Reservoir sedimentation management: practical guidelines for the implementation of mitigation measurements

M. Launay, M. Leite Ribeiro
Stucky SA
Renens
Switzerland

C. Juez, M. J. Franca and A. J. Schleiss
Laboratory of Hydraulic Constructions
Ecole Polytechnique Fédérale de Lausanne, EPFL,
Ecublens, Switzerland

1 Introduction

Worldwide's annual mean loss of storage capacity due to sedimentation is higher than the increase of capacity by construction of new reservoirs (Schleiss&Oehy 2002, Boillat et al. 2003). From this point of view, reservoirs are non-sustainable infrastructures. The necessity of sustainable sediment management was neglected for a long time which led to massive reservoir sedimentation worldwide (Basson 2009). In any project, all aspects related to reservoir sedimentation has to be considered since the planning and design phase, including the processes of erosion, transportation and deposition of sediments (Schleiss et al. 2010).

An integrated approach for sediment management is required in order to balance the sediment budget across reservoirs (Morris & Fan 1998). This includes the adequate physical analysis of the problem and the application of a corresponding strategy. There is a wide range of measures against reservoir sedimentation. They are usually classified in three groups, depending on the location in the basin where they are applied: in the river catchment upstream the reservoir, in the reservoir and at the dam (Fig. 1). Although the mitigation measures are well defined, the selection criteria are not clearly established and remains to the discretion of end-users.

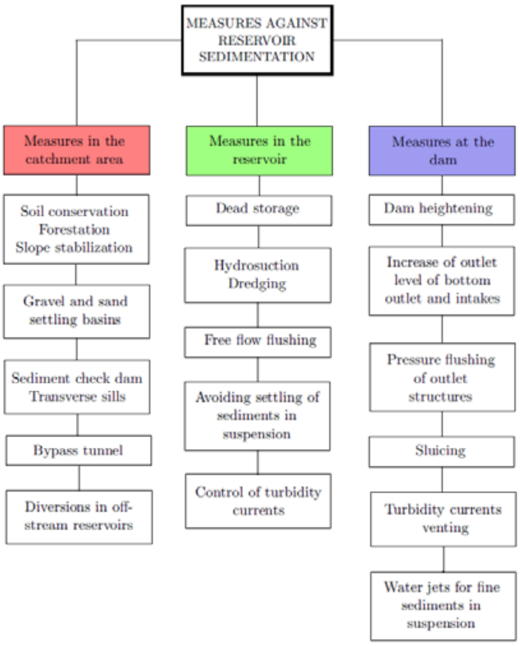


Fig. 1. Overview of measures for the mitigation of reservoir sedimentation after Schleiss and Oehy (2002)

The choice of the measures to mitigate the reservoir sedimentation requires a systematic approach. In this paper, a practical methodology which defines guidelines for the identification of the adequate mitigation measures against reservoir sedimentation, depending on the different characteristics of the projects under analysis is presented.

2 Negative effects of sediment trapping by reservoirs

The concept of sediment continuum embraces the sediment production in the river catchment and the sediment transport within the river, including deposition and erosion processes. The river morphodynamics reflects the sediment supply from upstream and is strongly influenced by implementation of artificial structures. Any alteration of the quantity of sediment supply or sediment quality may affect the morphological appearance of a reach and determine its deviation from an undisturbed condition (Sedalp, 2015). When building a reservoir, this interrupts the sediment continuum.

Fig. 2 illustrates the impact of the construction of a dam on a river. Once the reservoir is full of water, the water continuum can be kept to some extent. But in general, most of the sediments remain trapped in the reservoir, as no structures allow their transport through the dam. Downstream of the reservoir, the lack of sediment in the river leads to alterations of its morphology. As the river tends to regain the amount of sediment lost in the reservoir, erosion processes of the bank and of the bed takes place. This could result in disconnecting the river from its floodplain, and locally increasing the flood risk. The alteration of geomorphic pattern leads to negative impacts from the environmental point of view.

