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RESERVOIR SEDIMENTATION PART 2

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INNOVATIVE STRATEGIES FOR MANAGING RESERVOIR SEDIMENTATION IN JAPAN

SEE PAGE 100

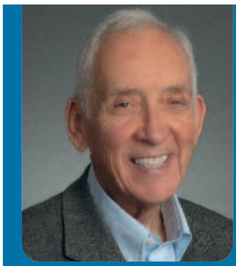
SILTING OF RECHARGE DAMS IN OMAN

SEE PAGE 115

RESERVOIR SEDIMENTATION: CHALLENGES AND MANAGEMENT STRATEGIES

EDITORIAL BY KAMAL EL KADI ABDERREZZAK & ANGELOS N. FINDIKAKIS

The last issue of Hydrolink focused on reservoir sedimentation with articles on the problems experienced in different parts of the world and the mitigation measures taken in response. Because of the large interest among IAHR members and the broader water resources management community, the current issue includes more articles on the subject where researchers and other technical experts from different countries share their views on how to deal with this problem. This is the second of three issues of Hydrolink focusing on the challenges related to reservoir sedimentation and aiming at disseminating knowledge and lessons learned on successful sediment management strategies.



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Hydrolink Editor

Kamal El kadi Abderrezzak
Guest Editor

As already mentioned in several of the articles published in the previous issue, sedimentation reduces reservoir storage capacity and the benefits derived therefrom, such as flood and drought control, water supply, hydropower, irrigation, groundwater recharge, fish and wild life conservation, and recreation. In addition, the sediment imbalance throughout the water system caused by dams operated without sediment management facilities (*e.g.* bottom outlets, spillways, bypass tunnels) leads to significant infrastructure and environmental damages both upstream and downstream of the reservoir.

The traditional approach in the design of reservoirs was to create a storage volume sufficiently large to contain sediment deposits for a specified period, known as the economic life of the project or "design life" (typically 50 or 100 years). After their "design life" is reached, dams and reservoirs would have to be taken out of service, leaving future generations to have to deal with dam decommissioning and the handling of the sediments. Yet, dam decommissioning is getting costlier and removal of deposited sediment is not a simple task, because the volume of deposited sediment in a reservoir over its design life can amount to millions, if not billions, of cubic meters[1]. For example, the net cost of decommissioning the Tarbela Dam in Pakistan, whose storage capacity as of last year had been reduced by 40% due to sedimentation[2], according to one estimate is US$2.5 billion[1]. Dam owners and operators have therefore strong interest in finding ways for extending the life of reservoirs, continuing to generate economic and social benefits even if they are not as large as in the original condition of the project.

With increasing demand for water supply and hydropower, aging infrastructure, coupled with the limited number of feasible and economical sites available for the construction of new reservoirs[1], the importance of converting non-sustainable reservoirs into sustainable elements of the water infrastructure for future generations is evident. While the 20th century was concerned with dam reservoir development, the current century needs to focus on reservoir sustainability through sedimentation management[3]. Solutions are needed for the removal of both fine sediments (clay and silt), as well as coarse sediments (sand and gravel).

It is possible to manage reservoir sedimentation by using one or more techniques[4]. The three main strategies for dealing with reservoir sedimentation are:

(1) reducing incoming sediment yield into reservoirs through watershed management, upstream check dams and off-channel storage;

(2) managing sediments within the reservoir through suitable dam operating rules for protecting the intakes from the ingress of sediments, tactical dredging in the vicinity of the dam outlets, and the construction of barriers to keep the outlets clear; and

(3) removing deposited sediment from reservoirs by flushing, sluicing, venting of a sediment-laden density current, bypass tunnels, dredging, dry excavation or hydrosuction.

Each technique has its advantages and shortcomings in terms of cost, applicability and environmental impacts, as described by Kondolf and Schmitt in the previous issue of Hydrolink. A perfectly sustainable strategy for every situation does not exist, but efforts can be optimized for the particular conditions of each reservoir. In the current issue, examples of operations and strategies are given from Japan by Sumi and Kantoush and from Taiwan by Wang and Kuo, showing that current and new facilities need to be designed, re-operated, and/or retrofitted to limit the loss of reservoir capacity due to sedimentation. Both articles provide lessons to help guide planning and design of new dams, and establish design standards for sustainable reservoir management.

