring how to optimize the operating rules for the gates. In recent years, the specific rules for storing clear water and releasing muddy flow have been further optimized and refined[7] to meet the sustainable development of the society and the economy, under the condition that the flood risk can be well controlled and the sediment deposition within the reservoir is permitted. For example, some experimental operations and works have been carried out in the Three Gorges Reservoir, such as storing

Figure 4. Sediment concentration in the discharge piping system at the Xiao Liu Gou reservoir

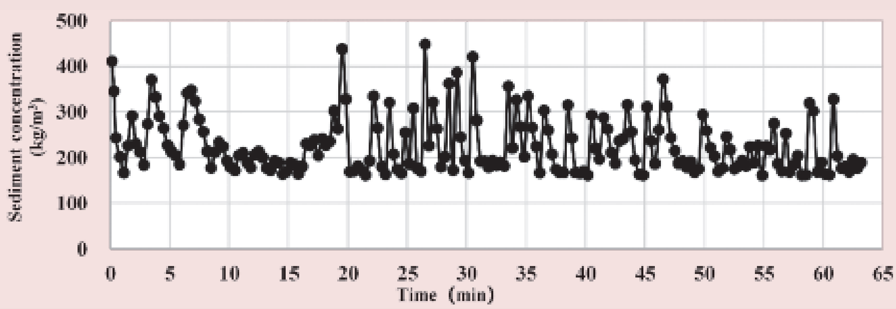
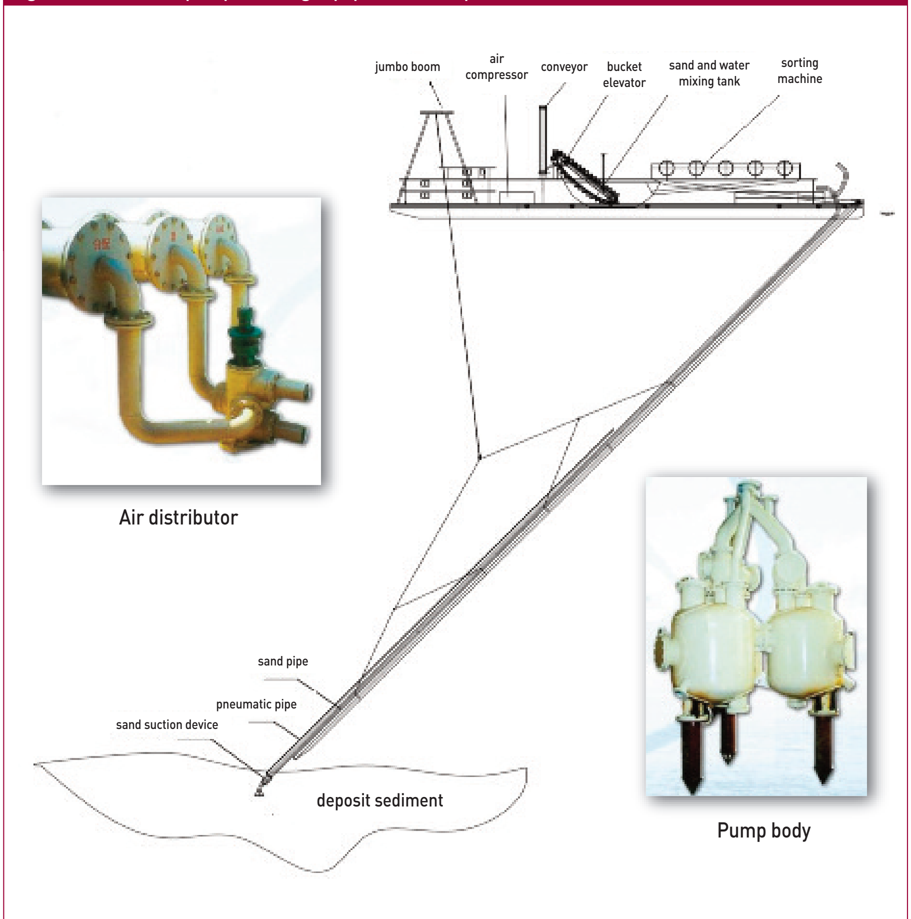


Figure 5. Pneumatic pump desilting equipment in deep water



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water earlier than before the end of the flood season (from mid-June to late September), controlling small and medium floods of less than 55 000 m^3s^{-1} during the flood season, silt control at the tail (upstream end) of the reservoir, and ecological operations. Since the first ecological operation of the Three Gorges Reservoir in 2011, twelve ecological operational experiments have been carried out in eight consecutive years, creating suitable flow conditions for fish spawning, promoting fish breeding in the downstream reaches.

Recovering the storage capacity

Hydraulic and mechanical desilting techniques are commonly used to remove sediment from reservoirs for recovering partially, or totally the initial storage capacity. Setting sediment discharge pipes, or self-suction sediment-piping system from the reservoir to the downstream reaches takes advantage of the head difference between upstream and downstream of the dam. A mud suction head is installed at the pipeline inlet, and the sediment is hydraulically sucked into the pipe and then discharged out of the reservoir (Figure 3). This technology needs a suction head with high capacity and efficiency for inhaling the high-density silt in the reservoir. Because of the limited working range of the suction head, it is necessary to move the head of the pipe up and down, or left to right depending on the sediment deposition conditions.

In recent years, the self-suction sediment piping technology has been improved. For instance, the Yellow River Institute of Hydraulic Research (YRIHR) carried out numerical simulations and experiments on the efficiency of suction heads. From August to October 2017, the YRIHR conducted more than 30 field desilting tests at the Xiao Liu Gou Reservoir in Hami City in the Xinjiang Uygur Autonomous Region. The equipment layout and operation mode were optimized, with the average sediment concentration outlet reaching 247 kg/m^3 in approximately 2 to 3 hours (Figure 4).

Pneumatic pump desilting technology uses high-pressure air through a special release mechanism in the pipeline, forming a strong and continuous suction force in the pipe. The Jiang Yin Water Conservancy Mechanization Engineering Company Ltd has developed a series of deep-water pneumatic pump desilting equipment, suitable for various types of coarse deposits (diameter lower than 1 m), operating at a maximum depth of 120 m with a dredging capacity of 300 m^3/h. The principal components of the pneumatic desilting system are shown in Figure 5. The compressed air is continuously released into the head of the acquisition device through the pressure-resistant pipe, and then released into the material pipe, resulting in the pressure outside the material pipe being greater than the pressure inside the pipe. Under the action of this pressure difference, sediments near the mouth of the material pipe are sucked and transported to surface ships or pipelines. Four material pipe diameters are available, 0.20 m, 0.35 m, 0.60 m and 1 m. The pneumatic pump desilting technology has been successfully applied in many sites in China, including the Zhentouba Reservoir in the Dadu River, the Jinping-II hydropower station in the Yalong River (Figure 6) and the Longkou reservoir in the Yellow River (Figure 7).

Acknowledgements

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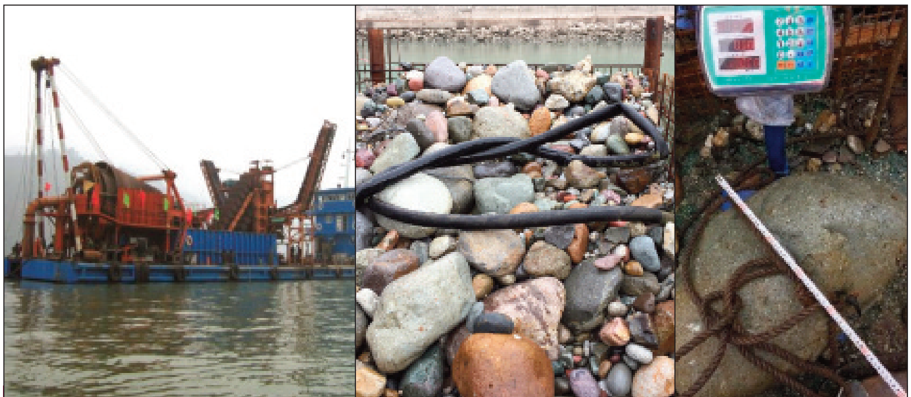

Figure 6. Jinping-II hydropower station in the Yalong Rive - Dredging operation showing the barge and removed material

Figure 7. Dredging project of the tailrace canal of the Longkou reservoir in the Yellow River. The material diameter was 1 m.

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IMPROVED ESTIMATION OF LONG TERM SEDIMENT INPUT TO RESERVOIRS

BY FÉLIX FRANCÉS

One of the factors to be considered in the design of a new dam, or in the re-assessment of an existing one, is its reservoir siltation (Figure 1). Reservoir siltation is important, and in some cases crucial to surface water management, because it affects the lifetime of the dam and, therefore, the required direct and indirect investments for maintaining the long-term dam functionality. There are many examples all around the world of dams out of operation few years after their construction. One such dam is the Doña Aldonza dam built in the 1950's on the Guadalquivir River, Spain. The dam, 32 m height with initial reservoir storage of 23 Mm^3, was fully-silted in less than 20 years due to a mean siltation rate higher than 1 Mm^3/year.

Reservoir siltation involves two main factors, namely i) the sediment yield entering the reservoir from the upstream catchment (a hydrological problem) and ii) the sediment trapping and deposition within the reservoir (a hydraulic problem). Both are equally important, but the sediment yield remains less well understood than the process of reservoir sedimentation. This article focuses on the catchment sediment delivery into a reservoir.

The best way to evaluate, quantify and predict soil erosion and sediment transport at catchment scale is through mathematical modelling. The traditional model used in engineering practice for calculating the catchment soil erosion is the well-known Universal Soil Loss Equation (USLE)[1]. This empirically-based lumped equation and most of its variants are used to calculate soil erosion as a function of the physical characteristics of the watershed. The resulting sediment production is often considered as the sediment yield into a reservoir. However, the USLE gives only annual mean value for the sediment yield, it is fully empirical and it does not account for transport and deposition within the catchment. A proper model for the estimation of catchment sediment yield needs to be distributed in space and be as much physically based as possible, where sources and sinks of sediments, connectivity and storage processes can be included.

On one hand, distributed models can reproduce not only the temporal, but also the inherent spatial variability of inputs (e.g. precipitation, temperature) and basin hydrological characteristics, include connectivity into the model conceptualization, provide important information about sediment transport, erosion and deposition zones, and incorporate Land Use/Land Cover (LULC) changes within the catchment. Using a distributed model, a map can be obtained (Figure 2), locating clearly the main sources of sediment in the watershed. Distributed models help decision-makers identify spots where interventions are necessary to prevent sediment from reaching the reservoir, and optimize future mitigation actions (*e.g.* reforestation areas, check dams, retention basins, bypass channels).

On the other hand, physically based models (or at least with physically sound parameters) have a better predictability than empirical or statistical models. Unfortunately, it is not possible to describe mathematically all physical processes involved in soil erosion, sediment transport and deposition (*e.g.* influence of vegetation cover). Therefore, some processes must be described empirically and, for this reason, parts of USLE still are and will still be in use in the near future.