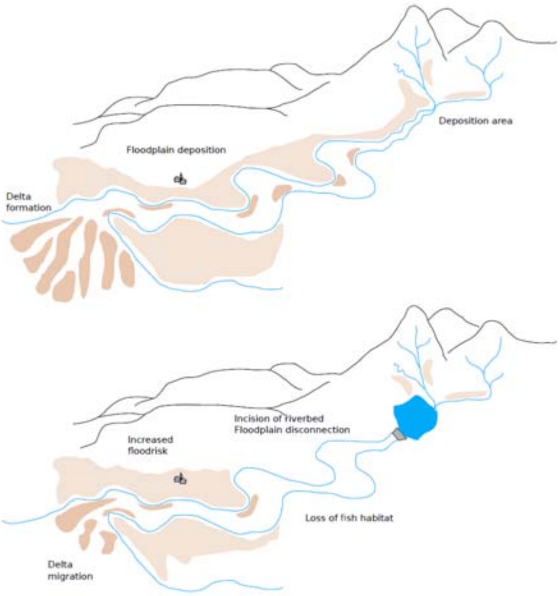


Fig. 2. Impact of reservoir construction on the sediment continuum

The accumulating sediments successively reduce the water storage capacity of the reservoir. Consequently, at long-term the reservoir operates only at reduced functional efficiency. Declining the storage volume reduces and eventually eliminates the capacity for flow regulation along with water supply, energy, and flood control benefits (ICOLD 1989, ICOLD 2012).

Reservoir sedimentation can even lead to a perturbation of the operating intakes as well as bottom outlets, and to sediment entrainment in waterway systems and hydropower schemes. Depending on the degree of sediment accumulation, the outlet works may be clogged by sediments. Blockage of intake and bottom outlet structures or damage to gates not designed for sediment passage present also severe security problems. Other consequences are sediments reaching intakes resulting in abrasion of hydraulic machinery, decreasing their efficiency and increasing maintenance cost.

As it was pointed out in Network (2004), the importance of the pollutants that may be trapped/stored by certain reservoirs should be also addressed. These contaminants can be degraded or fixed to sediment components, thus modifying their bioavailability. At a certain level, contaminants in sediment will start to impact the ecological or chemical water quality status and complicate sediment management. In the end, effects may occur such as the decreased abundance of sediment dwelling (benthic) species or a decreased reproduction or health of animals consuming contaminated benthic species. Contaminated sediments remain potential sources of adverse affects on water resources through the release of contaminants to surface waters and groundwater. Furthermore, contamination adversely effects sediment management, as handling of contaminated material, e.g. in the case of dredging, is several times more expensive than handling clean material.

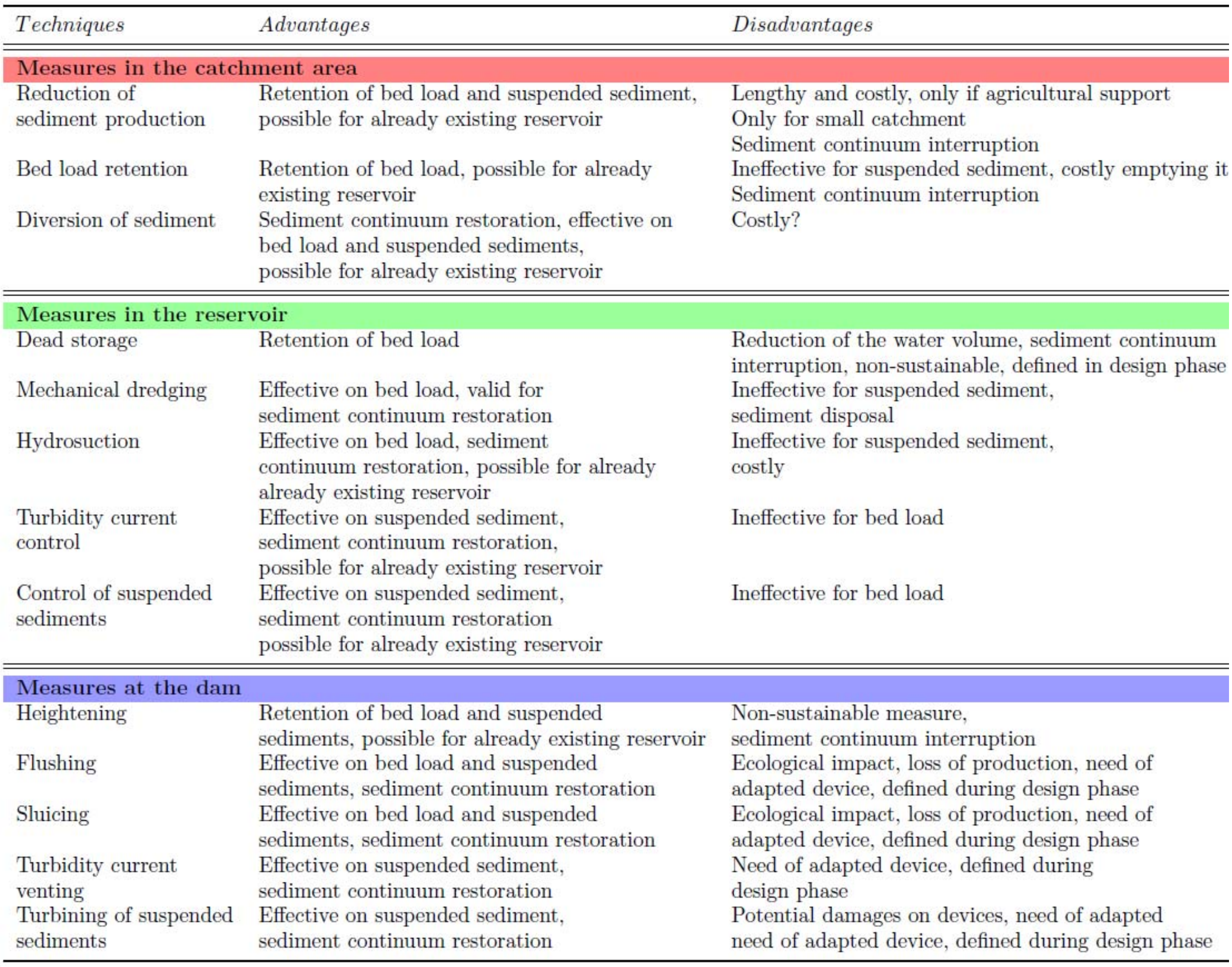
An adequate timing and pro-active management of the reservoir sedimentation helps in the mitigation of these mentioned problems.

