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

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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.

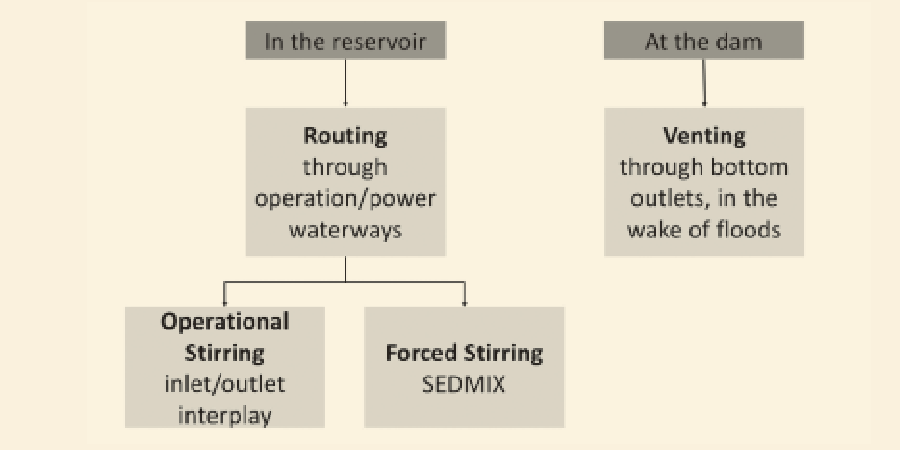


Figure 2. Innovative solutions for fine sediment management in seasonal reservoirs developed at EPFL

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.

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

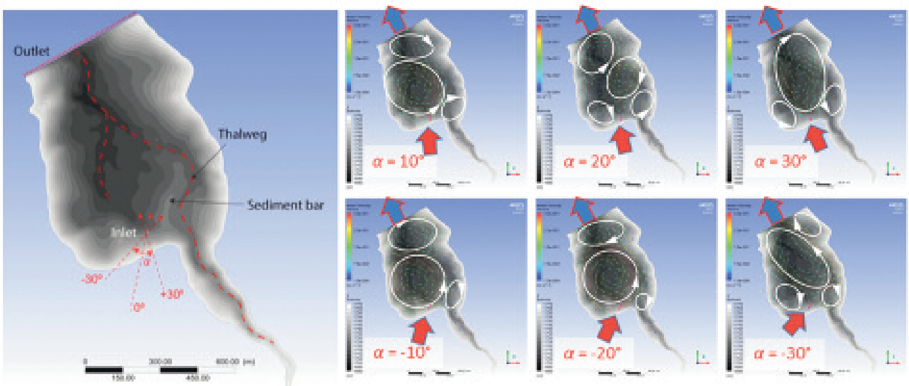
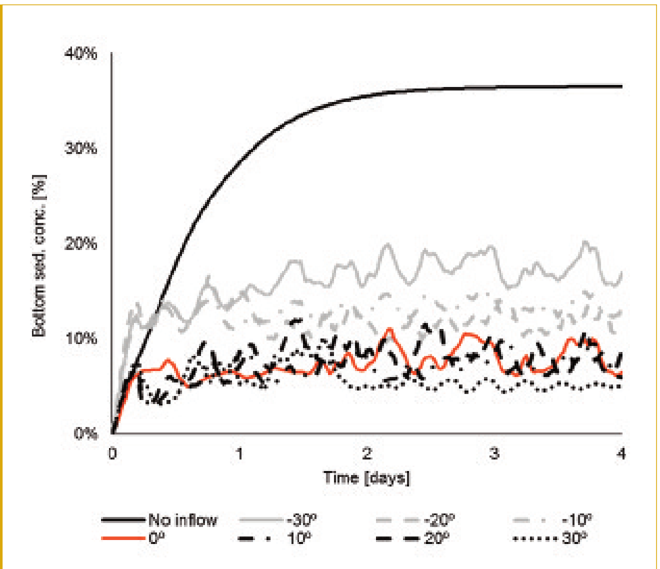


Figure 3. Bed topography and velocity vectors at the water surface for the flow discharge of 90 m^3/s considering seven alternative water release (flow into the reservoir, red arrow) angles α varying from +30° to -30° [4]. The power intake is located at the dam location (blue arrow, see also Figure 1)

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



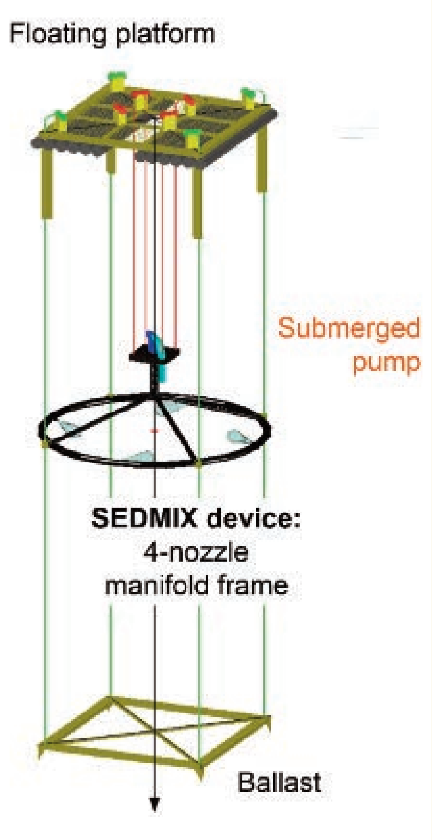


Figure 5. Schematic drawing of the SEDMIX device with a floating platform and a ballast anchor structure on the reservoir bottom