Reservoir siltation has been used since the 1950s to estimate the catchment sediment yield. This approach not only requires accurate and repeated surveys of the reservoir bathymetry, but also needs estimates of the amount of untrapped sediment and the temporal evolution of the density of deposited sediments within the reservoir. All these data are highly valuable for the calibration and validation of mathematical

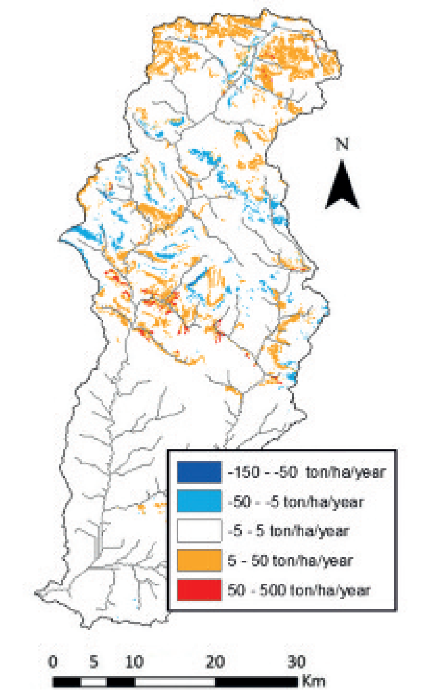
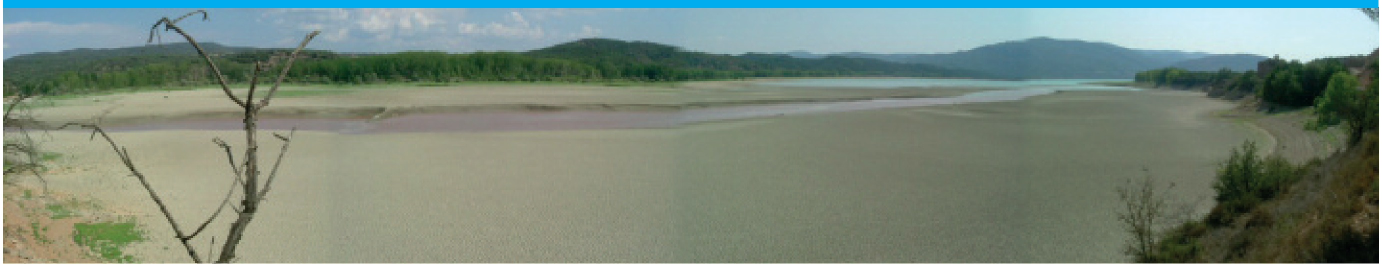


Figure 2. Spatial differences in soil erosion rate in Esera River's catchment (Barasona Reservoir is located near the outlet) between a future climate scenario and present climatic conditions.

Figure 1. General view from upstream of Barasona Reservoir in Spain. The Barasona Dam was commissioned in 1932 with an initial capacity of 71 Mm^3, increased up to 92.2 Mm^3 in 1973. Some flushing and dredging operations were conducted in the 1970's and 1990's, and nowadays the live storage capacity of the reservoir is estimated to be around 70 Mm^3



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models[2] (Figure 3). Moreover, not only data from large reservoirs can be used, but also from smaller reservoirs, such as check dams or irrigation and water supply ponds, which can be a valuable source of information[3].

Actually, the lifetime of a reservoir is a random variable, since catchment soil erosion depends non-linearly on the magnitude of flood events, as it can be clearly seen in the jumps of reservoir storage evolution in Figure 3. If the topography and soil characteristics of a catchment are fixed in time, the sediment yield cycle will depend on climatic conditions and LULC. In most cases, these two drivers have changed over time in the past and will continue doing so in the future.

The effect of climate change on sediment yield is related to the spatial-temporal changes in rainfall patterns that can produce increased rainfall erosivity. During the last fifteen years, distributed models have been coupled with downscaled future climate scenarios and used to assess the impact of climate change on the sediment cycle at the catchment scale. One good and recent example is the application of the TETIS model[4] on the Yi'an catchment in China[5]. The modeling results for the four Representative Concentration Pathway (RCP) scenarios for climate change relative to the present conditions under the same LULC indicate an increase in water discharge in all cases (higher by 71.4% for RCP 8.5) and a more pronounced increase in the sediment yield (170% for RCP 8.5). This implies an amplification of the impact of climate change on sediment yield compared with its impact on the water cycle. In a similar study on the Barasona Reservoir in Spain (Figure 1), which is in an area with semiarid climate and has experienced severe historical siltation problems, it was found that a general reduction of future water resources due to a decrease in precipitation and increase in temperatures should be expected. In this area, all climatic models predict an increment of precipitation torrentiality, but this does not translate into an increase in the sediment yield. This is due to a decrease in soil moisture at the beginning of the storm events, reducing the runoff and erosivity[2]. In other words, the present expected lifetime of the dam is not expected to change significantly in the future due to climate change. It should be underlined that this conclusion would not have been reached without considering the interactions described above using a proper model. LULC and cropping management are also key factors affecting the catchment soil erodibility. Changes in LULC will impact the catchment sediment yield. One interesting case study is the Upper Citarum catchment in west Java (Indonesia), draining into the Saguling Reservoir, which was commissioned in 1985 with a storage capacity of 889 Mm^3. This reservoir plays a crucial role in Indonesia, supplying water and hydroelectricity for the region. Severe LULC changes within the catchment have resulted in significant increase in the sediment yield to the Saguling Reservoir. The observed reservoir sedimentation rate has increased over time, reducing the storage capacity from 889 Mm^3 in 1985 to 779 Hm^3 in 2014, *i.e.* a mean siltation rate of 3.7 Mm^3/year.

To analyse this problem from the LULC changes point of view, the TETIS model was also used. Three different LULC scenarios with present climatic conditions were tested: two historical scenarios, corresponding to years 1994 and

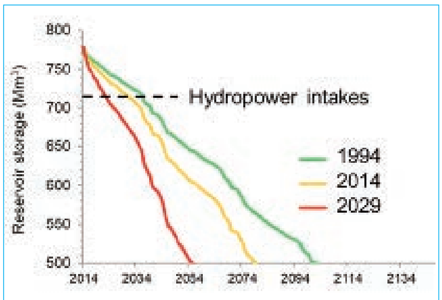
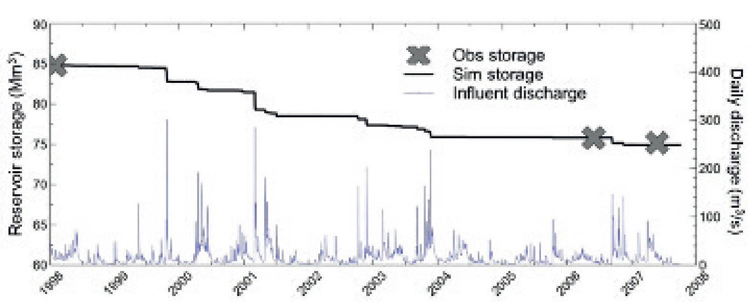


Figure 4. Storage evolution of the Saguling Reservoir in Indonesia for different LULC scenarios: past (corresponding to year 1994), present (2014) and projected LULC for year 2029

2014 and one forecasted scenario using a multi-layer perceptron neural network for the horizon 2029[6]. The differences in sediment yield are significant, decreasing the expected lifetime of the reservoir from 239 years predicted with the 1994 scenario to 113 years predicted with the 2029 forecast; *i.e.* LULC changes can reduce the lifetime of the reservoir by a factor of two. The energy production is threatened also, because the elevation of the hydropower water intakes corresponds to the reservoir storage capacity of 722 Mm^3 (dotted line in Figure 4), which means that problems could be expected in less than twenty years for the worst-case scenarios.

It is clear that climate change and LULC changes will affect the runoff and sediment yield in a catchment. Depending on the case, the impact can be more, or less significant and it is not possible to assess *a priori* which of these two factors, climate or LULC, will have the greater impact and in which direction (positive or negative). The good news is that there is an opportunity to use proper LULC management to mitigate the negative impacts of climate change on water flows and sediment yields. ■

Figure 3. Simulated reconstruction of the historical storage evolution of Barasona Reservoir, Spain, using TETIS model



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ESTIMATING SEDIMENT YIELD FROM A SEDIMENT BALANCE IN THE OFF-STREAM REGULATION POND OF EL CANADÁ HPP, GUATEMALA

BY JAVIER ZAMORA

The extent of storage loss in a reservoir due to sedimentation depends on a number of factors, including the sediment yield of the river catchment. A method for estimating the sediment yield in the catchment of the Samalá River in Guatemala was developed using sediment data collected from the off-stream regulation pond of El Canadá Hydropower plant (HPP). The method consists of a back-calculation of the sediment load based on a sediment balance in the pond and the sediment load distribution along the power plant facility.

Background

The Samalá River is on the Pacific side of Guatemala (Figure 1). The river supplies water to El Canadá hydropower plant (HPP), a 47 MW run-of-river facility (Figure 2). The upper part of the river catchment, above the water intake of El Canadá HPP, covers 822 km^2 of land and includes Quetzaltenango, the second largest city in Guatemala. The sediment yield in the catchment is high because of four volcanoes, one of which is still active, uncontrolled human activities (*e.g*. agriculture, rock extraction, illegal dumps), and high rainfall, with very intense precipitation during large storms.

The high sediment yield of the catchment has been affecting the power plant since its commission in 2003, especially the 200,000 m^3 off-stream regulation pond which provides daily flow regulation for power peaking. (Figure 3). Approximately 100,000 m^3 of sediment accumulate annually in the pond, which means that the pond could be fully silted in 2 years if deposits are not removed. The fine, highly cohesive sediment deposit contains garbage and debris, affecting greatly the power plant operation (Figure 4 and Figure 5). Several strategies have been implemented to reduce the sedimentation, including removal of sediment deposits from the pond using conventional hydraulic and hydro-suction dredging techniques.

A monitoring strategy was developed during the dredging operation, allowing the collection of daily relevant sediment-related data over the last 7 years. This data is used to describe changes in water storage capacity of the pond and to estimate watershed sediment yield.

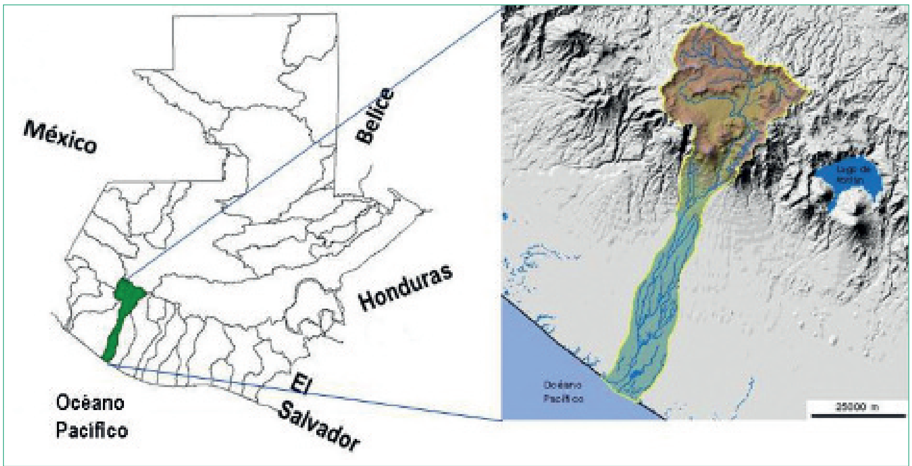

Figure 1. Location of Samalá catchment (Source: Cedepem[1])

Figure 2. El Canada HPP general arrangement

Figure 3. Off-stream regulation pond of El Canadá HPP

Figure 4. Silting in the off-stream regulation pond in 2011 (Source: El Canadá HPP)

Figure 5. Nozzle wear of the El Canadá HPP turbine due to abrasive sediment particles (Source: El Canadá HPP)

Method Of Estimating Sediment Yield

Sediment yield, commonly expressed in tons or cubic meter per year (t or m^3/year), is defined as the annual amount of sediment transported by a watercourse at a specific point, in a specific catchment area. The sediment yield per unit of drainage area is the sediment yield rate (t or m^3/km^2-year). A common approach for estimating sediment yield of a drainage area is based on empirical relationships, such as the Universal Soil Loss Equation (USLE)[2].
Sediment yield can also be estimated directly by measuring sediment concentrations travelling through the drainage network to a downstream measuring or control point. However, these approaches may underestimate the sediment yield because they do not consider bedload and temporal and spatial variability of sediment transport. A more accurate approach is to survey sediment deposition directly into traps, but this method is not commonly used due to the required infrastructure and its maintenance. Conveniently, surveys of the regulation pond for determining the loss of storage capacity are available as part of the operational data from El Canadá HPP.

A methodology for estimating sediment yield from traps in the river was proposed by Verstraeten and Poes[3]. Nevertheless, the El Canadá case is complex due to the location of off-stream pond which receives only a portion of the deviated river flow at the intake. The measured sediment deposition in the pond represents only a portion of the total catchment sediment load.

The sediment yield can be estimated as:

$$SY = \frac{SD}{TF} \quad (1)$$

where *SY* is the sediment yield rate in t/year, *SD* is the annual quantity of sediment deposited in the pond (t/year) and *TF* is the Trapping Factor which is defined as the ratio of the deposited sediment in the pond to the total sediment inflow.
The sediment inflow estimated at the off-stream regulation pond does not account for the sediment load not trapped between the river and the pond (Figure 6), namely:

- The run-of-river power plant designed to let bedload travel through the intake.When the river flow discharge exceeds the design discharge of the HPP, the portion of the suspended sediment transported by the overflow does not enter the power plant, especially during floods, because the power plant stops production.