3 Existing sediment management techniques

A comparison of the well known mitigation measures is presented in Table *1*. Some of the advantages and disadvantages presented are of course subjective and mainly driven by the interests of the reader/user. The following parameters are considered:

- the effectiveness of the measure on bed load and suspended sediments,
- the restoration of the sediment continuum, or its interruption,
- the short-term or long-term character of the measure, i.e. its sustainability,
- the maintenance costs, and the need of a solution for sediment disposal,
- the need for a particular support or context to apply the measure.
- the possibility to set up a measure for an already existing reservoir.

Table 1: Advantages and inconvenient of each mitigation measure



Techniques	*Advantages*	*Disadvantages*
Measures in the catchment area		
Reduction of sediment production	Retention of bed load and suspended sediment, possible for already existing reservoir	Lengthy and costly, only if agricultural support Only for small catchment Sediment continuum interruption
Bed load retention	Retention of bed load, possible for already existing reservoir	Ineffective for suspended sediment, costly emptying it Sediment continuum interruption
Diversion of sediment	Sediment continuum restoration, effective on bed load and suspended sediments, possible for already existing reservoir	Costly?
Measures in the reservoir		
Dead storage	Retention of bed load	Reduction of the water volume, sediment continuum interruption, non-sustainable, defined in design phase
Mechanical dredging	Effective on bed load, valid for sediment continuum restoration	Ineffective for suspended sediment, sediment disposal
Hydrosuction	Effective on bed load, sediment continuum restoration, possible for already already existing reservoir	Ineffective for suspended sediment, costly
Turbidity current control	Effective on suspended sediment, sediment continuum restoration, possible for already existing reservoir	Ineffective for bed load
Control of suspended sediments	Effective on suspended sediment, sediment continuum restoration possible for already existing reservoir	Ineffective for bed load
Measures at the dam		
Heightening	Retention of bed load and suspended sediments, possible for already existing reservoir	Non-sustainable measure, sediment continuum interruption
Flushing	Effective on bed load and suspended sediments, sediment continuum restoration	Ecological impact, loss of production, need of adapted device, defined during design phase
Sluicing	Effective on bed load and suspended sediments, sediment continuum restoration	Ecological impact, loss of production, need of adapted device, defined during design phase
Turbidity current venting	Effective on suspended sediment, sediment continuum restoration	Need of adapted device, defined during design phase
Turbining of suspended sediments	Effective on suspended sediment, sediment continuum restoration	Potential damages on devices, need of adapted need of adapted device, defined during design phase

4 Methodology for the choice of management solution

4.1 Concept of the methodology

The proposed methodology to help the decision makers to define the most adapted mitigation solution to their reservoir is depicted in Fig. 3. This methodology relies on three main steps.

