The importance of venting turbidity currents on the sustainable use of reservoirs

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Introduction

Reservoir sedimentation is an issue endangering the sustainability of reservoirs. Apart from reducing the capacity of a reservoir, sedimentation causes damages in hydraulic structures such as turbine intakes and bottom outlets. Additionally, downstream problems related to the river's ecosystem are also observed. Numerous techniques are tested worldwide in order to avoid or reduce the impact of reservoir sedimentation. Therefore, many techniques for avoiding and reducing reservoir sedimentation are being investigated and tested. Upstream measures are undertaken in the watershed where sediments are being trapped or deviated from reaching the reservoir. Other measures take place in the reservoir such as designing a dead storage, sediment bypass (Kantoush and Sumi, 2010), flushing (Lowe and Fox, 1995), dredging (Boillat et al., 2000), or venting of turbidity currents (Chamoun et al., 2016). Turbidity currents are sediment-laden flows that occur during yearly flood events and are driven by density differences. Once they reach the dam, unless evacuated by an intake or outlet, these currents deposit all their sediments, thus filling the reservoir and blocking outlet structures. To avoid these consequences, turbidity currents reaching the dam should be evacuated before the settling of the sediments they entrain. Generally, venting is performed through bottom outlets or power intakes. It helps in preserving a certain continuity of the natural morphology of the river while keeping the loss of water low due to relatively small required outflow discharges. If the reservoir is full during the flood event, venting allows releasing sediment-laden water instead of discharging clear water over the spillway.

The efficiency of a venting operation, defined as the ratio between the sediment mass vented to the inflowing sediment mass, is highly variable from one reservoir to another due to differences in sediment yield, reservoir dimensions and operational venting parameters. For instance, efficiencies can go from less than 1% such as the case of the Sefid Rud Reservoir (Morris and Fan, 1997) up to 100% in the Bajiazui Reservoir (Wang and Lin, 2004). Concerning the former, the reservoir's bed was lower than the bottom outlet when venting was firstly applied, which resulted in low venting efficiencies that increased drastically once the volume between the outlet and the bed of the reservoir was filled with sediments. While for the latter reservoir, the venting operation included sediments not only from the turbidity current but also sediments that settled close to the dam during past events. Field experiences also showed that efficiencies can be highly variable for the same reservoir. However, venting of turbidity currents has not been largely investigated in the past despite the fact that many researchers pointed out the importance of such a measure to prevent reservoir sedimentation. In literature, most of the discussions are based on field measurements and very few studies using experimental or numerical approaches has been done. However, before conducting research studies, it is important to review past venting experiences and identify the knowledge gaps.

The goal of this paper is to define and present the main conditions for venting. Then, a brief overview of the application of venting worldwide is given. On another hand, the major parameters affecting the efficiency of venting turbidity currents are exposed. Such parameters include the outflow discharge as well as the position and height of the outlet. Additionally, the main measuring instruments used in the field are presented followed by challenges that dam operators commonly face during venting. Finally, a conclusion and outlook for future work and research are given.

1. Conditions and efficiency of venting

Venting of turbidity currents is a reservoir sediment management technique that requires more data in advance than most of the other techniques. In fact, during such operations, not only hydraulic structures should be well-controlled, but also turbidity currents should be monitored. The understanding of the dynamics of turbidity currents has a direct effect on the efficiency of venting.

Before opting for such an operation, dam operators should verify some conditions. Firstly, the dam should preferably have a low-level or bottom outlet (Fig. 1) with sufficient capacity. Then, the presence of turbidity currents should be checked for the concerned reservoir. There are many indicators such as the observation of debris accumulation at the upstream end of the reservoir or the measurement of deposition forming a horizontal bed in the vicinity of the dam (Morris and Fan, 1997). For example, narrow and deep Alpine reservoirs were shown to have favourable conditions for the formation of turbidity currents (Oehy et al., 2000). Another crucial condition consists in the currents to reach the dam. In some cases, turbidity currents dissipate before reaching the dam and lead to low venting efficiencies. In Lake Mead reservoir for instance, a minimum inflow sediment concentration of 0.1 kg/m^3 is required for the turbidity current to reach the dam (Ren and Ning, 1985). This value is around 20 kg/m^3 for the Guanting reservoir (Chien and Wan, 1999). Finally, venting operations can last for long hours or days and thus the downstream river capacity should be capable of containing the released volumes of water and sediments.