Figure 6. Distribution of sediment load at the headworks (left) and the pond (right) of El Canadá HPP

- The de-sander, located immediately after the intake, retains particles larger than 0.2 mm in diameter. This trapped sediment is often flushed back to the river.
- The regulation pond has a trapping efficiency, *i.e.* part of the incoming sediment continues through the pond outlet and the power house.

The Trapping Factor *TF* for the run-of-river configuration of El Canadá HPP is defined as:

$$TF = (1 - BL) \times (1 - 2 \times OF) \times (1 - TE_D) \times TE_P \quad (2)$$

where *BL* is the bedload portion of the total load, *OF* is the ratio of the overflow volume to the total water volume, TE_D is the desander trapping efficiency, and TE_P is the pond trapping efficiency. Sediment transport occurs mainly during flood events. This is accounted for in Eq. 2 by using a factor of two for the Overflow parameter *OF*.

Two main assumptions were made in this calculation: firstly, the Santa María reservoir, located upstream of El Canadá's intake, is assumed to be in balance, which means that it has no significant impact on the sediment routing through the Samalá River. Secondly, the river grain size distribution is assumed to be similar to the distribution found by Chao and Ahmed[4].

Calculation of sediment deposition (*SD*), bedload portion (*BL*), overflow portion (*OF*), and Trap efficiency (TE_D, TE_P)

The annual volume of sediment deposition within the pond (*SD*) was estimated by adding up the sediment deposit, measured from bathymetric surveys, and the sediment volume removed by dredging. The bathymetric surveys are performed at least once per year, using an optical light method. Daily dredging is performed continuously during the whole year. Both measurements were done under different sediment compaction conditions. The sediment in the pond accumulated for several weeks or months and was subject to frequent drawdown operations. Measurements on the dredged sediment, were, however, performed only after 24 hours of deposition; the dredged sediment is less compacted than the sediment deposit in the pond. Using laboratory tests, the dry bulk density of the dredged sediment was 0.48 t/m^3.

Values of initial (first-year) bulk density (*i.e.* specific weight) of sediment deposited in the pond was estimated by the Lara and Pemberton[5] method based on the inflowing particle size distribution and reservoir operation. This method requires that reservoir operation be classed into one of four categories[5]: (1) sediment always submerged or nearly submerged such that dewatering does not occur, (2) moderate to considerable drawdown during normal reservoir operation resulting in periodic dewatering of the sediment, (3) reservoir normally empty such as in a flood detention structure, and (4) riverbed sediment. The sediment composition must also be divided among the sand, silt, and clay fractions. Some 1,300 samples from USA reservoirs were statistically analyzed by Lara and Pemberton[5] for determining the initial (first-year) bulk density r_b as:

$$r_b = r_c p_c + r_m p_m + r_s p_s \quad (3)$$

where p_c, p_m, and p_s are the percentages of clay (c), silt (m), and sand (s), respectively, for the deposited sediment; and r_c, r_m and r_s are the initial bulk densities for clay, silt and sand, respectively. Values for r_c, r_m and r_s were proposed by Lara and Pemberton[5] according to the reservoir operation (Table 1). Periodic drawdown operations are performed at the Canadá HPP regulation; r_c = 561 kg/m^3, r_m = 1140 kg/m^3, and r_s = 1550 kg/m^3 (Table 1).

Table 1. Values of initial bulk density for use in Lara-Pemberton Equation[5]

Reservoir operational condition	Initial weight (kg/m^3)		
	r_c	r_m	r_s
Continuously submerged	416	1,120	1,554
Moderate to considerable drawdown	561	1,140	1,554
Normally empty reservoir	641	1,150	1,554
Riverbed sediment	961	1,170	1,554

Table 2. Sediment balance at the off-stream regulation pond (t/year)

Year	Deposited in the pond	Removed by Hydrosuction	Removed by Diesel	Total sediment income to the pond
2011	87,447	-	-	-
2012	95,274	139,634	8,477	155,938
2013	65,666	118,012	19,603	108,007
2014	58,920	99,041	17,538	109,833
2015	36,461	125,597	237	103,36
2016	36,093	121,824	7,721	129,175
2017	51,849	75,020	5,027	95,804
			Average	117,022

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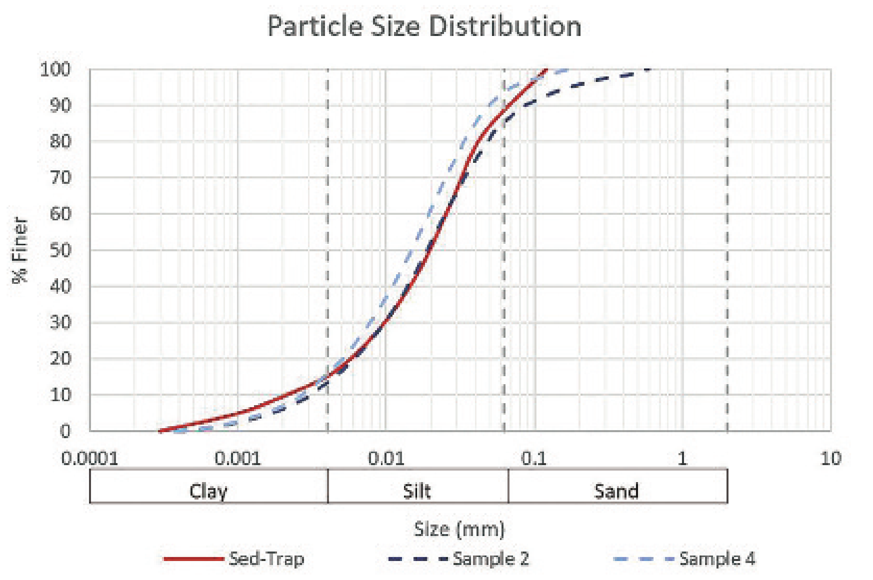
The percentages p_c, p_m, and p_s are 15%, 75%, and 10%, respectively, according to particle sampling in the pond. The dry bulk density of the sediment deposited in the pond is therefore r_b = 1.09 t/m^3.

The hydrosuction dredge flow discharge was 1,000 m^3/h and the annual average sediment concentration varied from 7.2% to 10%. The conventional diesel dredge flow discharge was 450 m^3/h with an average sediment concentration of 6%. Table 2 summarizes the different estimated sediment weights (tons) and the total sediment income for years 2012 to 2017. On average, 117,022 tons accumulated in the pond every year, corresponding to an annual average volume of 107,108 m^3. This is approximately 50% of the storage volume of the pond. Bedload data at the catchment scale is scarce. Earlier measurements of suspended load in different periods between 1964 and 1988, and bed load measurements in 1992, performed at few kilometers upstream of the power plant, showed that bedload was 27% of the total load. Values of bedload from 5% to 30% or more are commonly used[2,6]. In the current case, sediment transport occurs mainly during floods; *BL* = 20% was therefore chosen for the calculation. The overflow percentage *OF* was obtained from the duration curve and the design discharge (15 m^3/s) of El Canadá HPP; *OF* was equal to 19.6%.

Figure 7. Comparison of particle size distributions estimated with Sed-Trap and sampled at the regulation pond



The one-chamber de-sander has a flow discharge of 15 m^3/s, a net depth of 6.3 m, a width of 12.2 m and an effective length of 85 m. The pond has the same discharge, a width of 200 m, an effective length of 180 m, but the depth varied accordingly to the sediment deposits. From 2009 to 2017, the average depth at high regulation water levels was 5.8 m. In addition, the pond was drawdown daily to the level of the sediment deposits. Therefore, the net depth was defined as half of the average water depth, *i.e*. 2,9 m.

The trapping efficiency of the desander, TE_D, and of the regulation pond, TE_P, were calculated using the 2D Sed-Trap numerical model[7], a simplified version of the 3D code SSIM, an open source software developed by Nils Reidar Olsen[7]. Sed-Trap calculates the particle fall velocity using a log-law distribution. The main inputs required are the discharge, the specific weight of sediment and their grain size distribution, the geometry of the basin, and the Manning coefficient. The river grain size distribution was assumed similar to the distribution found by Chao and Ahmed[4] from a river with similar characteristics in Pakistan (*e.g*. steep, mountainous, large sediment transport capacity). The grain size distribution was described using percentiles (*i.e*. d_{10}, d_{20}, …, d_{100}).

The Sed-Trap model was set up first for the de-sander chamber, using the particle size distribution. This calculation allowed the estimation of the particle size distribution of the sediment passing the de-sander, which are those reaching the pond. The calculated grain size distribution reaching the pond was compared to

Table 3. Sediment yield (t/year) obtained by back-calculation

Year	Sediment deposited	Sediment Yield
2012	155,938	770,201
2013	108,007	533,465
2014	109,833	542,484
2015	103,376	510,588
2016	129,175	638,017
2017	95,804	473,192
	Average	577,991

two field samples (Figure 7), showing a remarkably agreement.

The trapping efficiency was calculated for each grain size. The overall trapping efficiency was calculated by adding the trapped portion of each grain size. The resulting trapping efficiency was TE_D = 25 % for the desander and TE_P = 55.5 % for the pond.

Calculation of the Trapping Factor, TF, and Sediment Yield SY

The Trapping Factor in the pond *TF* calculated from Eq. 2 is 20.2 %. The sediment yield *SY* calculated using Eq. 1 (Table 3) ranges from 770,201 t/year in 2012 to 473,192 t/year in 2017; the average sediment yield is approximately 578,000 t/year. Knowing that the catchment area is 822 km^2, the sediment yield rate is 703 t/km^2-year. These values are within the expected range, but still higher than previous estimates. The back-calculation method estimates the sediment yield from reliable *in-situ* measurements. This method can be used to calibrate empirically based models, such as the USLE model. This model or its variants are widely used for analyzing the impacts of climate change and land use on the watershed erosion and reservoir sedimentation. The calibrated model would allow foreseeing the sediment yield in the mid and long-terms, thus helping decision-makers plan appropriate countermeasures.

Acknowledgment

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EVALUATION OF SEDIMENT CONTROL WORKS IN THE CAMURÍ GRANDE BASIN, VARGAS STATE, VENEZUELA

BY KAROL SANCHEZ & FRANÇOIS COURTEL

The Camurí Grande basin in Venezuela was strongly affected by the debris flow event of December 1999. Channelization works and six sediment retention dams were built in the upper parts of the basin as structural countermeasures. The influence of these works on the safety of the lower areas was studied by applying a two-dimensional numerical model. The numerical model allowed estimations of the amount of sediments retained by the existing dams according to different silting conditions. The model also evaluated the influence of the dams on the lower areas through a comparison of hazard maps.

The Camurí Grande basin is in the Vargas state, Venezuela. This mountainous basin has an area of 42.6 km^2, above the confluence of the Camurí and Migueleno rivers, which converge before discharging to the Caribbean Sea (Figure 1). The steep upper area of the basin is part of the Ávila National Park. The alluvial fan has been occupied since the 1960's by households, educational institutions, and recreational places. The Camurí Grande basin is a site of episodic, rainfall-induced landslides (mostly debris flows) and flash floods carrying extremely high sediment loads.

The Camurí Grande basin was affected by several debris flow events. The most severe one occurred in December 1999[1], a catastrophic event with a return period of approximately 500 years, a maximum flow discharge of 880 m^3/s and a transported sediment volume estimated between 1.3 Mm^3[2] and 2.2 Mm^3[3]. Intense rains induced a huge mass movement (*e.g*. landslides, debris flows) in the northern coastal region of Venezuela, leading to torrential avalanches that descended from the mountain to the alluvial fans of the Vargas state. Towns and urbanized areas were destroyed, causing thousands of casualties and heavy economic damage. This event was the worst natural disaster in the history of Venezuela[1].

As part of structural countermeasures for mitigating debris flow disasters in the Vargas state, several sediment control works, especially check dams were built between 2006 and 2008. Sixty-three dams were built in the canyons of torrents. Twenty-six structures were open-type dams, designed to allow clear-water floods to pass, whilst offering enough resistance to trap debris flows. Thirty-seven structures were close-type dams.