The first step is a technical analysis of the problem. It aims at defining the feasible measures by relating a characterization of the problem through key parameters and the panel of available technics. The main goal of this first part is the definition of these key parameters, and their connection or influence on available technics described in Table 1. As for the mitigation measures, the characterization parameters can be related to the four parts of the problem: the catchment area, the reservoir itself, the structure closing the reservoir (dam, weir), and the downstream area.

The characterization of the downstream area is more difficult to generalize, as it strongly depends on the local context. Therefore, it is proposed to be considered it in a second step. The characterization parameters are numerous and their relation with the mitigation technics would be fastidious. For simplification purpose, we propose to gather this information in so-called key-parameters.

The second step consists in the definition of the adapted solutions, by taking into account the local context of the problems. This step allows to consider ecological, economical, political, legislation, and other local constraints, particular to each problem.

The third step is the implementation and the monitoring of the chosen measures.

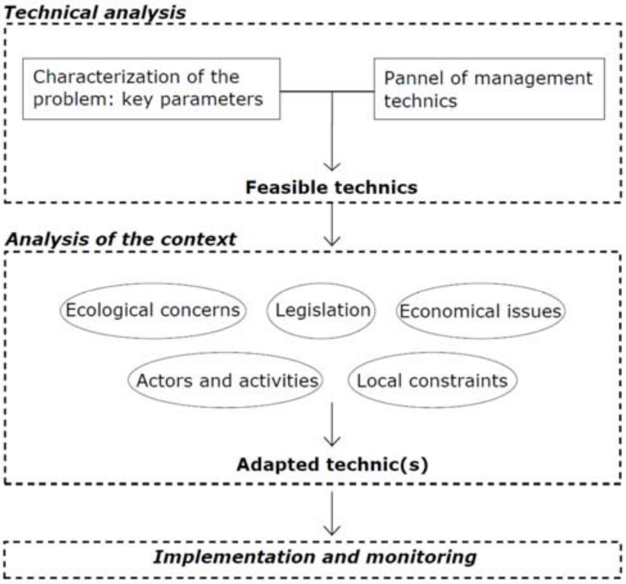


Fig. 3. Methodology for the choice of the management solution

4.2 Technical analysis (step 1): determination of feasible measures

Characterization of the problem: the fact-sheet

The mitigation of reservoir sedimentation is conducted by a list of techniques which helps in this goal. However, the choice, feasibility and success of these strategies require firstly the definition of the particularities surrounding each reservoir. As for the mitigation measures, the characterization parameters can be related to the four parts of the problem: (i) the catchment area, (ii) the reservoir itself, (iii) the structure closing the reservoir, and (iv) the downstream area. In order to help the manager to characterize its problem, a fact-sheet listing the four areas of the problem, and summarizing their related parameters and options is proposed (Table 2).

Key parameters and relations with mitigation measures

The mitigation of reservoir sedimentation requires a systematic approach. The characterization parameters can be defined for the four parts of the problem. Some parameters can be gathered in some key parameters that give influencing information for the choice of mitigation measures:

For the catchment,

- The quantity of sediment entering the reservoir. This value can be expressed with the help of the Sediment Delivery Ratio (SDR).
- The grain-size of the sediment entering the reservoir, expressed for instance as the median diameter of the grain-size distribution. This key parameter gathers information on the soil composition, geology, as well as sediment transport processes occurring upstream of the reservoir.
- The chemical quality of the sediment. This is representative of the land-use, and activities within the catchment.

For the reservoir,

- The relative size of the reservoir, given by the ratio between the volume of the reservoir and the area of the catchment. The use of the reservoir life indicator, calculated as the ratio between the initial capacity of the reservoir and the mean annual sediment (MAS) inflow (Sumi and Kantoush, 2011) can also be used.
- The purpose of the reservoir.
- The state of the project and the existing structures available for sedimentation management.

The determination of these key parameters should allow the decision makers to define the mitigation measures that can be applied to their problem.

Table 3 summarizes the relations between the key parameters and the existing measures.

Table 2: Fact-sheet for the characterization of the problem.