An example of a specific field case is presented in the current issue by Peteuil who describes a successful example of sediment management in cascade reservoir dams on the Rhône River from the Swiss border to the Mediterranean Sea. Sediment is managed in reservoirs and channels of the Upper Rhône by flushing, such that the opening of the gates for the sediment release is coordinated from dam to dam. Routing and regulation of fine suspended sediment concentrations discharged from the upper Swiss reservoirs are performed in the French Génissiat reservoir where the dam is equipped with three outlets. The sediment flushing is conducted under extremely strict restrictions on suspended sediment concentrations. This "environmentally friendly flushing" from the Génissiat Dam limits the potential adverse impacts to the downstream environment (*e.g.* aquatic life, restored side-channel habitats) and water supply intakes. An interesting analysis of the effects of sediment flushing is presented in the article by Castillo and Carrillo who investigated the morphological changes in the Paute River (Ecuador - South America) as a result of the future construction of the Paute - Cardenillo Dam and associated sediment flushing operations.

Water resources are limited in arid counties. In the case of the Sultanate of Oman, recharge dam reservoirs are widely used for enhancing groundwater resources through making use of stored flood waters, which otherwise would have flowed to the sea and or spread in the desert. These reservoirs are facing, however, serious problems of sedimentation, which reduces their storage capacity and decreases the rate of water infiltration in the subsurface, as described by Al-Maktoumi in the current issue. The same article discusses different measures for dealing with this problem.

Some of the problems associated with reservoir sedimentation are studied by different research organizations. For example, at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, Switzerland, field, laboratory and numerical research projects on reservoir sedimentation are conducted. Research topics cover reservoir sedimentation in the periglacial environment under climate change, hydroabrasion of sediment bypass tunnels, and transport fine sediment through turbines as countermeasure against reservoir sedimentation. More details on these challenging research programs are given by Albayrak *et al.* in the current issue.

The U.S. Army Corps of Engineers (USACE) is continually sharing its sustainable reservoir management knowledge base. An example of such effort is given by Shelley *et al.* in this issue, illustrating a collaboration between reservoir sedimentation experts from the USACE and the Government of Lao People's Democratic Republic (Lao PDR). The overall goal of this collaboration is to improve the environmental and social sustainability of hydropower development in the Mekong River Basin.

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Cover picture: Wujie Reservoir on the Zhuoshui (also spelled Choshui) River in Taiwan; construction of the dam was completed in 1934; photograph taken in early 2018. (Courtesy Hsiao-Wen Wang, Department of Hydraulic and Ocean Engineering, National Cheng Kung University)

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IN THIS ISSUE

RESERVOIR SEDIMENTATION PART 2

INNOVATIVE STRATEGIES FOR MANAGING RESERVOIR SEDIMENTATION IN JAPAN

BY TETSUYA SUMI AND SAMEH A. KANTOUSH

The major threat to extend the life expectancy of dams in Japan is reservoir sedimentation. Upgrading and retrofitting aging dams is mandatory to maintain their purposes and safety over the productive life cycle. A perfectly sustainable solution for every situation does not exist, but it is essential to select a sediment management strategy appropriate for the particulars of each reservoir, considering both the sedimentation issues in the reservoir and environmental conditions in the channels downstream of the dam. The key criteria are timing of implementation and an appropriate combination of viable sediment management strategies.

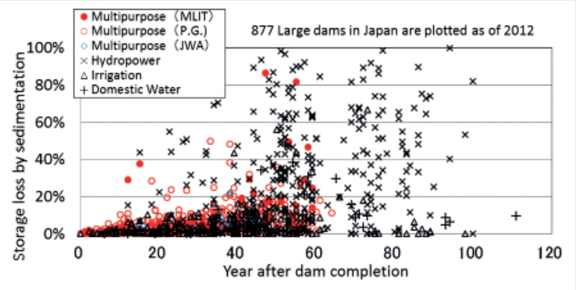


Figure 1. Evolution of the reservoir sedimentation rate over dam's age. (MLIT: Ministry of Land, Infrastructure, Transport and Tourism, P.G.: Prefectural Government, JWA: Japan Water Agency)