Figure 1. Camurí Grande basin and control works built in the Camurí and Migueleno rivers

The existing works in the Camurí Grande basin (*i.e*. channelization works and six dams) were designed basically for a 100-year return period event and without estimating the sediment volume to be trapped by dams[4]. Upstream of the alluvial fan, four closed-type check dams and two open-type dams (1 m x 1 m windows), made with gabions, 5 m high and variable width (42 m to 97 m) were built on the Migueleno and Camurí rivers (Figure 1).

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A trapezoidal gabion type channel was built downstream of the dams to channelize the flow and sediment before discharging to the Caribbean Sea. Currently, the channel has some structural damage, such as cracks and fractures in the bed sills due to the lack of maintenance and growth of vegetation. In addition, the dams are mostly silted because of previous minor events, such as the event of November 2011 with an estimated return period lower than 10 years (Figure 2). The open-type dams in the Camurí River have a failure in the right side.

A numerical study was performed to evaluate the pertinence of the aforementioned control works. The methodology that was adopted consisted of numerical simulations of various cases of debris flow events, using different control work configurations and comparing the resulting hazard maps. Four cases were

Figure 2. Open dam built in the Camurí River. Downstream views in 2008 (left) and 2011 (right)[9]

simulated: without control works (Case 1), with channelization works only (Case 2), with channelization works and empty dams (Case 3), and with channelization works and dams filled up with sediments at the equilibrium slope[5] (Case 4 - considered as the current one). According to the analysis of recorded previous bed profiles[6], the actual bed slope upstream of the dams was deemed as being at equilibrium. The events generated by rainfall of 10, 100 and 500 year return periods were analyzed with 24 hours duration storms[3] using the numerical model RiverFlow2DPlus[7].

Numerical modeling approach: Data and methodology

RiverFlow2DPlus is a two-dimensional hydro-dynamic model, with a finite-volume scheme and flexible-mesh[7]. The public domain geographic information system platform QGIS was used as a graphical interface. RiverFlow2DPlus includes a conventional sediment transport module (bed load and suspended load) (ST), and a non-Newtonian hyper concentrated flow module (Mud and Debris Flows) (MD). The ST module simulates sediment deposition and erosion but requires much greater computational capacity than the MD module. The MD module considers the water-sediment mixture as monophasic, reproduces its rheological characteristics while ignoring the sedimentation process. The flow volumetric concentration in the Camurí Grande is between conventional flows and fully developed debris flow (from 10% to 30%).

The ST and MD modules were employed separately, namely (i) the MD model was applied to the lower area of the basin (cases 1, 2, 3 and 4), and (ii) the ST was applied upstream of dams (cases 3 and 4).

The February 7-10th 2005 event was simulated to calibrate the numerical model (*e.g.* for cell size and roughness) using the observed flow and sediment deposit depths. During this event, the rainfall was continuously recorded at the Naiguatá station located within the Camurí river basin; the flow hydrograph (*i.e.* runoff) was estimated using the numerical model HEC-HMS[8]. Simulating the 2005 event, the numerical results agreed closely with the field data, in terms of maximum flow depths and deposited sediment depths.

Table 1. Volume of retained sediments

		Case 3		Case 4	
Return period event	Total sediment volume (m^3)	Retained volume (m^3)	Retained percentage (%)	Retained volume (m^3)	Retained percentage (%)
500-years	2,370,896	416,790	17.6	230,748	9.7
100-years	1,467,711	341,540	23.3	171,340	11.7
10-years	406,296	159,345	39.2	70,434	17.3

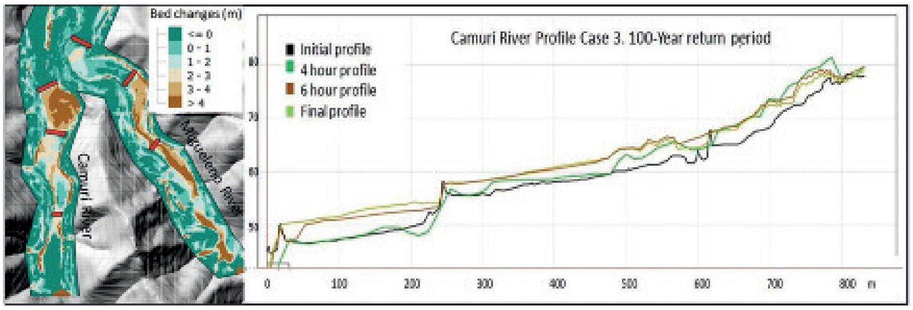

Figure 3. Results for Case 3- Sedimentation upstream of the dams due to a 100-year return period debris flow. The time evolution of the longitudinal bed profile is also shown. The flow pic discharge occurred at hour 5

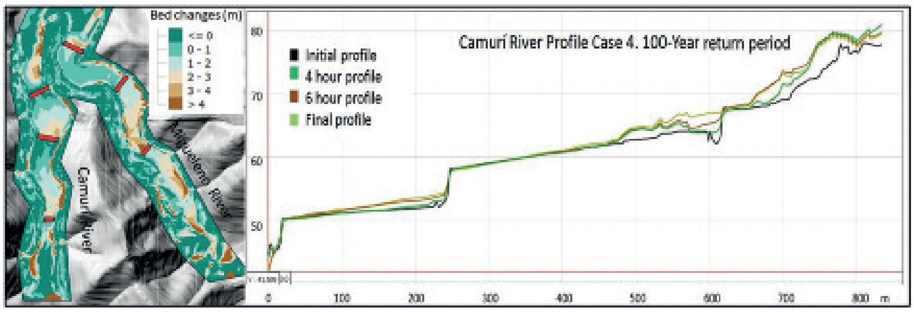

Figure 4. Results for Case 4- Sedimentation upstream of the dams due to a 100-year return period debris flow. The time evolution of the longitudinal bed profile is also shown

Results

The ST module was used to predict sediment deposition upstream of the dams (Case 3, *i.e.* channelization works and initial empty dams). A simplification in the sediment size range was applied, considering only the sand fraction.

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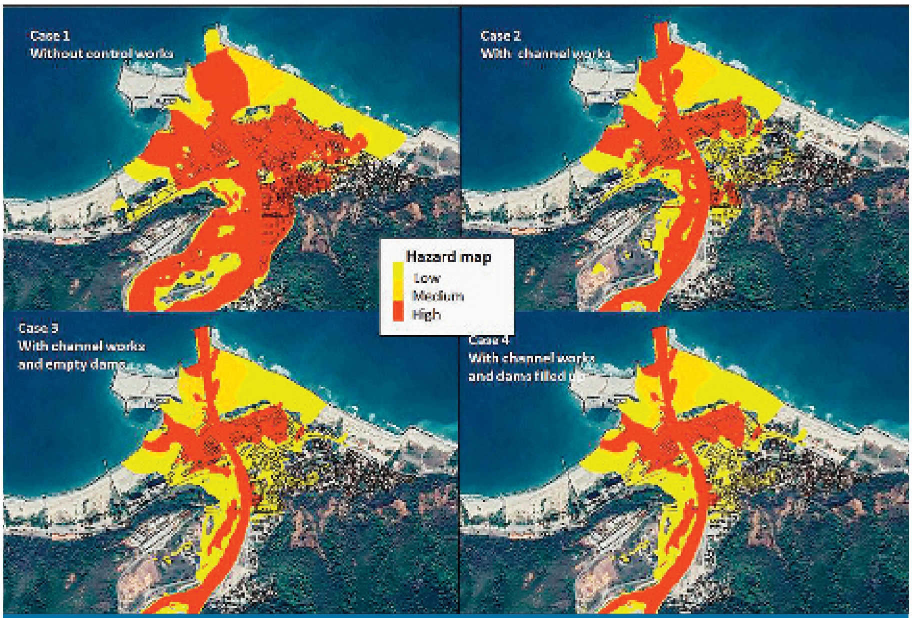

Figure 5. Hazard maps for Cases 1, 2, 3 and 4

The transport of boulders cannot be simulated by the ST model. The Meyer-Peter and Müller[7] formula computed the sediment discharge. Figure 3 shows the final bed sedimentation profile upstream of the dams in the Case 3. It was found that the six existing dams can retain almost 18%, 23% and 39% of the total sediment volume associated with 500-, 100- and 10-year return period events, respectively (Table 1).

Figure 4 displays the results for Case 4 (*i.e*. channelization works and dams filled up with sediments), showing sediment deposition upstream of the dams, although the river bed was considered to be in equilibrium. This process, which occurs during exceptional floods[6], allows a temporally additional, appreciable sediment retention capacity, as in Case 4 dams retain around 50% of the sediment volume retained by the empty dams in Case 3. In Case 4 the six existing dams can retain almost 10%, 12% and 17% of the total sediment volume associated with 500-, 100- and 10-year return period events, respectively (Table 1).

In the urban area, where hazard maps are required[10], the MD module was applied, due to its more physically realistic description of debris flows and its low computational costs. The MD module used the quadratic rheological formulation, which includes inertial and viscous terms[11]. The criteria for the development of hazard maps were based on maximum flow depth and velocity, following the Venezuelan regulations[10,12]. The following hazard levels were considered:

- Red (High hazard level): people inside and outside of buildings are in danger. There is a high risk of buildings being destroyed. The marked area corresponds essentially to be a prohibited zone.
- Orange (Medium hazard level): people outside of buildings are in danger, but are safe when inside. Houses and buildings can be damaged but not destroyed. The orange zone is essentially a regulatory zone.
- Yellow (Low hazard level): the danger for people is low or nonexistent. Buildings may suffer minor damage. The yellow zone is essentially an area where the only action to be taken is to raise awareness about the potential of debris flows.

The influence of the control works against debris flow was evaluated in each case, comparing the hazard maps and considering the three hazard levels (Figure 5). All comparisons were made in relation to Case 1 (*i.e*. without control works). A relevant result is that in Case 2 the total hazard area (*i.e*. red, orange and yellow areas) decreased by 22% and the red hazard area decreased by 48%. In Case 3 the total area decreased by 25% and the red hazard area decreased by 66%. In Case 4 the total and high hazard areas were very similar to those in Case 3, demonstrating that dams in their equilibrium conditions can also contribute to reduce the hazard. However, periodic extractions of sediments are recommended.

Conclusion and recommendations

The present study provides insights into risk management in the Camurí Grande basin. The existing structures play an important role in decreasing the consequences of debris flows on the lower parts of the basin. According to the hazard map, the reduction of the high hazard level is of the order of 66%. It must be noted that the Venezuelan hazard map criteria[10,12] include the 500-year event, greater than the 100-year event which was used to design the control works. The residual hazard should be dealt by non-structural measures, such as land use restrictions, Early Warning System (EWS), emergency plans and education of the local population about the potential hazards.
To improve the structural countermeasures for debris flow disasters in the Camurí Grande basin, it is recommended to develop an accurate estimation of the available sediments in the basin (riverbeds and hillsides), to improve the channel capacity and to build new check dams for trapping boulders and larger size sediments, following the scheme of a series of open-type and closed-type dams implemented in other basins in the Vargas state. ■