The efficiency of venting is most commonly calculated based on the ratio between vented sediment masses and inflowing turbidity current sediment masses (Morris and Fan, 1997; Lee et al., 2014). However, it should be noted that while venting of turbidity currents the sediment deposits inside the dam, away from the outlet, cannot be eroded and released. In fact, due to the relatively low outlet discharges, and unlike flushing operations, there is no retrogressive erosion. Therefore, in order to have more significant efficiency values, deposited masses of the turbidity current away from the dam should be subtracted from the inflowing sediment masses. This approach should be rather used in numerical or experimental investigations due to the difficulty in measuring real-time deposition in the field. To overcome this difficulty, concentration measurements should be done in the vicinity of the dam. This provides the mass of sediments that actually reaches the dam before a venting operation.

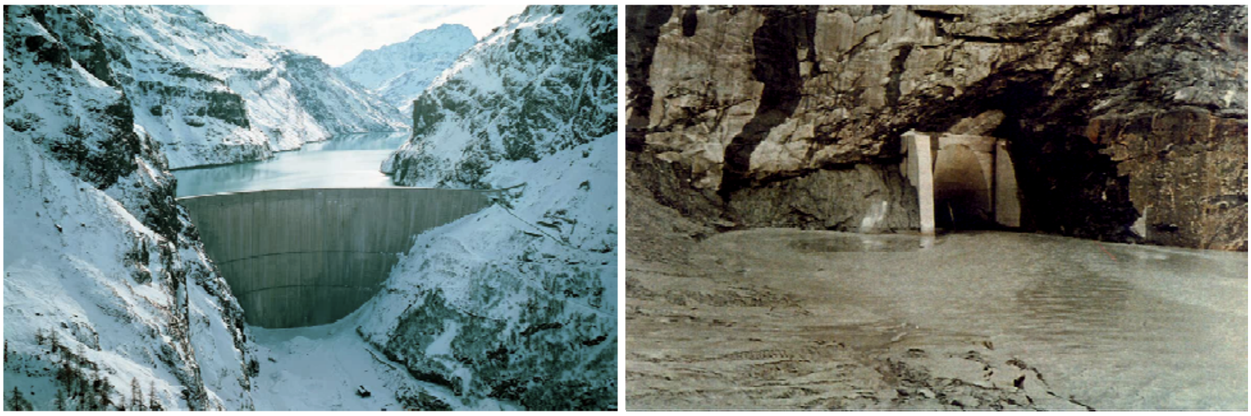

Fig. 1: (a) Mauvoisin dam (source: FMM) and (b) its bottom outlet showing high deposition

2. Venting worldwide

The first researcher to suggest that venting of turbidity currents can be used to reduce reservoir sedimentation was Bell (1942). However, turbidity currents were released earlier in 1919 at the Elephant Butte reservoir in the United States (Lee et al., 2014). Since then, venting of turbidity currents is being applied for different reservoirs where turbidity currents are detected. The map in Fig. 2 resumes the geographical distribution of the reservoirs where venting is or should be potentially applied. Note that this map does not include cases where no published data were found.

Fig. 2: Map showing the location and density of reservoirs where turbidity currents were observed and venting is applied