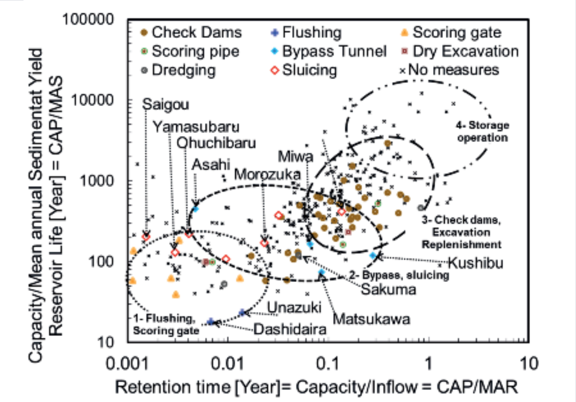


Figure 2. Plot of projects in Japan with different sediment management strategies. Reservoir life is indicated by the ratio between the reservoir storage capacity and the mean annual inflow sediment to the reservoir (CAP/MAS). The residence time of water (called also retention time, impoundment ratio) is defined as reservoir capacity volume/mean annual river inflow to the reservoir (CAP/MAR)

Reservoir sedimentation issues in Japan

In Japan, there are more than 2700 operating large dams, *i.e.* dams higher than 15 m, with a median age of 61 years. Among them, 900 dams have reservoir volumes larger than one million m^3 (1 Mm^3). The total reservoir storage capacity remains, however, limited, approximately 23,000 Mm^3. The sediment yield is relatively high due to the topographical, geological and hydrological conditions of the drainage basins. Based on annual data from 877 reservoirs, the sediment yield rate was found to range from several hundred to several thousand m^3/km^2-year. The annual storage capacity loss due to reservoir sedimentation is low, approximately 0.24%, with a high average of 0.42% in the high mountainous central Japan region that is on tectonic lines[1]. Figure 1 shows the reservoir capacity loss due to sedimentation (*i.e.* sedimentation volume/reservoir gross storage capacity) over the dam age. The cumulative storage loss due to sedimentation reaches 60% to 80 % in some hydroelectric reservoirs operating for more than 50 years. Multi-purpose reservoir dams show less sedimentation losses, *i.e.* 20% to 40 % in general.

The aging of dams and continuous loss of water storage capacity due to sedimentation, coupled with increasing environmental needs, have

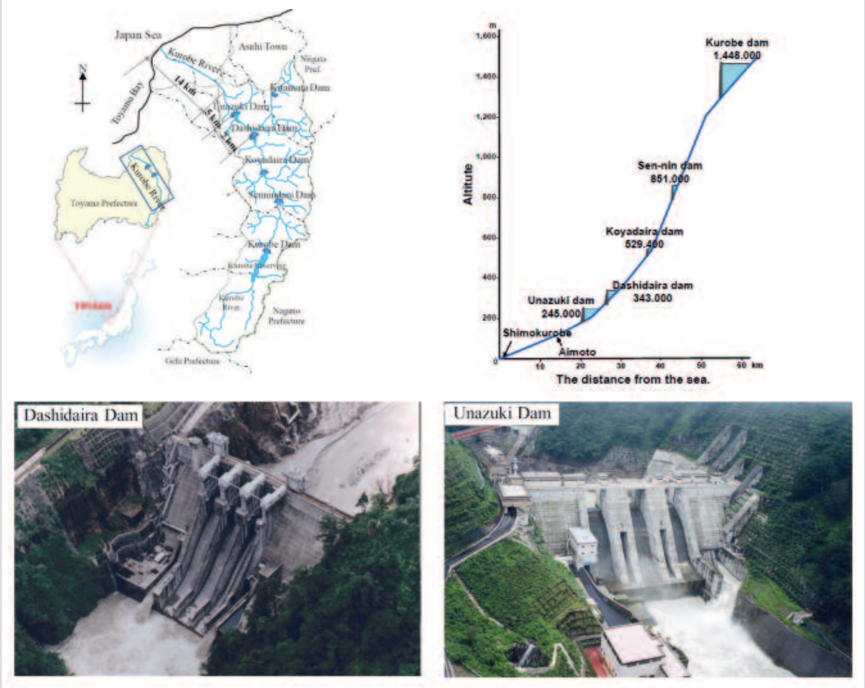


Figure 3. Location map of the Dashidaira Dam (high: 76.7 m, initial storage capacity: 9 Mm^3, annual sediment inflow: 0.62 Mm^3) and the Unzauki Dam (high: 97 m, initial storage capacity: 24.7 Mm^3, annual sediment inflow: 0.96 Mm^3). Photos show the two dams during a coordinated sediment flushing operation

caused growing concerns on social, economic, and environmental fronts[2]. Preventing the accumulation of sediment in multi-purpose reservoirs is a key issue for sustainable use of the resource and to safeguard the river environment.