Area	*Related parameters*	*Options*
Catchment	Climate	Tropical, Dry, Moderate, Continental, Polar
	Area	Small, medium, large
	Mean slope	Flat, moderate, steep
	Elevation	Low, intermediate, high
	Hydrographic network	Natural/branched, engineered/linear
	Hydraulic regime	Subcritical, supercritical, regulated
	Land use/land cover	Agriculture, bare soil, forest, etc.
	Geology	Detritic, metamorphic, etc.
	Sediment grain size	Coarse, Fine
	Sediment nature	Non-cohesive, cohesive
	Sediment quality	Polluted, clean
Reservoir	Volume	Small, medium, large
	Shape	Linear-dendritic, Oval circular
	Purpose	Water supply, flood protection, energy production, leisure, ecology
	Flooding periodicity	Long, short, seasonal floods
	State of the project	Already existing, projected
Existing structures	Dam	Evacuation systems, turbines
	Bypass tunnel	Evacuation systems
Downstream	Ecological issues	Protected species, ecological flow, etc.
	Legislation	Flood protection, safety of infrastructures, etc.
	Actors and activities	Multi-use, fishing activity, leisures, etc.
	Economical issues	

Table 3: Relation between mitigation measures and key parameters. TC: turbidity current, SS: suspended sediment

		Catchment area			Reservoir					Dam				
Key parameters		Reduction production	Bed load retention	Diversion	Dead storage	Dredging	Hydrosuction	TC control	Control of SS	Heightening	Flushing	Sluicing	TC venting	Turbining of SS
Quantity of sediment	Small	x	x		x	x	x	x	x	x	x	x	x	x
	Intermediate	x	x	x		x	x	x	x	x	x	x	x	x
	High	x		x				x	x		x	x	x	x
Grain-size of sediment	Fine	x		x				x	x	x	x	x	x	x
	Coarse	x	x	x	x	x	x			x	x	x		
Chemistry of sediment	Polluted	x	x		x	x	x			x				
	Clean	x		x	x	x	x	x	x	x	x	x	x	x
Reservoir life	Short		x	x		x	x				x	x	x	x
	Intermediate	x	x	x		x	x	x	x		x	x	x	x
	Long	x	x	x	x			x	x	x	x	x	x	x
Purpose of reservoir	Water supply	x	x		x					x				
	Flood protection	x	x	x	x	x	x	x	x	x	x	x	x	x
	Energy production	x	x	x	x	x	x	x	x	x	(x)	(x)	x	x
State of reservoir	Existing	x	x	x	x	x	x	x	x	x	x	x	x	x
	Planned	x	x	x	x	x	x	x	(x)		x	x	x	x

4.3 Analysis of the context (step 2): determination of adapted measures

The second step of the methodology consists in taking into account the local constraints. Ecological issues, legislation, other actors and activities should be considered. The design and later management of reservoir sedimentation also require a sustainable planning in order to minimize the ecological effects. In some cases, the legislation imposes ecological flow downstream of the reservoir. Maximum sediment concentration values can also be determined to preserve the natural life of the river during flushing events. In case of pollution identified upstream of the reservoir, the quality of the sediment delivered downstream should be carefully controlled in order to prevent contamination.

The management of sediment should also be conducted in accordance with the local politics in terms of flood protection, safety of the populations and infrastructures. It implies for instance that the sediment continuum should be preserved to prevent erosion of the banks and disconnection of the river from its floodplain.

The river may also contribute to other activities downstream of the reservoir. The local actors should be consulted for the definition of the sediment management strategy. And finally, economical issues would be of high relevance for the determination of the final strategy (Annandale, 2014).

4.4 Implementation and monitoring of the measures (step 3)

The implementation of the adapted measures would be mainly driven by the state of the project. If the reservoir already exists, some adaptations of the devices could be necessary. In the case of a planned project, the sediment strategy would be integrated to the project. It is of high importance to consider this question during the first stages of the project to keep as much possibilities as possible.

The monitoring of the sedimentation processes taking place in the reservoir should also be planned during the design phases. It should be performed by (i) measuring the sediment input and output of the reservoir, (ii) controlling the sediment quality (grain-size and composition), (iii) performing bathymetry of the reservoir regularly to control the sedimentation evolution.

5 Conclusion

An integrated approach for sediment management is required in order to balance the sediment budget across reservoirs. Integrated sediment management includes the analysis of the problem with its particularities and application of a range of strategies. This document provides practical guidelines for the choice of a mitigation measures to prevent reservoir sedimentation.

The proposed methodology relies on the characterization of the problem through technical key parameters. Local constraints that are more difficult to generalize are discussed.