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

BY JEAN-RENE MALAVOI & KAMAL EL KADI ABDERREZZAK

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

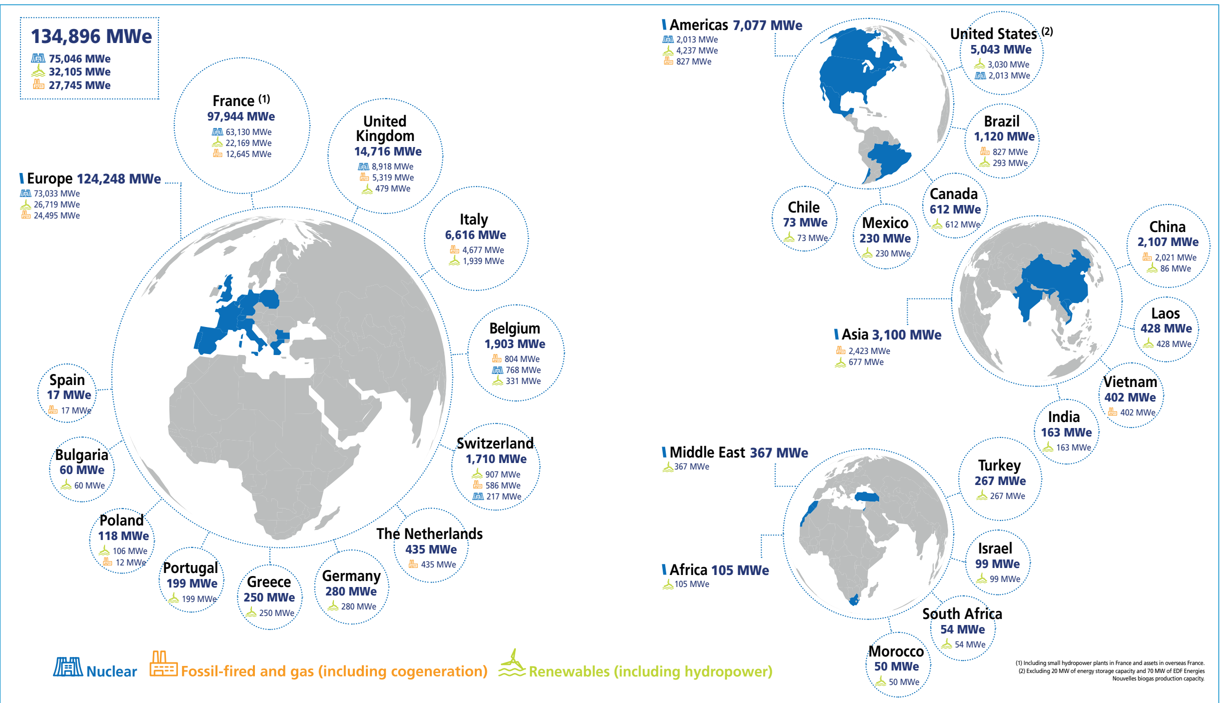

Figure 1. EDF group's net installed capacity worldwide in 2017[2]

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

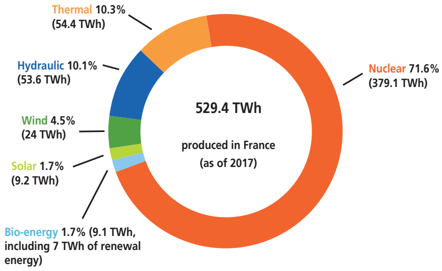

Figure 2. EDF's energy production in France (as of 2017, source: EDF)

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

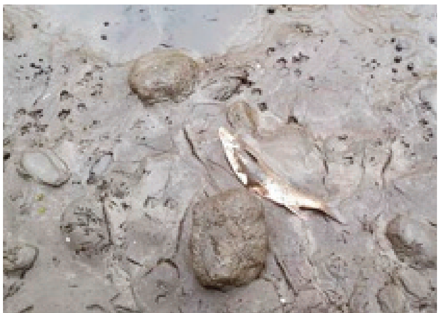

Figure 3. Fish mortality following a drawdown operation in an Italian reservoir. (Courtesy: S. Bastasi)

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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INNOVATIVE METHODS TO RELEASE FINE SEDIMENTS FROM RESERVOIRS DEVELOPED AT EPFL, SWITZERLAND

BY GIOVANNI DE CESARE, PEDRO F. A. MANSO, SABINE CHAMOUN, AZIN AMINI & ANTON J. SCHLEISS

Electricity generation, water supply, flood protection, flow regulation and navigation are amongst the main services provided by reservoirs. Sedimentation affects the sustainability of reservoirs, by reducing their storage capacity, and increases the negative impacts of dams on downstream rivers due to sediment impoverishment. For these reasons, reservoir sedimentation must be considered in dam planning, design, commissioning and operation[1,2]. Typically, fine, mostly suspended sediments enter reservoirs during flood events, glacier melt periods or during operation of upstream infrastructure. This article describes innovative methods developed at the Platform of Hydraulics Constructions (PL-LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL) to cope with the accumulation of fine sediments within alpine reservoirs in Switzerland.

A plethora of technical solutions exists for reservoir sedimentation management, each of which has its advantages and shortcomings in terms of cost, effectiveness, efficiency and environmental impacts[2]. Adequate planning of sediment release operations is necessary to prevent harmful effects downstream of the dam, such as riverbed clogging by fine sediments, local bed aggradation increasing the risk of flooding, and high sediment concentrations or anaerobic conditions for river fauna. Fine sediments (silt and clay) travel along the reservoir thalweg as turbidity currents triggered by the density difference between the overlying, lower density ambient water in the reservoir and the sediment-laden inflow. Driven by the density difference, the turbidity currents progress downstream to the deepest area of the reservoir near the dam and appurtenant structures (*e.g.* bottom outlets, spillways, water intakes for powerhouse, irrigation or water supply). In this area, fine sediments are deposited and may hinder partially or totally the hydraulic capacity of the water release structures (Figure 1).

Alpine hydropower schemes are often composed of multiple reservoirs with different sizes and geometries. The existing power intakes and dam bottom outlets of these reservoirs were not primarily designed with consideration of sediment management. The use of these facilities for sediment routing requires improved insight into the hydrodynamics within the reservoirs and the level of turbulence in particular

Figure 1. Räterichsboden reservoir in Switzerland during the emptying operation in 2014. The view is toward the bottom outlet (center) situated right below the power intake. Carved channels with steep-sloped banks on the sediment deposits converge to the bottom outlet. The dam and spillway are on the background on the right-hand side. Photo: M. Müller

Approaches for managing fine sediments in reservoirs

Besides stopping turbidity currents in the reservoir by screens and obstacles[3], the PL-LCH at EPFL has been developing over the past years several innovative solutions for fine sediment management in large reservoirs for seasonal storage (Figure 2). Two of these solutions aim at keeping fine sediments in suspension for subsequent routing downstream through the hydropower waterways, without water losses for production and without disrupting regular hydropower withdrawal operations. Another solution is to allow the fine sediment-laden water to pass through bottom outlet(s) of the dam (*i.e.* turbidity current *venting*), which must be properly located and sized to be timely operated in the wake of flood events. In any of the three approaches, operation timing and reservoir hydrodynamics are of paramount importance for a performant operation.

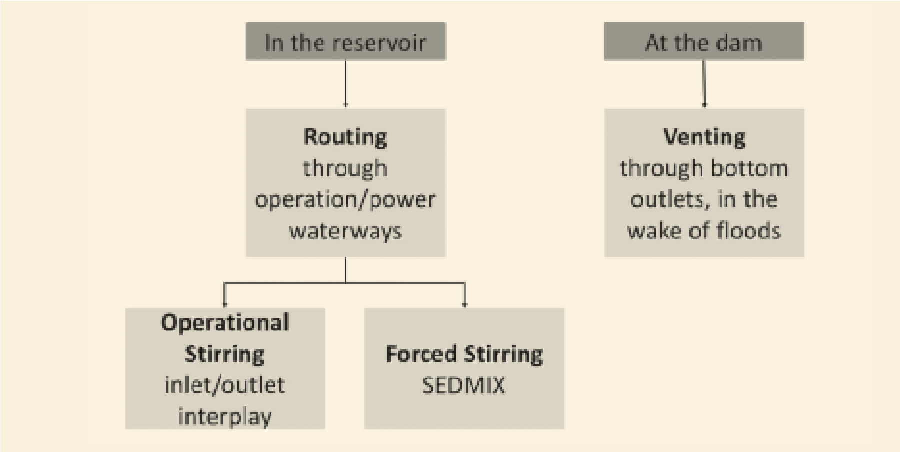


Figure 2. Innovative solutions for fine sediment management in seasonal reservoirs developed at EPFL

Preventing fine sediment settling for subsequent routing through power waterways

Operational stirring

This first innovative solution makes use of the inflows and outflows in the reservoir to maintain turbulence levels above a given "minimum threshold level", which prevents fine sediment deposition depending on the size and settling properties of the particles. If properly integrated in the design of new projects, or in the expansion of existing ones, the assessment of reservoir hydrodynamics and induced sediment motion can assist in selecting the most adequate location, orientation and layout of the power intake structures, which provide flow into the reservoir, and/or the outlet structures discharging water from the reservoir. The power intake is an outlet structure, but it can work in both flow directions in pump-storage facilities.

Previous studies have reported that pumped-storage hydropower plants alter reservoir stratification and sediment transport dynamics[4]. Therefore, in hydropower schemes that have, or may include pumped-storage in the future, the cyclic flow exchange between the upper and lower reservoirs can help inhibit sediment settling, by maintaining or increasing turbulence in the vicinity of the water inlet/outlet structures[5]. Based on laboratory experiments, Müller *et al*.[4] reported that settling of fine sediments near the outlet structures can be considerably reduced by the nature of the inflow and the outflow sequences. They showed that high water discharge operations with short pumped-storage sequences reduced the settling of fine sediments brought into the reservoir by turbidity currents.

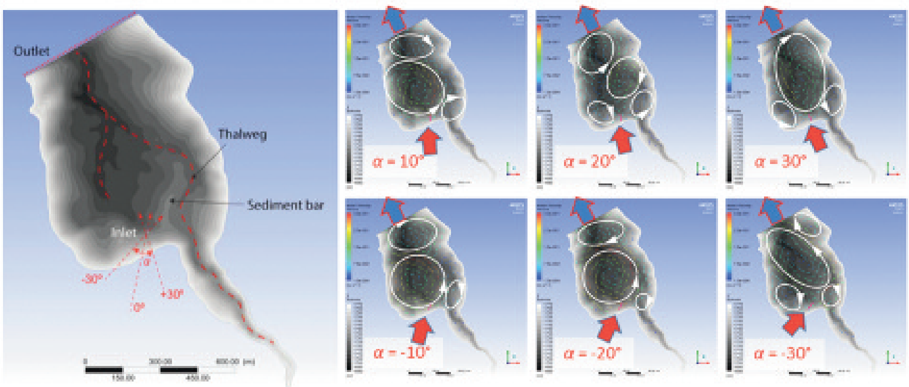
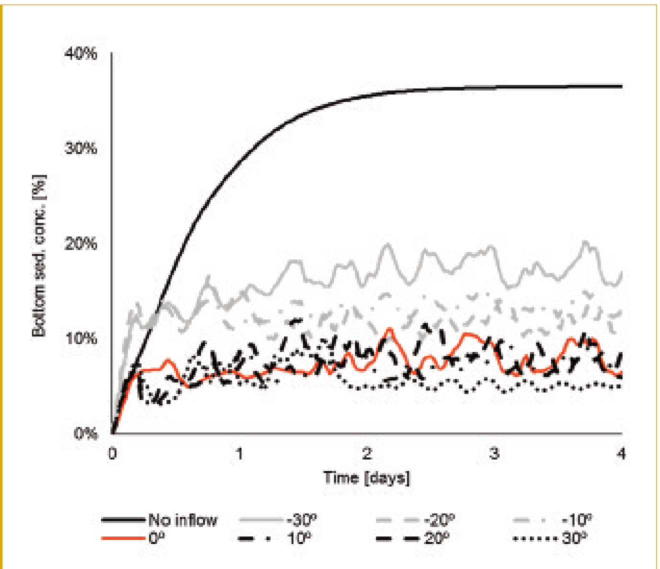


Figure 3. Bed topography and velocity vectors at the water surface for the flow discharge of 90 m^3/s considering seven alternative water release (flow into the reservoir, red arrow) angles α varying from +30° to -30° [4]. The power intake is located at the dam location (blue arrow, see also Figure 1)

Figure 4. Time-evolution of sediment concentration on the Räterichsboden Reservoir bottom in front of the power intake for various angles α of the upstream water release into the reservoir (see Figure 3), with respect to the initial concentration[6]., no Inflow implies that the reservoir water is stagnant, and the curve corresponds to the natural sedimentation process of suspended particles, leading on the long-term to the filling-up of the reservoir



Guillén-Ludeña *et al*.[6] analyzed numerically the influence of the flow rate and the horizontal orientation of the water outlet of an upstream hydropower plant releasing water into the reservoir on the fine sediment settling in the Räterichsboden Reservoir in the Swiss Alps. The results reveal that the settling of fine sediments correlates with the turbulence intensity within the reservoir (Figures 3 and 4). In the studied case, the suspended sediment concertation on the reservoir bottom is lowest when the water release and power intake structures are aligned and they are along the direction of the thalweg of the reservoir. This prevents sediment deposition during hydropower operations, thus diminishing reservoir sedimentation.