Japan is a world leader in the variety of implemented sediment management techniques, such as trapping sediments by check dams (*i.e*. *Sabo*), dredging, sluicing (*i.e*. sediment pass-through), flushing, bypassing, and adding sediments to river channels below dams (*i.e*. gravel augmentation or replenishment). Figure 2 illustrates the range of techniques implemented in Japan. More than one technique may be applied at a given reservoir, either sequentially or concurrently, depending on the reservoir's hydrologic capacity. Supplying the excavated gravel material to reaches below dams to support development of bars and other complex channel features, which are essential for the flora and fauna of the aquatic environment, is widely promoted and used in Japan[3].

Currently, reservoir sedimentation management in Japan is entering a new stage from two perspectives[3]. First, in contrast to conventional countermeasures, such as dredging and dry excavation, sediment flushing and bypass systems are being progressively introduced with the aim of radically abating sediment deposition in reservoirs. Secondly, integrated approaches for restoring effective sediment transport in the routing system, from mountains to coastal areas, is being initiated. However, sediment flushing and bypassing have only been applied in a limited number of cases; further studies are indeed required. This article describes examples of sustainable sediment management techniques by flushing in the Dashidaira and Unazuki dams in the Kurobe River, sluicing in the Mimi River, and by adding gravel to the river below dams (*i.e*. sediment replenishment/ augmentation).

Coordinated flushing and sluicing operations in the Kurobe River

The Kurobe River on the eastern Toyama Prefecture is a typical steep river, 85 km long for a drainage area of 682 km^2. The average annual rainfall and total sediment yield are 4000 mm and 1.4 Mm^3/year, respectively. The river is one of the most important rivers in Japan due to the cascade reservoir system constructed along the watercourse and the considerable power energy produced (Figure 3).

Figure 4. Flushing and sluicing operations in the Dashidaira and Unzauki dams

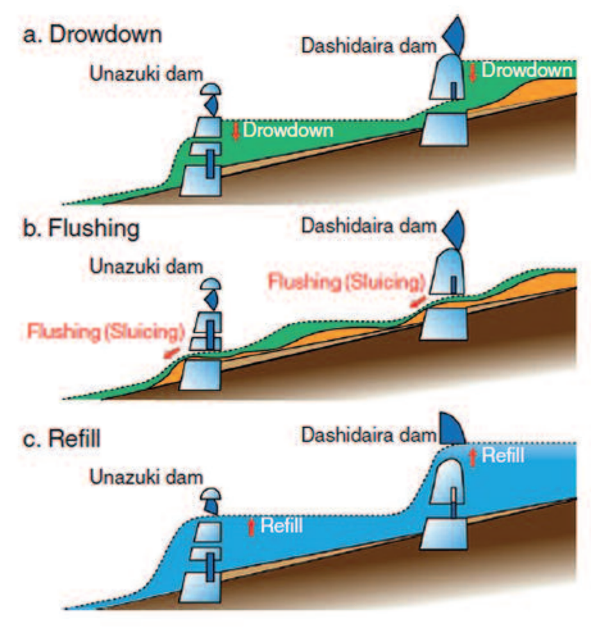
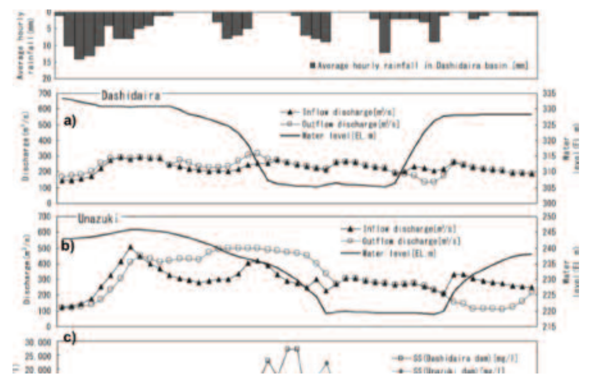


Figure 5. Coordinated flushing at reservoirs in the Kurobe River, 1–3 July 2006[6]. Inflow and outflow hydrographs and reservoir stage for (a) Dashidaira and (b) Unazuki dams. (c) resultant suspended sediment (SS) concentrations. Shimokurobe is near the river outlet at Japan Sea



graphic incomplete?