China is the country where venting is mostly applied. This is due to the presence of the Yellow River, the river that has the highest sediment load in the world (Morris and Fan, 1997). Venting efficiency in the Chinese reservoirs ranges from 18% in the Sanmexia reservoir (Wan et al., 2010) to 65% in the Fengjiashan reservoir (Ren and Ning, 1985) where several bottom outlets were placed at the right and left banks of the thalweg (Batuca and Jordaan, 2000). To the west of China, Iran's Sefid-Rud and Dez Dam reservoirs are the main two reservoirs where turbidity currents were observed. The former releases turbidity currents with an efficiency ranging from 2.3% to 35% (Morris and Fan, 1997). In Taiwan, typhoon events lead to the formation of turbidity currents transporting large amounts of fine sediments to the Shihmen and the Tsengwen reservoirs. In the former, one of the hydro-power turbines and its runner was transformed to a sediment sluice to release the sediments. A numerical study was conducted and showed that the efficiency of venting turbidity currents in this reservoir increased from 21% to 40% by adding an extra sluicing tunnel (Sloff et al., 2016). In the Tsengwen reservoir, Lee et al. (2014) used a combined experimental, theoretical and numerical approach to investigate the operation of venting. Efficiencies measured in the field for two different typhoon events did not exceed 1% when performed through the intake or the bottom outlet while the spillway could release sediments with an efficiency of 17% (Lee et al., 2014). In North of Africa, the Oued Neckar reservoir in Morocco and the Iril Emda reservoir in Algeria apply venting. The latter reservoir has venting efficiencies between 45% and 60% (Batuca and Jordaan, 2000). During the first year of operation, these values were lower because the sill of the outlets was 7 m above the bed (Raud, 1958). In Tunisia, the Nebeur reservoir performs venting operations depending on the concentration of the turbidity current reaching the dam (Abid, 1980 as cited by Ren and Ning, 1985). A minimum turbidity current density of 1020 kg/m^3 is required in order to operate the outlets. In Switzerland, the main venting operations take place in Mapragg reservoir where a ''venting alarm'' is triggered only when concentration are higher than 2 g/l. For lower concentrations, venting is less beneficial than a future dredging of sediment deposits (Müller and De Cesare, 2009). In the United States, the Lake Mead reservoir is where the longest travel distance of a turbidity current was observed. Efficiencies in this reservoir range from 18% to 39% (Ren and Ning, 1985). Another reservoir is the Elephant Butte build on the Rio Grande River, known with its high sediment load. Venting is applied with an efficiency of 9% to 23% (Lara, 1960). Finally, turbidity currents were also observed in other reservoirs such as the Sautet reservoir in France (Nizery et al., 1952), Daesti, Valcea and Raureni in Romania (Rosca et al., 1982), Ciudsko-Pskovskoe Reservoir in Russia (Filatova and Kalejarv, 1973) and venting operations are recommended.

3. Parameters affecting venting efficiency

The success of a venting operation depends not only on a good usage of hydraulic structures but most importantly on the understanding of the dynamics of turbidity currents. Hence, several parameters can affect the success and efficiency of this operation. Some parameters are operational and are thus related to the outlet such as: the position, dimensions, outlet discharge, timing of outlet opening, duration of venting, etc. On another hand, the concentration, grain size distribution, discharge and height of the turbidity current reaching the dam highly affect the venting efficiency. Additionally, morphological aspects of the watershed, the slope of the thalweg, and the length of the reservoir have a major role. Secondary parameters could include the legal, economic (Palmieri et al., 2001), and environmental aspects that also influence the decision-making in venting operations.
In order to assess and quantify the impact of each parameter, experimental and numerical approaches are a primary need. The parameters that were shown to be the most influential in literature (i.e., outlet discharge, position and height of the outlet) (Fig. 3) are discussed below.

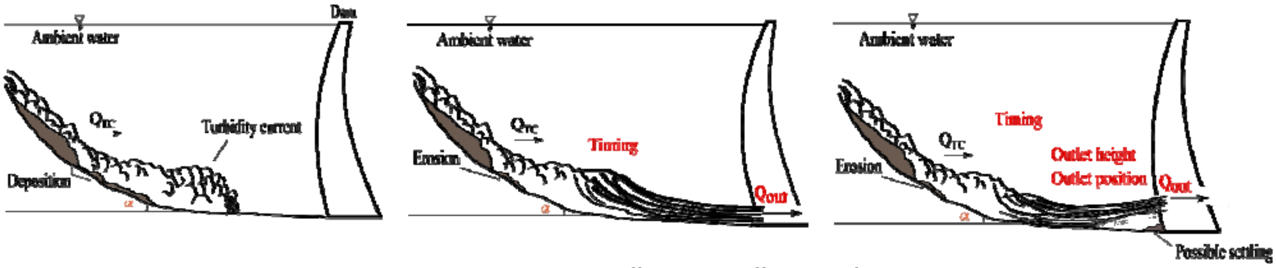

Fig. 3: Illustration highlighting the most important parameters affecting the efficiency of venting turbidity currents