It is important to keep in mind that every reservoir is a prototype problem and no general applicable mitigation measures can be given except to analyse the problem with a well-defined and systematic methodology as proposed.

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The Authors

Dr. Marina Launay graduated in Water Sciences and Technology from the École Polytechnique Universitaire of Montpellier (France) in 2010. After joining the National Research Institute of Science and Technology for Environment and Agriculture (Irstea) in Lyon (France), she obtained in January 2014 a Doctorate of hydraulic and environmental chemistry on the topic of fluxes of suspended particulate matters and associated PCBs and mercury in the Rhône river, from lake Geneva to the Mediterranean Sea. In August 2014 she started working as a research and design engineer at Stucky SA, Renens, Switzerland. She is involved in the SEDITRANS project as an experienced researcher to conduct engineering applications on fluvial hydraulics.

Dr. Marcelo Leite Ribeiro is a civil engineer with around 15 years of experience in fluvial hydraulics, sediment transport, hydraulic structures and hydropower projects. After 2 years of experience in small hydropower projects in Brazil, he moved to Switzerland where he followed a Master of Advanced Studies in Hydraulic Schemes (MAS, 2003-2005, part-time) and he was awarded a PhD in Civil Engineering (2011), both at the Ecole Polytechnique Fédérale de Lausanne (EPFL). In Switzerland, he worked as an engineer at the Laboratory of Hydraulic Constructions (LCH-EPFL) for 7 years in both research (MAS and PhD) and private projects. During that time, he acquired a considerable experience in physical and numerical hydraulic modeling. The subjects of his MAS and PhD were reservoir sedimentation and morphodynamic of river confluences respectively. Since 2011, he is working at Stucky SA in projects involving mainly conception, design, technical-economic analysis and construction of different parts of a hydropower scheme. He is currently the Stucky's Project Manager of SEDITRANS Project.

Dr. Carmelo Juez graduated as Industrial Engineer at Universidad de Zaragoza, Zaragoza (Spain) in 2010. Afterwards, he conducted a Master degree in Applied Mechanics, focusing on computational fluid-dinamics techniques. In September 2011, he joined the Computational Hydraulics Group at Universidad de Zaragoza and he worked in both research and private projects and also as a developer of commercial codes (http://www.hydronia.net/). His field of research was focused on the study of geomorphological flows in two fields: 1) sediment transport with uniform and non-uniform grain size mixtures in alluvial channels and 2) hazardous landslides over steep areas. Additionally, efficient computation with up-to-date techniques, such as OMP parallelization and GPU, were also considered during his work. He finally obtained his Doctorate under the supervision of Dr. Javier Murillo in May 2014 (http://zaguan.unizar.es/record/15604). From June 2014 to Octuber 2014 he worked at the Université Catholique de Louvain (Belgium) carrying out several experiments for studying the effects of steep slopes over the bedload sediment transport. Finally, he was enrolled in SEDITRANS Project as an experienced researcher for conducting experiments on turbidity currents, studying morphological changes in reservoirs and in the vicinity of man-made structures due to the transfer of fine sediments by turbidity currents. Additionally, he will transfer the academic knowledge about sediment transport modelling and reservoir sedimentation to the industrial partners. The combination of analytical and numerical modelling with laboratory experiments and field cases constitutes the basis of his research.

Dr. Mário J. Franca is Research and Teaching Associate of the Laboratory of Hydraulic Constructions of the École Polytechnique Fédérale de Lausanne (EPFL) and Assistant Professor (on leave) of the Universidade Nova de Lisboa. Graduated from the University of Lisbon (IST) as a civil engineer in 1998 and as a MSc. in Hydraulics and Water Resources in 2002. In 2005 he obtained a doctoral degree in sciences at EPFL in the field of fluvial hydraulics/fluid mechanics. His present research focus on fluvial hydraulics, namely in turbulence in open-channel flows, sediment transport, fluvial geomorphology, and density currents. He is author of several scientific publications and he gives regularly invited seminars in these fields of research. He is part of the leading teams of the IAHR sections on Fluvial Hydraulics and on Experimental Methods and Instrumentation. He served as hydraulic engineer several times having worked in more than 70 projects in water supply, drainage, dams, hydropower schemes, river engineering, emergency planning, safety of hydraulics infrastructures, rehabilitation of mining sites, and master plans. He is associate editor of Water Resources Research.

Prof. Dr. Anton 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. Currently 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.