The Dashidaira dam was completed in 1985 by the Kansai Electric Power Co, Ltd., and the Unazuki Dam, 7 km downstream, was completed in 2001 by the Ministry of Land, Infrastructure, Transport and Tourism. Dashidaira and Unazuki were the first dams in Japan fitted with full-scale sediment flushing facilities (bottom outlets, gates) in place of handling the incoming sediments over the next 100 years without affecting the operation of the dam. These two in-series dam reservoirs are facing extremely large amounts of sediment inflow compared to their gross storage capacities. The large flood event in 1995 led to the accumulation of 7.34 Mm^3 of sediment in the Dashidaira Reservoir, which corresponds to almost 82% of its initial storage capacity.

Sediment management at both reservoirs aims at sustaining their original functions (*e.g*. flood control, power generation) and maintaining sediment routing through the basin system to the coastal area where beach erosion is gradually progressing. The first sediment flushing operation was conducted at the Dashidaira Dam in 1991. Due to limited experience in the flushing process, the operation was conducted in winter during low flows. Subsequently, the accumulated sediment within six years was flushed downstream to the estuary zone. The flushed sediment was rich in organic matter, resulting in many negative impacts on the aquatic environment[4]. Since 1995, the flushing operation has been performed every year during the first major flood event in the rainy season from June to July. A stable flushing channel in the reservoir has developed from these operations[5]. Since 2001, the Dashidaira and Unazuki dams are operated in sequential coordination almost annually, with high runoff triggering flushing of the upstream Dashidaira dam and sluicing through the

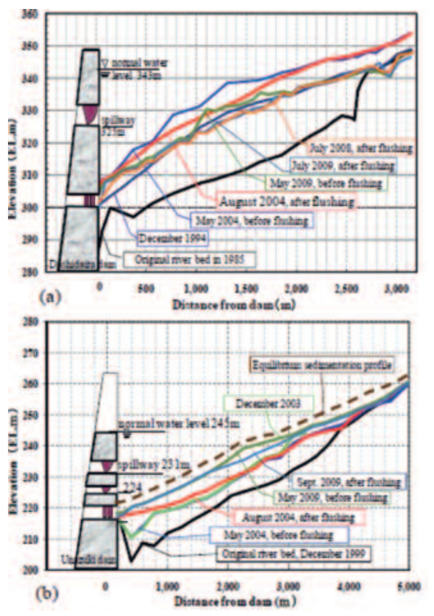
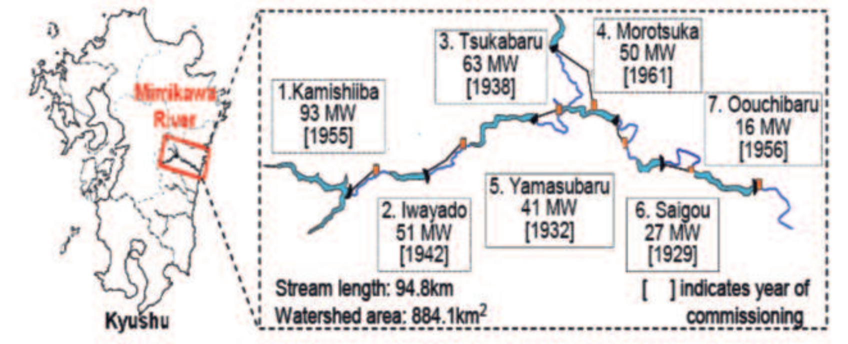


Figure 6. Measured longitudinal profiles before and after flushing operations[7]. (a) Dashidaira Reservoir, (b) Unazuki Reservoir

Dam	Service year	Height (m)	Initial capacity (Mm^3)	Total sedimentation volume (Mm^3)	Annual sediment volume (10^3m^3)
Kamishiiba	1955	110	91.5	12.6	217.8
Iwayado	1942	57.5	8.3	5.6	77.2
Tsukabaru	1938	87	34.3	7.0	91.8
Morotsuka	1961	59	3.5	1.1	20.3
Yamasubaru	1932	29.4	4.2	2.6	32.0
Saigo	1929	20	2.4	1.0	12.0
Ouchibaru	1956	25.5	7.5	1.9	33.8

Table 1. Dams and reservoir sedimentation in the Mimi River

Figure 7. Dams and power plants along the Mimi River Basin[10]



downstream Unazuki dam with minimal sediment redeposition.