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

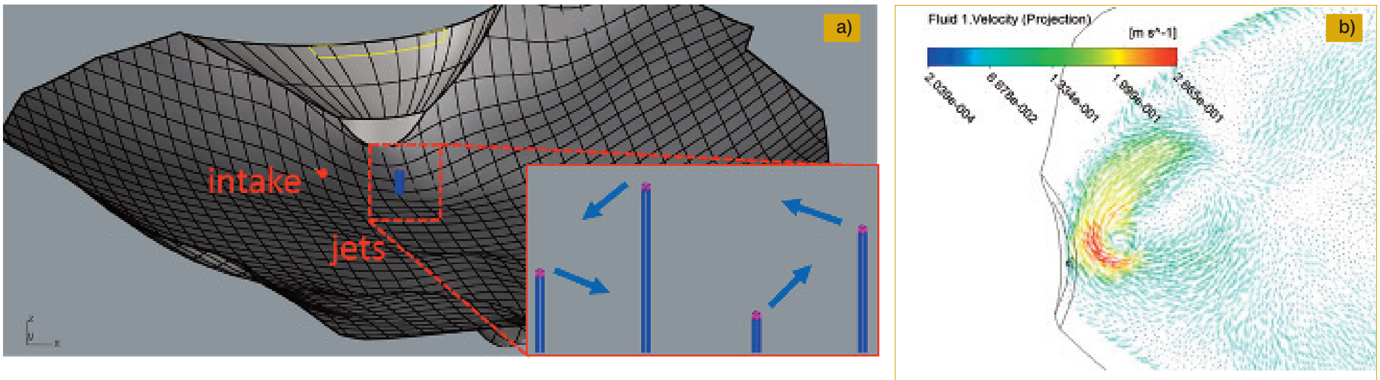


Figure 6. a) Water intake and SEDMIX jet location in the numerical model of the Trift Reservoir in the Swiss Alps, the jets discharge horizontally; and b) induced flow field on the horizontal jet plane

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.

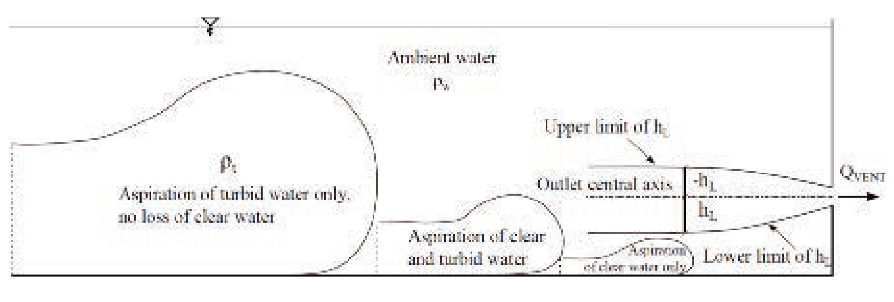


Figure 7. Schematic drawing showing the aspiration height hL with its upper and lower limits relatively to the central axis of the outlet delimitating the area that can be reached by the outlet flow field to evacuate sediments[11]

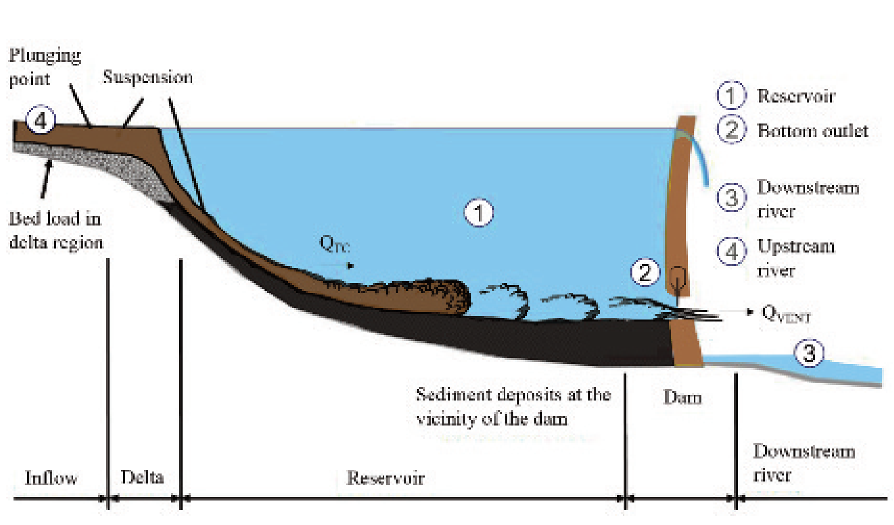


Figure 8. Turbidity currents traveling along the reservoir bottom at a discharge QTC with a projection of its venting through the bottom outlet at a discharge Q_{VENT}[11]

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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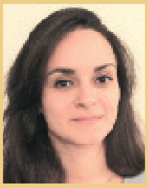
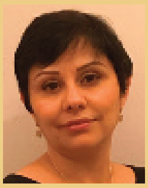


Sabine CHAMOUN accomplished her PhD at the Laboratory of Hydraulic Constructions (LCH) at the Ecole Polytechnique Fédérale de Lausanne (EPFL). During her doctorate, she worked on the management of reservoir sedimentation by venting turbidity currents. After a brief experience in operation and maintenance of African hydropower plants, she is now performing research on the renovation of Swiss hydropower plants.



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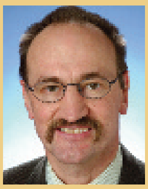

Anton J. SCHLEISS obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design in 1986. He worked for 11 years for Electrowatt Engineering Ltd (now Pöyry). In 1997, he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) of the EPFL. After retirement from teaching, he became Honorary Professor at EPFL in March 2018. He is also honorary President of the International Commission on Large Dams (ICOLD).

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