3.1 Outlet discharge

The outlet discharge Q_{out} used during venting operations highly impacts the efficiency of the operation. Morris and Fan (1997) showed, based on data from the Sanmenxia reservoir, that increasing outlet discharges results in increasing venting efficiencies. Contrarily, Lee et al. (2014) concluded the opposite based on their experimental work. However, the outlet discharge should be chosen depending on the discharge of the turbidity current approaching the dam Q_{TC}. Thus, the normalized parameter Q_{out}/Q_{TC} is crucial. Commonly, Q_{out} is relatively low compared to Q_{TC} and venting is usually performed under restrained outflow discharges. In fact, Q_{TC} is a parameter that is difficult to measure and is usually related to the inflow discharge measured upstream of the reservoir. Since turbidity currents occur during floods, they can be put into relation with the flood discharges flowing into the reservoir. Nevertheless, depending on reservoir morphology, Q_{TC} are normally considerably higher than the inflowing floods with low frequencies. Table 1 below provides, for 22 large Swiss reservoirs, the capacity of the outlets Q_{outmax}, the direct watershed surface A, the 2 and 10 years return period flood discharges, and the maximum venting discharge ratio for each flood case Q_{outmax}/Q_2 and Q_{outmax}/Q_{10}.

Note that for the estimation of Q_2 and Q_{10} below, Francou coefficients k_2 and k_{10} (Francou and Rodier, 1967), as a function of the watershed surface and the flood discharge, were calculated for a 2 and 10 years flood discharges based on discharge and watershed data of 26 hydrometric stations (source: hydrodaten.ch) in Switzerland. The values obtained are $k_2 = 2.9$ and $k_{10} = 3.2$. It was then possible to calculate Q_2 and Q_{10} for the 22 chosen Swiss reservoirs knowing their direct watershed surface.

In Table 1, reservoirs are sorted starting from the lowest to the highest Q_{outmax}/Q_2. Results shows that in case of venting in reservoirs such as Schiffenen, Moiry, and Rossens, Q_{outmax}/Q_2 and Q_{outmax}/Q_{10} < 100% and outflow discharges are restrained compared to outflow discharges. For the remaining reservoirs, Q_{outmax}/Q_2 and Q_{outmax}/Q_{10} > 100% mean that the capacity of the outlet is higher than the 2 and 10 years flood discharges. Nevertheless, the full capacity of outlets is rarely used, even during flushing operations. The main reason for this discharge limit is that the downstream river capacity is not high enough to contain the maximum discharge of the outlet for long periods of time. High discharges can lead to risks of flooding and environmental disasters in the downstream river. For example, in the Luzzone reservoir, even if the $Q_{BOmax} = 52$ m^3/s, the highest flushing discharge that was used is 40 m^3/s while the most frequently used discharge is around 30 m^3/s (OFIBLE, 1992, 1993, 1994). This, for instance, leads to Q_{outmax}/Q_2 = 110% instead of Q_{outmax}/Q_2 = 193% in case of the Luzzone reservoir.
On a different note, as mentioned above, the discharge of the turbidity current reaching the dam Q_{TC} is usually higher than the flood discharge measured upstream. This is due to clear water entrainment of the turbidity current while flowing in the reservoir before reaching the dam. Therefore, Q_2 and Q_{10} below underestimate Q_{TC}. This leads once more to generally lower Q_{outmax}/Q_2 and Q_{outmax}/Q_{10}. Thus, it can be concluded that, in terms of

outlet discharge, operations of venting turbidity currents through bottom outlets are rather limited or slightly higher than the discharge of the turbidity current.