When a flood inflow discharge exceeds 300 m^3/s (250 m^3/s in some particular cases) at the Dashidaira Dam for the first time of the year between June and August, a coordination sediment flushing is performed. When a flood inflow discharge exceeds 480 m^3/s at the Dashidaira Dam after sediment flushing, sediment sluicing is performed. These operations are conducted in coordination with the Kurobe River Sediment Flushing Evaluation Committee and the Kurobe Sediment Management Council, monitoring the natural flow and sediment discharges in the river downstream of the dams. The flushing/sluicing operations are followed by release of a clear-water “rinsing” flow to remove accumulated sediment from the river downstream (Figure 4). The duration of the free-flow sediment flushing operation depends largely on the target amount of sediment to be flushed out, which is planned before the sediment flushing operation.

During the flushing/sluicing operations, detailed monitoring programs are conducted at three major stations downstream where the water temperatures, pH, Dissolved Oxygen (DO), turbidity, and Suspended Sediment concentration (SS) were monitored on an hourly basis. Figure 5 illustrates results from the flushing operation of July 2006 when a free-flow condition was maintained for 12 h, removing out 240,000 m^3 of deposited sediment. During the free-flow flushing period, the maximum measured SS was approximately 30,000 to 50,000 mg/l depending on the sediment accumulation volume in the previous year and the reservoir drawdown speed. No harmful water quality data was recorded.

The coordinated flushing operations have been efficient in reducing the reservoir sedimentation (Figure 6). From 1991 to 2014, the aggregated volume in the Dashidaira Reservoir increased only by 9% to 4.29 Mm^3 and 88% of all incoming sediments were flushed. The Dashidaira Reservoir is currently at an equilibrium state and the amount of sediment passing through the dam outlets is approximately 1 Mm^3/year. In the Unazuki Reservoir, the flushing and sluicing operations have removed 73% of the total sediment inflow which is mainly composed of material less than 2 mm in diameter. Coarse material, larger than 2 mm in diameter and flushed from the Dashidaira Reservoir or supplied by a tributary of the river, is mostly trapped behind the dam; only 10% is flushed/sluiced downstream. The Unazuki Reservoir is not at an equilibrium state yet. Active sand bars have been observed in the river channel downstream, demonstrating the positive effects of the coordinated sediment flushing operations. The supply of sand material has reversed the bed armoring downstream of the dams, creating bed forms with high aquatic habitat value, especially for fish. The rinsing discharge from both dams prevents excessive accumulation of fine sediment on the sand bars after the flushing and sluicing operations. Upstream of the dams, the flushing operations ensure that the surface layer of accumulated sediment is continually replaced with fresh sediments, decreasing the organic materials and the eutrophication indices. Finally, evacuation channels have been prepared as shelters for many species of fish in the river, such as Ayu (*Plecoglossus altivelis*), during the high turbidity periods due to flushing operations. For more details, readers may refer to the works by Sumi *et al*.[8] and Minami *et al*.[9].

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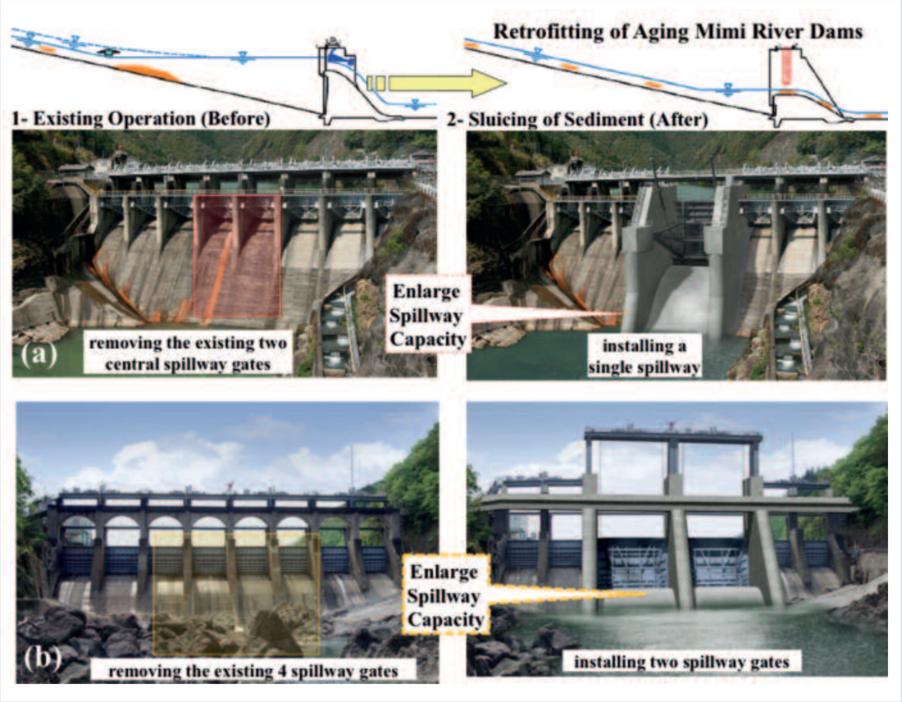