The efficiency of the operational stirring in inhibiting the settling of fine sediments depends on the geometry of the reservoir, the layout of the power inlet/outlet, the sequence and discharge of inflow and outflow, the characteristics of the sediments and their concentration. Field work carried out at the Grimsel pumped-storage hydropower project[4], which included detailed turbidity measurements in both the upper and the lower reservoirs for several weeks, led to the conclusion that the overall sediment exchanges were balanced, or in short, that the upper reservoir was not becoming silted due to pumping from the lower reservoir. This

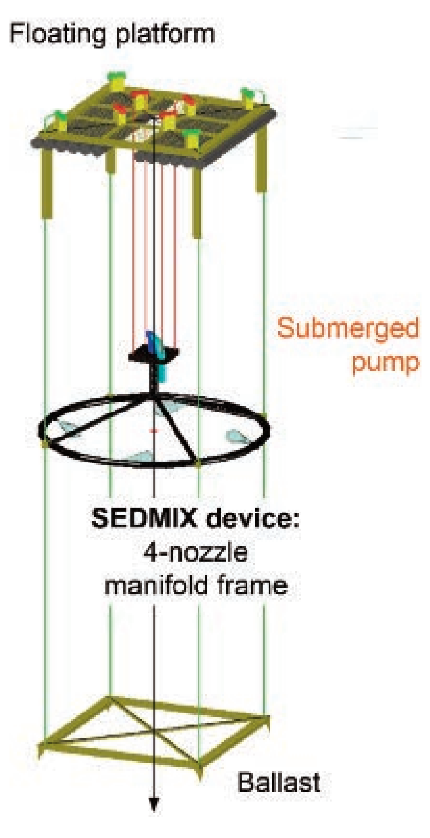


Figure 5. Schematic drawing of the SEDMIX device with a floating platform and a ballast anchor structure on the reservoir bottom

confirms the ability of the intermittent generation of jet-inflows, through pumping at the upper reservoir and through turbine operation at the lower reservoir, to maintain fine sediments in suspension.

Forced stirring

The forced stirring solution relies on artificially generating upward sediment motion at critical locations within the reservoir by a multi-nozzle water jet generator, supplied by gravity or pumping, hereafter labelled "SEDMIX". Depending on the reservoir morphology and management operations, the jet generator is fixed or mobile.

A recent concept elaborated by the PL-LCH for the SEDMIX system (Figure 5) makes use of a specific arrangement of several water jets[7]. The device induces an adequate level of upwind turbulence preventing sediments from settling near the dam, keeping them in suspension for progressive evacuation through the power intake during normal operation of the hydropower plant. This innovative system can be installed in several reservoirs worldwide in order to avoid reservoir siltation due to fine sediments.

The SEDMIX device was tested successfully in the laboratory with four jets in a circle on a horizontal plane in a 2 m wide, 4 m long and 1.5 m deep rectangular tank[7]. The efficiency of this technique was evaluated by comparing the sediment release obtained with and without jets. The performance of the SEDMIX device has not yet been investigated in real-life reservoir conditions or implemented on a specific site. A research project proposal is under preparation, with an overall estimated site installation cost of some CHF 600 000 (approximately US$ 608 000).

The SEDMIX device was tested numerically for a new dam project in Switzerland (Figure 6). The ongoing project in the Trift Valley currently being developed by Kraftwerke Oberhasli SA (KWO) is an opportunity to implement for the first time this new system. A three-dimensional model of the Trift Reservoir including the SEDMIX device was developed and used under different scenarios[8]. The study investigated a transient routing of fine sediments through a reservoir outlet (in this case the water intake) during and after a sediment-laden flood event. The numerical results showed that with one single deployed SEDMIX device, up to 70% of the fine sediment inflow would be transported[8]. These findings show a promising future for the SEDMIXs solution which can be customized to site conditions and operational practice.

Turbidity current venting

Depending on the sediment concentration and the reservoir geometry, turbidity currents can flow over long distances until they reach the dam (Figure 6). In this case, unless evacuated through outlets or intakes, the obstructed turbidity currents climb up. A muddy lake forms near the dam, blocking the outlet structures and progressively reducing the reservoir capacity.

Venting allows the direct transit of turbidity currents through low-level hydraulic structures (*e.g.* bottom outlets) while they are approaching the dam. The optimal outflow discharge inducing the largest venting efficiency depends on the turbidity current discharge. Hence, there is usually no need to lower the water level in the reservoir, thus reducing clear water losses. Also, venting reintroduces suspended sediment to downstream reaches, which is needed for the health of the ecosystem. However, despite the economic and environmental benefits of venting and its worldwide application, only few studies have evaluated this technique to develop formulas and methodologies for the characterization of turbidity currents in reservoirs and the estimation of the resulting outflow sediment concentration.

Recently, several influential parameters on venting were assessed by Chamoun *et al.*[9, 10], using experimental and numerical approaches. To evaluate the efficiency of venting, the outflowing sediment masses can be compared

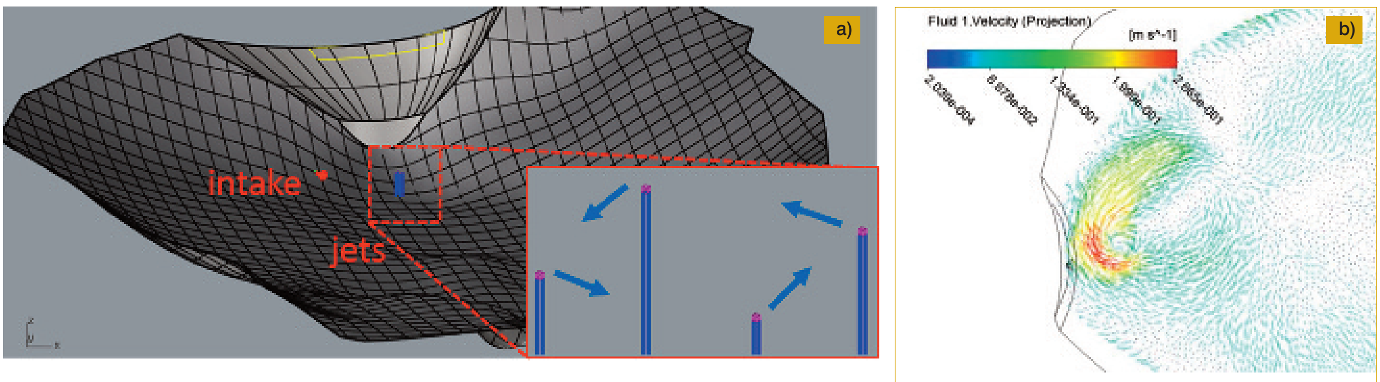


Figure 6. a) Water intake and SEDMIX jet location in the numerical model of the Trift Reservoir in the Swiss Alps, the jets discharge horizontally; and b) induced flow field on the horizontal jet plane

to the inflowing sediment masses. Nevertheless, because venting does not induce retrogressive erosion in the reservoir (unlike flushing), the deposited portion of the inflow sediments should not be considered since it has negligible potential to be evacuated during venting. Another indicator for high/low efficiency is the loss of water. A compromise between sediment release and water loss should be found in a way that maximizes the former while keeping the latter minimal. Chamoun *et al*.[10] used this approach in a systematic investigation of parameters including outflow discharge, operational timing, bed slope, as well as outlet dimensions and position. Results show that the outflow discharge leading to the highest efficiency differs when dealing with a near-horizontal bed in the vicinity of the dam (which is common for reservoirs where turbidity currents occur) than in the case of an inclined bed (*i.e*. slopes of 2.4% and 5.0%). In the former case, an outflow discharge corresponding to 100% of the turbidity current discharge leads to the highest efficiency while in the latter, the ''optimal'' outflow discharge is around 135% of the turbidity current discharge. Steeper bed slopes lead to higher venting efficiency, mainly because the reflection of the turbidity currents on an upslope bed is more difficult and thus sediments are trapped near the dam.

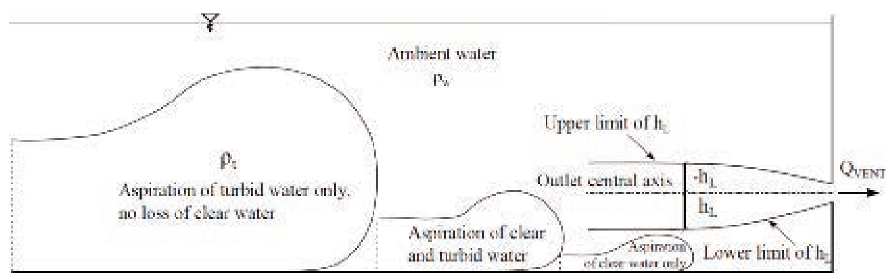


Figure 7. Schematic drawing showing the aspiration height hL with its upper and lower limits relatively to the central axis of the outlet delimitating the area that can be reached by the outlet flow field to evacuate sediments[11]

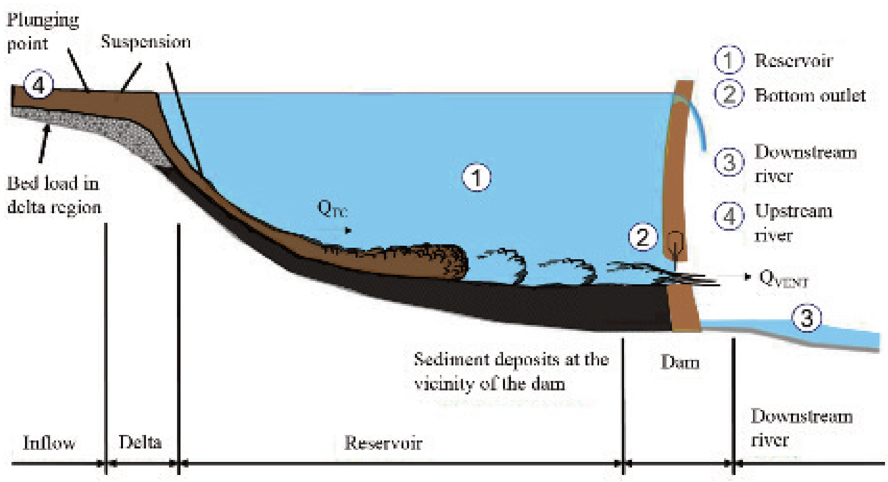


Figure 8. Turbidity currents traveling along the reservoir bottom at a discharge QTC with a projection of its venting through the bottom outlet at a discharge Q_{VENT}[11]

Therefore, venting should be conducted from the very beginning of the dam operation. The beginning of venting should be timed to coincide with the arrival of the turbidity currents at the dam in order to avoid the reflection of the current and sediment settling behind the dam. The gate opening should be scheduled once the turbidity currents are at approximately 300 m upstream of the outlet. This distance was estimated based on the average velocity of the turbidity currents and the time that it takes for the flow field to establish in front of the outlet after the gate opening. Venting should last at least as long as the flood exists and while the turbidity currents approach the outlet. After the end of the flood event, turbidity currents tend to die out immediately, but the concentrated muddy water near the dam may persist longer. Therefore, venting should be maintained for a certain time that depends on the outflow discharge. The outflow concentration should be monitored downstream of the dam in order to avoid both downstream ecological impacts and high water losses.

The dimensions and position of the outlet are closely related to the aspiration height of the outlet which depends on the outflow discharge and turbidity current density. The aspiration height (Figure 7) has an upper and a lower limit (relatively to the central axis of the outlet) delimitating the area that can be reached by the outlet flow field to evacuate sediments. The higher the level of the outlet, the higher the lower limit of the aspiration height and the more significant the upstream reflection of the current will be. Thus, outlets placed at high levels will cause more reservoir sedimentation. The outlet should be placed at the lowest level possible, provided that venting is performed frequently after the beginning of the dam operation. The dimensions of outlets should be chosen so that the vertical and lateral aspiration limits are reached while including the largest portion of the turbidity currents. Using a certain outflow discharge, the outlet might be easily clogged if its dimensions are small. However, if dimensions are too large, the water losses can increase. Commonly, the dimensions of turbidity currents surpass the dimensions of the outlets. In this case, increasing the number of outlets in the vertical/lateral direction should be considered.