Table 1: The outlet capacity, watershed area, two and ten-year flood discharges, and corresponding outflow to inflow discharge ratios of 22 Swiss dams

Dam	Q_{outmax} [m³/s]	A [km²]	Q_2 [m³/s]	Q_{10} [m³/s]	Q_{outmax}/Q_2 [%]	Q_{outmax}/Q_{10} [%]
Schiffenen (3 outlets each)	133	1400	358	500	37	27
Moiry	55	245	104	153	53	36
Rossens (2 outlets each)	150	908	263	373	57	40
Grande Dixence (direct)	35	46	32	49	110	71
Emosson	95	183	84	125	112	75
Mattmark	57	88	50	76	114	75
Rossinière (2 outlets each)	193	398	146	213	131	90
Oberaar	26	21	18	29	143	90
Nalps	91	102	56	84	163	108
Mauvoisin	100	114	60	91	166	110
Zervreila	150	200	90	133	167	112
Punt dal Gall	200	295	118	174	169	115
Valle di Lei	123	137	69	103	179	119
Luzzone (direct)	52	37	27	42	193	123
Palagnedra	140	138	69	103	203	135
Santa Maria	124	102	56	84	223	147
Sambuco (direct)	53	30	23	36	228	145
Mapragg	214	159	76	114	280	188
Contra	340	233	100	148	339	230
Gebidem	250	150	73	110	342	228
Gigerwald	129	52	34	53	373	242
Rempen	192	83	48	73	400	263

3.2 Outlet height and position

Other important parameters of the venting include the outlet height and position. In fact, the importance of these parameters are directly linked to the height of aspiration of the outlet. It represents the height above and below the outlet opening where turbidity currents can be reached and evacuated. The height of aspiration was introduced and developed experimentally and theoretically by Gariel (1949) and Craya (1949) respectively. It is linked to the outlet discharge and to the density of the turbidity current being vented.

Depending on the height of the turbidity current approaching the dam and the position of the outlet, the height of aspiration includes part or the totality of the turbidity current to be released. Ideally, the outlet should be placed at the bottom as turbidity currents commonly flow at the bottom of the reservoir due to their high density. However, when placed at the bottom, the risk of early blockage is high. When placed at higher level, it was shown that the efficiency of venting is low until the space between the bottom of the reservoir and the lower sill of the outlet is filled. For this reason, the position of the outlet should be set depending on the height of aspiration of the outlet. In Fig. 4, the outlet is placed at the bottom. Its height is lower than the height of the head of the turbidity current approaching it. Thus, depending on the density of the current and the discharge of the outlet, the height of aspiration will include part or all of the sediment approaching the outlet.

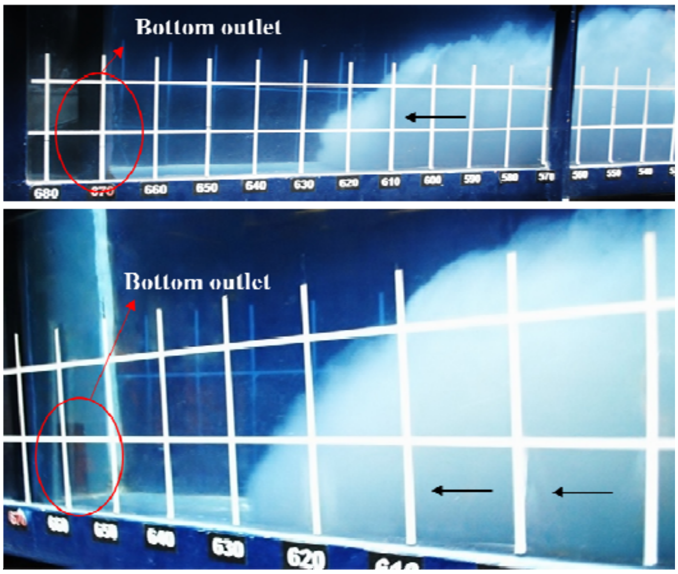

Fig.4: Case where the bottom outlet has a lower height than the head of the turbidity current