Field monitoring is paramount for successful and efficient venting operations. Field data are necessary to indicate the occurrence, discharge and position of turbidity currents. An overview of some instruments (*e.g*. Acoustic Doppler Current Profiler (ADCP), turbidity probes) is given by Chamoun et al.[9]. In cases that no monitoring system is set at a reservoir, the debris left at the plunge point can be visually observed and considered as an indicator of the formation of turbidity currents. If possible, the turbidity current discharge should be measured and the progression of the currents tracked along the reservoir. Besides the mentioned timing, measuring the outflow discharge is paramount. Finally, numerical tools can be used to simulate the dynamics of turbidity currents in the reservoir in support of the selection of appropriate venting strategies[10] as well as physical model experiments[12].

Conclusions and recommendations

The research work at the PL-LCH of EPFL has led to the following main conclusions, supported by field observations and frequent exchanges with dam owners and operators:

1. The interplay between jet-like flow from reservoir outlets and the approaching flow to the power intake may facilitate routing sediments from one reservoir to the next one in a cascade configuration or within pumped-storage hydropower projects. This "operational stirring" of sediments requests an adequate selection of the inlet/outlet relative location, orientation and geometry, considering the induced reservoir hydrodynamics and sediment fluxes. Fine sediments are routed downstream through the turbines during normal power station operations without water loss, provided that the concentration of fines is acceptable in terms of equipment wear protection and downstream ecosystem safeguard. The efficiency of this solution is generally highly dependent on local conditions, in particular on reservoir morphology and inertia (*i.e.* volume). Interest in this technique is high due to its low cost and environmental advantages.

2. The "forced stirring" of sediments with the "SEDMIX" facility has similar advantages as the previous solution with the additional advantage of allowing full customization. The device can be installed at different locations if necessary and can be used on demand. The only comparative drawback is the mobilization costs and any eventual energy costs in case that installing a pump is required.
Computational investigations at a prototype scale indicate sediment release rates of up to 70% in terms of daily balance between inflows/outflows for a specific case studied in the Swiss Alps. These results are promising and shall be consolidated with further research and prototype demonstrations in the coming years. The costs per volume of sediments evacuated are relatively small and far below the cost of conventional measures such as hydro-suction.

3. Venting of fine sediments through bottom outlets during floods is the product of the combination of sediment management and the operation of the bottom outlet structure. The presented research led to the development of design criteria for bottom outlets, as function of the local turbidity current characteristics, hydrologic conditions (characteristics of flood events) and the reservoir morphology. These new design principles may be used by practitioners to size and design bottom outlet structures, their equipment, and their operation and maintenance plans. The efficiency of turbidity current venting is highly variable depending on local conditions and the quantity of the released water volumes.
Finally, monitoring of sediment yields at the catchment scale prior to dam construction and after impounding is paramount to understand the local context and prevent future sediment-related problems within the reservoir. Detailed follow-up of the implementation of any sedimentation management procedure, including the three innovative solutions mentioned above, is the only means to assess their real performance and introduce any required adjustments throughout the lifetime of the reservoir, considering land-use, climate and reservoir operation changes.

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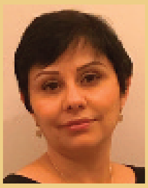

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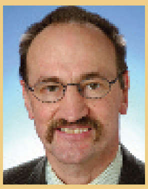

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BENEFICIAL REUSE OF DREDGED RESERVOIR FINE SEDIMENTS

BY SEBASTIEN MENU, FRANÇOIS THERY & VIOLAINE BROCHIER-FORE

As described in previous issues of Hydrolink on reservoir sedimentation[1, 2], the loss of storage capacity in hydropower reservoirs reduces flexibility in generation, because the hydropower facilities become dependent on seasonal flows that might not occur when energy is needed. In addition, the maintenance cost increases as the fine sediment-laden flows passing hydropower turbines may be highly abrasive. Therefore, reservoir sediments must be managed and preventative/mitigating measures must be taken to preserve the hydropower generation and facilities, while respecting the environment and complying with sediment relevant legislation.

In some cases, the feasibility of usual strategies, such as sediment flushing, sluicing and mechanical removal (*i.e.* dredging, dry excavation, hydrosuction), may not be possible for the evacuation of sediments from the reservoir and their transfer to the downstream waterways. Instead, the operators of the dam have to dredge (or excavate under dry conditions) sediments from the reservoir and dispose of the material in neighboring lands. Land application (*i.e.* land management) of the dredged sediments is possible when the chemistry of the sediments has no potential impact on aquatic life and plants within the land.

The growing difficulty in locating new disposal areas and the associated escalating costs call for innovative sustainable management of the dredged reservoir sediments. In the current European legislative framework, sediments, once removed from the reservoir and disposed on upland, are considered as waste[3]. In some cases coarse material may be reused as construction fill or for similar purposes, but reservoir sediments may consist of large volumes of fines (silt and clay) potentially contaminated.

Although fine material can be a liability, it can be viewed as an asset also (*i.e.* "waste to resource" concept). Fine material can be a valuable potential alternative resource to be integrated into a circular economy, innovatively reused on its own in place of a usable commercial product or blended, amended or incorporated into a manufactured product (Figure 1). Examples of

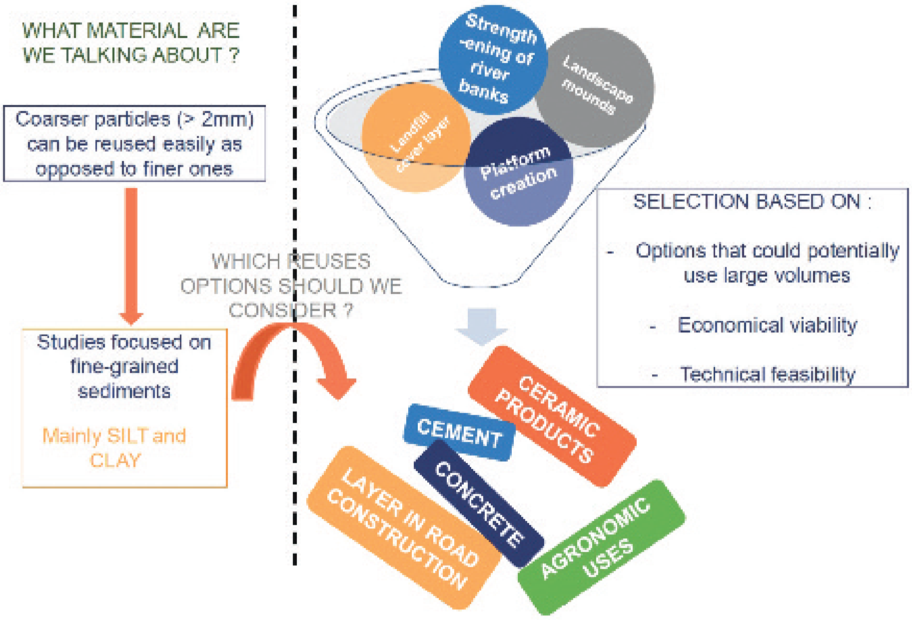

Figure 1. Illustration of potential reuses of dredged fine material disposed on landfill[4]

beneficial reuses include habitat development (*e.g.* building and maintain of productive plant and animal habitat), agriculture, landscape restoration at abandoned strip mines, highway borders, construction (*e.g.* brick making, ceramics, glass tiles, lightweight aggregate), provided that the properties of the fine sediments are adequate and will not harm the environment and public health.

In this context, and as part of its hydroelectric production activities Electricité de France (EDF: www.edf.com) has set up a project over seven years to find innovative solutions for beneficial reuse of dredged reservoir fine sediments. The work undertaken within the project combine two aspects:

- investigation of the valuable part of sediments (*i.e.* mineralogical and agronomic) and their suitability for industrial reuse, and
- quantification of the chemical and organic properties of contaminants within the material to ensure the safety of the industrial reuse options.

Investigation of the valuable part of dredged sediments

The first work package of the project has addressed the technical conditions required for a beneficial reuse of dredged fine sediments. The generic requirements usually employed for traditional raw materials, likely to be replaced by the dredged fine material, were used. A wide range of mineralogical (*e.g.* grain size analysis, water content, organic matter content, Atterberg limits or methylene blue value, carbonate content, quantitative analysis of the elementary composition, thermal analysis) and agronomic (*e.g.* apparent density, N, P, K, Ca, Mg, organic matter content, pH) properties were reviewed[5]. A protocol for a minimal mineralogical and agronomic characterization of the dredged sediments was proposed to assess material suitability for beneficial reuse in the following pre-selected industrial ends[4]:

- Roadway bed material;
- Ceramic material (*e.g.* bricks, tils);
- Concrete or mortar;
- Portland cement clinker;
- Agricultural soil amendment (*e.g.* structure, texture, thickness);
- Soil construction;
- Filling of abandoned strip mines.

The above seven reuse options were chosen taking into account the following aspects: minimization of the volume of fine sediments to be disposed, while maximizing potential reuse;

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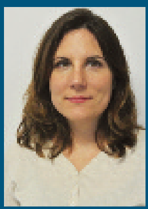


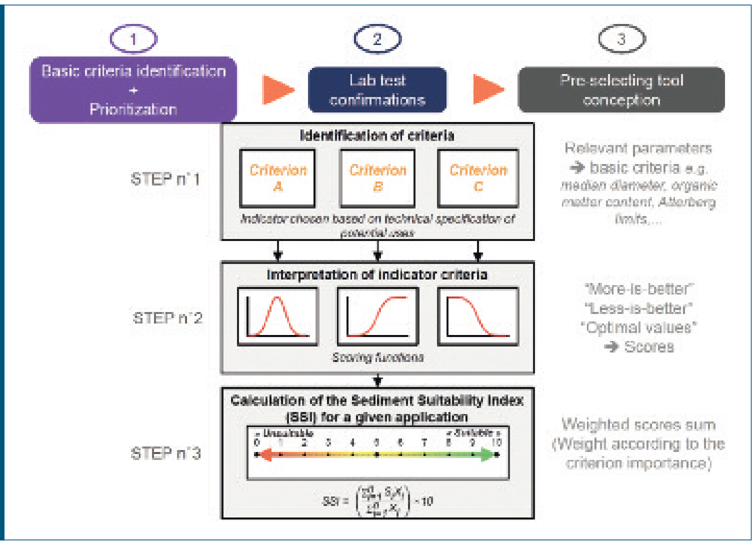
Violaine Brochier-Fore is Engineer at EDF since 2012, conducting studies and animating networks and programs on the valorization of sediments and monitoring of biodiversity in hydroelectric sites. From 2004 till 2012, she was working on the agronomical recovery of waste at Ville de Paris, and then at Veolia Environment. She is member of the Expert Group on Soil within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

ability to valorize large volumes of fines; implementation should be achieved at low cost; proximity of hydroelectric plants and dams; and respect of legislation and environmental policy[4].

Anger[5] proposed a decision-making tool for pre-screening the dredged sediments toward potential reuse among the seven options (Figure 2). For each industrial reuse, key input parameters were identified; for example particle size distribution, organic matter content and Atterberg limits for roadway bed material reuse. The tool systematically accounts for the territorial eligibility through a geographical inventory of industries close to the areas where the dredged material is disposed of. Two beneficial reuses qualified as the most realistic ones were retained by EDF for further investigation, namely cement clinker production and fertile land production for urban soil construction or ecological remediation.