4. Monitoring instruments and challenges

In order to apply venting in optimized conditions, good monitoring is required. The latter allows in-time and efficient evacuation of the turbidity currents. Despite the complexity of the conditions, the monitoring of turbidity currents in reservoirs is progressing. Many variables should be monitored on the site. Optimally, measurements should be performed upstream, downstream, and in the vicinity of the dam. Going from the visual observation to specific and detailed measurements, different techniques are used. Some of the most important parameters to be checked are: the plunging point (can be done through visual observation), velocity and concentration profiles, erosion and deposition (bedforms) rates. Table 2 below gives an overview of the most known instruments available for field measurement of turbidity currents.

Table 2: Overview of instruments to measure turbidity currents in a reservoir

Instrument	Measured parameter
Multibeam echosounder	Image of the turbidity currents and bathymetry (Czuba et al., 2011; Hage et al., 2016)
ADCP (Acoustic Doppler current profiler)	Vertical velocity and concentration profiles in time (Hage et al., 2016; Haun and Lizano, 2016); Bathymetry (Dinehart, 2005)
Chirp profiles	Image of the dense near-bed zone (Schock et al., 1989; Hage et al., 2016)
Time Domain Reflectometry (TDR) probes	Sediment concentration (Sloff et al., 2016)
Laser or electrical-resistance based instruments	Bathymetry (Chamoun et al., 2016)
LISST (Sequoi Scientific Inc., 2011)	Suspended sediment concentration point measurement, particle size distribution and temperature (Haun and Lizano, 2016)
Vibrating-tube density meters (VTDMs); Coriolis Flow density meters (CFDMs)	Suspended sediment concentration point measurement and temperature (Felix et al., 2016)
Single-frequency acoustic attenuation method	Sediment concentration profile (Felix et al., 2016)
Turbidimeters	Turbidity and suspended sediment concentration point measurement (Müller, 2012; Rai and Kumar, 2015)

4.1 Challenges

Turbidity currents are usually triggered during yearly floods. Thus, their monitoring can sometimes be complicated from a practical point of view. Such currents can be very powerful and cause damage to measuring equipment. Examples include the Monterey Canyon in California (Xu et al. (2004)) where instruments were dislodged and found buried under thick sediment deposits during the monitoring of a powerful gravity flow on the 20th of December 2001. Another example is in Lake Lugano in Switzerland (De Cesare et al., 2006) where instruments mounted at a measurement chain were also lost and broken during the measurements.

Economically, field measurements of turbidity currents can be costly (Lee et al., 2014) and require high initial investment even though venting is beneficial in long term. Additionally, the construction of a new low-level outlet for existing dams is hardly achievable, which endangers the sustainability of the reservoir.

5. Conclusions and outlook

Reservoir sedimentation is a process endangering reservoirs' sustainability. Turbidity currents entrain the major part of the fine suspended sediments reaching the dam. Therefore, venting of turbidity currents into the downstream river is a technique that has benefits on ecological and economic sides.
Before opting for venting, turbidity currents should be observed and their auto-maintenance to the dam checked. Venting is preferably applied through outlets placed at a low level, close to the bottom of the reservoir. In addition, downstream environmental conditions should be considered during long operations.
A review of literature showed that venting is applied worldwide with varying conditions and efficiencies. The latter is defined as the ratio between the mass of sediments released through venting and the mass of sediments entrained by the turbidity current.
Several parameters affect the efficiency of venting such as the outflow discharge, the timing of the outlet opening, and the height and position of the outlet. The outlet discharge is a crucial yet delicate parameter of the venting process, since small outflow discharges can be as harmful as high discharges. It was shown that most of reservoirs would potentially vent under restrained outflow discharges. In other words, the outlet's discharge is most probably lower or slightly higher than the discharge of the turbidity current to vent. On another hand, the height and position of the outlet affect the aspiration height that can be reached during venting and represents one of the most influential parameters.
Finally, for good decision-making and efficiency assessment of venting operations, field measurements are required. However, many challenges induced by complicated and flood conditions during turbidity current flows can be encountered. Thus, numerical and experimental laboratory investigations are highly needed in the field of venting of turbidity currents. In such cases, measurements can be done for different parameters and systematic tests performed in order to optimize the efficiency of sediment evacuation through venting.