Research work has been conducted by Faure[7] on the reuse of dredged reservoir sediments as alternative raw materials in the industry of hydraulic binders (Figure 3). Two reuse options were considered for the fine sediments: on one hand, as raw material for clinker production, and on the other hand as Pozzolanic additional constituent of Portland-composite cement[8]. The reuse of sediments as raw meal in the clinker production, instead of the clay fraction, was

Figure 2. Decision-making tool for potential reuse of dredged reservoir fine sediments[6]

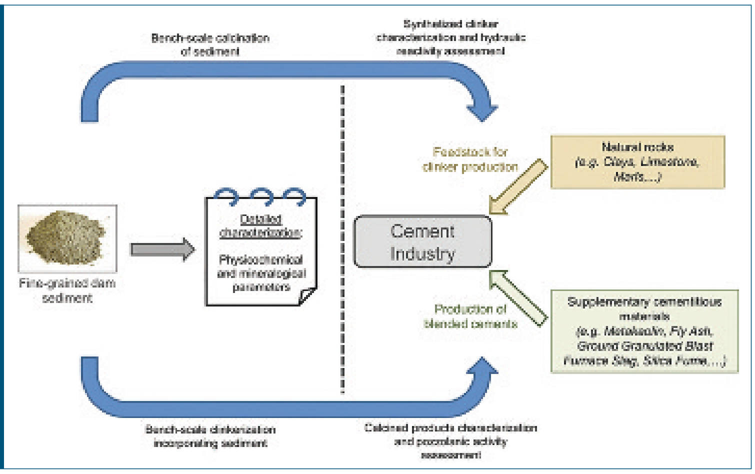


studied in the laboratory with fine sediments being sampled by EDF in various hydropower reservoirs. Clinkers maximizing the fine-grained sediment content, between 25 and 35 % (depending on the sediments), were synthetized. These clinkers showed some microstructural features that can be corrected by adding clay as a third compound. *In fine*, it was found that most fine sediments can replace part (10 to 15%) of the usual raw materials and that the clinker characteristics can be anticipated and adjusted for cement manufacturing. For instance, a CEM I 52.5 N cement was obtained by incorporating 11.4 % of fine sediments into the raw meal.

Concerning the valorization of fine sediments as Pozzolanic additional constituent of Portland-Composite, a survey of the physical and mineralogical properties of the dredged sediments according to the calcination temperature was conducted. In parallel, the Pozzolanic reactivity was assessed with both chemical and physical tests, with a partial substitution of Portland cement by calcined sediments in cement pastes, in order to determine an optimum calcination temperature. The Kaolinite content of approximately 10% for some of the studied samples led to a moderate to high Pozzolanic reactivity, which can be comparable to fly ash. However, for all the sediments containing calcite and only illite and chlorite clays, activation was found low or null.

Fourvel[9] conducted research on the suitability of dredged sediments for beneficial reuse in the construction of functional urban soils, such as green space and landscaping. Based on laboratory tests using fine sediments sampled from different hydropower reservoirs in France, he found that the agronomic quality of sediments was contrasted and directly related to the initial physicochemical properties of sediments[10]. A typology of sediments suitable for soil construction has been proposed, based on the intrinsic properties of the sediments combined with the envisaged utilization of the soil.

Figure 3. Reuse of fine sediments as alternative raw materials in the industry of hydraulic binders[8]



Environmental characteristics of sediments and industrial reuse options

In the second package of the project, the environmental constraints have been analyzed to determine whether a specific beneficial reuse of dredged material is possible without adverse impacts to the environment and public health. The French National Institute for Industrial Environment and Risks (INERIS) database of pollutants and corresponding concentrations in fine sediments (10,000 samples[11]) was compared to the database of EDF (500 samples from hydropower reservoirs).

The environmental characteristics used are:
- the total content of contaminants (*i.e.* trace metals, organic contaminants and emerging contaminants), and
- the leaching behavior of the constituents of the material to determine whether the material exhibits the characteristics of hazardous wastes according to the Decree of October 28th 2010.

For each of the seven reuse options, the environmental requirements for potential reuse of the dredged material are related to both the regulatory and technical aspects. However, the technical requirements are not always available. To fill this gap, stakeholders were contacted and the characteristics of materials usually incorporated into manufactured products were used.

A cross-analysis of the environmental characteristics and specific requirements was performed. This cross-analysis made it possible to estimate the proportion of potentially recoverable sediments for each of the seven end uses and to identify the most blocking chemical elements. Finally, it was found that based on both the EDF database and INERIS database, the sediments are mostly inert and not contaminated according to the criteria required by the seven envisaged reuse options.

Conclusions and perspectives

The EDF Group supports the use of reservoir dredged material as a valuable resource and works to prioritize beneficial reuse options over traditional dredged material placement methods. Past and current studies have shown that the mineral and agronomic characteristics of fine sediments meet the entry criteria for beneficial reuse in the industrial and agronomic sectors. From a technical point of view, the dredged fine sediments can be considered as raw materials. However, further work must be performed to optimize the economic conditions to actually implement the reuse practices. This includes the drying process of sediments, the regulatory conditions so that sediments are no longer considered as waste, and the economic conditions for beneficial reuse near the source of the dredged material. ■

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MODELING POLLUTANT EMISSIONS IN STAGNANT ENVIRONMENTS

BY PANAYOTIS C. YANNOPOULOS

Modeling pollutant emissions in stagnant environments has long been an important research area for the design and evaluation of disposal systems of wastewater in water bodies, or air pollutants in the atmosphere. This article gives an overview of the development of the Advanced Integral Model (AIM) for groups of interacting buoyant jets met in pollutant disposal systems. AIM's advantages include the low computer memory usage and the direct problem solution with acceptable accuracy, mostly of second order for cases that model assumptions are valid.

Interacting buoyant jet flows occur in many anthropogenic phenomena (disposal of wastewater, thermal effluent or brine discharges in water bodies, emissions of air pollutants or heat and moisture in the atmosphere, as well as plumes over humans due to temperature differences between bodies and surroundings). Some natural phenomena (density currents in lakes, sea and atmosphere, as well as gas escapes from earth faults, volcano eruptions etc.) may also form interacting buoyant jet flows.

The integral method is a popular procedure for solving the problems of interacting buoyant jets. For a single turbulent buoyant jet, plane or round, second order solutions can be obtained for the mean flow and mixing properties [1, 2, 3]. The solution of interacting buoyant jets is more difficult, because of the complicated flow and mixing fields. However, in the case of two adjacent vertical buoyant jets, a solution can be obtained by applying the Entrainment Restriction Approach (ERA) and, when the group consists of any number of closely located jets or plumes of arbitrary form, the Superposition Method (SM) can be used [4, 5]. The SM may be applied either to interacting jets, due to the conservation of momentum and buoyancy fluxes [6, 7, 8], or to interacting plumes, due to the conservation of kinetic energy and buoyancy fluxes [8, 9]. The case of a group of closely located interacting plumes includes also the plumes originated from areal sources, which are considered as composed by an infinite number of infinitesimal point or line sources (Figure 1) and, thus, the SM is successfully applied [9]. The validity of this method stems from the proof of the linear behavior of the partial differential equations of both the total kinetic energy of the mean flow, expressed in terms of the cubic power of the mean axial velocity, and the tracer and/or buoyancy conservation, expressed in terms of their mean fluxes in the main flow direction. Regarding jet-like flows, the linear behavior has also been proved for the partial differential equation of momentum, in terms of the squared mean axial velocity, under Reichardt's hypothesis [10]. Thus, the well-known solutions for point or line plumes or jets can be superimposed to synthesize the composite flow and mixing fields, without needing a core model or invoking the assumption of a virtual origin of the plume or jet.

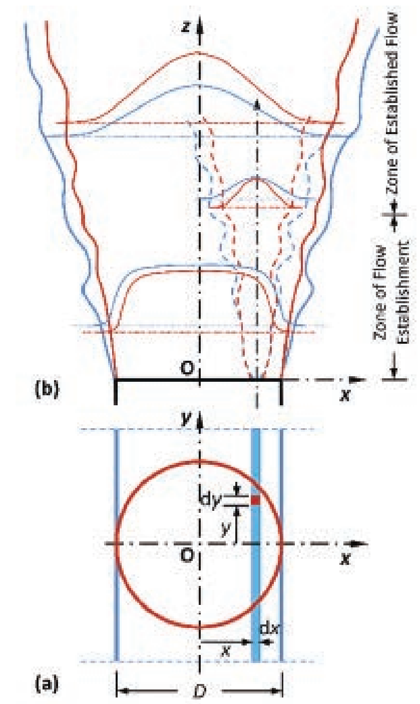

Figure 1. Actual plane and round buoyant jet composed by infinitesimal line/point plumes/jets: (a) Source plan view; (b) longitudinal cross-section

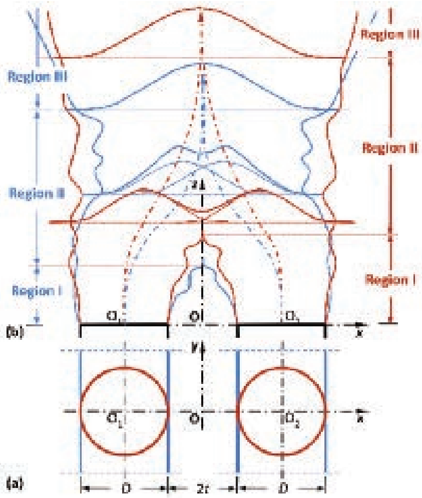

Figure 2. Interacting plane or round buoyant jets: (a) Sources plan view; (b) longitudinal cross-section

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AIM is developed to tackle arbitrary groups of buoyant jets that are interacting with each other. Before merging (Region I of Figure 2b), AIM employs the potential flow theory, assuming that the centerline of each buoyant jet consists of sinks, which entrain fluid causing a secondary flow (dynamic interaction) [11, 12, 13]. This flow interacts with the flow of each buoyant jet of the group causing reciprocal reattachment of all buoyant jets of the group, as shown in Figure 2a and b. During buoyant jet merging (Region II of Figure 2b), AIM takes into account the merging process by both the dynamic interaction and composite velocity and concentration profiles. These profiles are constructed by superimposing the conserved local fluxes of momentum and buoyancy for jet-like flows and of kinetic energy and buoyancy for plume-like flows [8, 9, 14, 15]. In Region III of Figure 2b, AIM takes into consideration the merger effect by employing the aforementioned composite profiles. A comparison of the results of AIM with experimental data has been presented in a recent publication[9].

This method can be used for the analysis of multiple buoyant jet flows in the design of multiport diffusers in water bodies, or in the atmosphere and/or for the evaluation of their efficiency. It may be also used to evaluate the performance of other software that simulates such flows. ■

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A CALL TO ALL IAHR MEMBERS TO VOTE ON OUR REVISED CONSTITUTION AND BYLAWS

Dear IAHR Colleagues,

Firstly many thanks from the Secretariat and Executive Committee - many thanks to you for your feedback over the years and to the Task Force members who have put hundreds of hours into researching and developing the revisions to our Constitution and Bylaws.

On behalf of the IAHR Council, we are pleased to submit for your review and approval a revised Constitution and Bylaws. This has been a 3-year endeavour and has sought input from YPNs in different regions, Technical Committees (twice) and Regional Divisions (twice) as well as past members of Council and our Institute Members.

The objectives are simple:

1. Ensure IAHR can be nimble and responsive to members needs and initiatives
2. Link the IAHR activities, actions and members more directly to leadership decisions
3. Enhance the attractiveness of IAHR to early career researchers and engineers.
4. Resolve inconsistencies or previously adopted changes that have not been formally included in the Bylaws and Constitutions that have arisen over the past few decades.

The full text of the proposed Constitution and Bylaws can be accessed online click here

In order to facilitate your review, the main changes are summarised below:

1. The President serves one 2-year term and one 2-year term as past president (rather than the current 2x2-yr terms).
2. The Council will be expanded to included chairs of Technical Committees (TCs) , chairs of Working Groups and Journal Editors. Regional Divisions will continue to be represented on Council.
3. The Council will meet every 2 years (at the World Congress) but it is expected that there will be Task Forces and other activities structured between Council meetings. The Council may also convene on-line meetings as necessary. The Council will also include one YPN member from each Region with IAHR support to participate.
4. The creativity and innovation of IAHR will be driven by Council. The more operational 'Business of IAHR' will be entrusted to the Executive Committee with a responsibility of reporting to Council regularly.
5. Vice-Presidents and Presidents will be elected as normal IAHR practice
6. These changes would take effect in 2021
7. There is no change to Technical Committees, Regional Divisions, YPNs or Working Groups.

On behalf of the many contributors, we invite you to indicate your approval of these changes via the option that is included in the electronic ballot for the IAHR Elections: The ballot shall be available to you by email and shall open from July 4th to September 4th. The results of the ballot shall be announced on September 5th.

For more information about IAHR governance, we invite you to visit www.iahr.org and click on about -> governance. If you have any questions, please do not hesitate to contact Elsa Incio at elsa.incio@iahr.org

Thank you for your attention to this matter that is critically important to the future of our Association.

Peter Goodwin
President

Tom Soo
Executive Director