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Dr. G. De Cesare is senior research associate and deputy-director of the Laboratory of hydraulic constructions LCH of the Ecole Polytechnique Fédérale de Lausanne EPFL in Lausanne, Switzerland. He is in charge of the hydraulic laboratory. He has more than 20 years of experience in physical and numerical modelling in all domains of hydraulic structures and schemes with more than 50 studies performed as well as several commissioned studies and expert reports in applied hydraulics and hydraulic constructions. He specialises in various fields such as reservoir sediment management and turbidity currents; special hydraulic works; rapid transients in pressure systems; Ultrasonic Doppler flow measurement and river training work. Giovanni De Cesare holds an MSc in Civil Engineering and a PhD in technical sciences from the EPFL where he studied reservoir sedimentation by turbidity currents with on-site measurements, numerical simulation as well as experimental tests. He studied for one year at the Georgia Institute of Technology in Atlanta, USA. He is author of more than 120 scientific papers in peer-reviewed journals, publications and conference proceedings. He is reviewer of many journals and science foundations. From 1999 to 2009 he was lecturer and administrator of the Master of advanced Studies (MAS) programme in water resources management and engineering. He is member of the scientific council of the LCH and member of the EPFL board of lecturers. He is lecturer in hydraulic and energetic networks at Master level as well as in hydraulic structures at bachelor level. He supervises three ongoing PhD projects on turbidity current venting, head losses in pressure systems as well as on flood forecast suing data assimilation. He teaches also hydraulics, water networks and hydraulic schemes at the University of Applied Sciences of Western Switzerland HEIG-VD in Yverdon-les-Bains.

Prof. Dr. A. J. Schleiss graduated in Civil Engineering from the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland, in 1978. After joining the Laboratory of Hydraulic, Hydrology and Glaciology at ETH as a research associate and senior assistant, he obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design in 1986. After that he worked for 11 years for Electrowatt Engineering Ltd. in Zurich and was involved in the design of many hydropower projects around the world as an expert on hydraulic engineering and underground waterways. Until 1996 he was Head of the Hydraulic Structures Section in the Hydropower Department at Electrowatt. In 1997 he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) in the Civil Engineering Department of the Swiss Federal Institute of Technology Lausanne (EPFL). The LCH activities comprise education, research and services in the field of both fundamental and applied hydraulics and design of hydraulic structures and schemes. The research focuses on the interaction between water, sediment-rock, air and hydraulic structures as well as associated environmental issues and involves both numerical and physical modeling. Actually 19 Ph.D. projects are ongoing at LCH under his guidance. From 1999 to 2009 he was Director of the Master of Advanced Studies (MAS) in Water Resources Management and Hydraulic Engineering held at EPFL in Lausanne in collaboration with ETH Zurich and the universities of Innsbruck (Austria), Munich (Germany), Grenoble (France) and Liège (Belgium). Prof. Schleiss is also involved as an international expert in several dam and hydropower plant projects worldwide as well as flood protection projects mainly in Switzerland. From 2006 to 2012 he was Director of the Civil Engineering program of EPFL and chairman of the Swiss Committee on Dams (SwissCOLD). In 2006 he obtained the ASCE Karl Emil Hilgard Hydraulic Price as well as the J. C. Stevens Award. He was listed in 2011 among the 20 international personalities that "have made the biggest difference to the sector Water Power & Dam Construction over the last 10 years". 2014 he became also Council member of International Association for Hydro-Environment Engineering and Research (IAHR) and chair of the Europe Regional Division of IAHR. For his outstanding contributions to advance the art and science of hydraulic structures engineering he obtained in 2015 the ASCE-EWRI Hydraulic Structures Medal. After having served as vice-president between 2012 and 2015 he was elected president of the International Commission on Large Dams (ICOLD) in 2015.