Figure 8. Existing and upgraded states by cutting down the crest of spillways of (a) Yamasubaru dam (two spillways retrofitted into one) and (b) Saigou Dam (four spillways retrofitted into two)[11]

Upgrading and retrofitting of Cascade Dams in Mimi River

The Mimi River is in the southeast of Kyushu in Miyazaki prefecture, Japan (Figure 7). The river is 94.80 km long for a drainage area of 884.1 km^2. Seven dams and hydropower plants were constructed in the Mimi River System between 1920 and 1960: Kamishiiba, Iwayado, Tsukabaru, Morotsuka, Yamasubaru, Saigo, and Ouchibaru dams. These dam reservoirs were designed to have a capacity to store 100 years of sediment in the deepest parts close to the dams.

In September 2005, Typhoon Nabi caused a heavy rain event, generating a flow volume that exceeded the designed flood for all seven dams. Power plants at Kamishiiba, Tsukabaru, Yamasubaru and Saigou were flooded rendering power generation impossible, while Tsukabaru, Yamasubaru and Saigou dams were overtopped and their dam control facilities flooded. The flood damage was amplified by tremendous landslides in 500 locations, delivering huge volumes of sediment and woody debris. A total of 10.6 Mm^3 of sediment flowed into the river system, with approximately 5.2 Mm^3 being deposited in the dam-regulating reservoirs (Table 1). Since an additional sediment volume, approximately 26.4 Mm^3, remained in the upper part of the river basin, the basin management authority had to seriously address this imminent threat. After detailed discussions among several stakeholders, a “Basin Integrated Sediment Flow Management Plan for the Mimikawa River” was established in October 2011 by the Miyazaki Prefecture.

The management plan defined the work to be carried out and the roles of stakeholders, with the aim of resolving problems caused by sediment in the basin. The Kyushu Electric Power Company (KEPCO), which is responsible for the dam cascade operation, retrofitted the existing spillway gates of selected dams so that sediment sluicing operations by partial drawdown could be conducted during flood events[10]. At the Yamasubaru Dam, the spillway crest was lowered by partially reducing the height of the weir section by 9.3 m; sluicing operations have started since 2017. At the Saigou Dam, the 4.3 m lowering of spillway crest is almost achieved (Figure 8).

Sediment replenishment in Japanese Rivers

As a common practice in Japan, low check dams upstream of reservoir deltas have widely been implemented to trap sediment (*i.e.* sand, gravel). The trapped sediment is regularly excavated mechanically, and traditionally used as construction material. To compensate for the lack of sediment supply downstream of dams, the excavated material has been recently supplied to the channel, where it can be mobilized by natural or artificial floods in bars and riffles, which have high habitat value[12]. In most cases, sediment replenishment is focusing both on reducing the reservoir sedimentation and on enhancing river channel improvements, *i.e.* detaching algae on the riverbed material[13], creating new habitats for spawning and other fish life-stages.

The annual volume of excavated sediment that is supplied downstream of more than 27 dams in Japan remains limited (*i.e.* between 0.1% to 10% of annual reservoir sedimentation) and insufficient to make up for the sediment deficit caused by the construction of the dams[12]. In Japan, sediment augmentation is commonly done as sand/gravel deposition along the margins of the river, where it can be mobilized by high flow (*i.e.* high-flow and point-bar stockpiles)[14], preventing therefore artificial turbid flow that is released through the side bank erosion at low flows (Figure 9). The grain size distribution of replenished sediment depend on the location of the check dams and on the ecological sensitivity of the river downstream of the dam which may restrict the addition of specific sediments (*e.g.* fine particles).

Figure 9. Sediment replenishment projects in Japan. (a) High-flow Stockpile, and (b) Point bar Stockpile

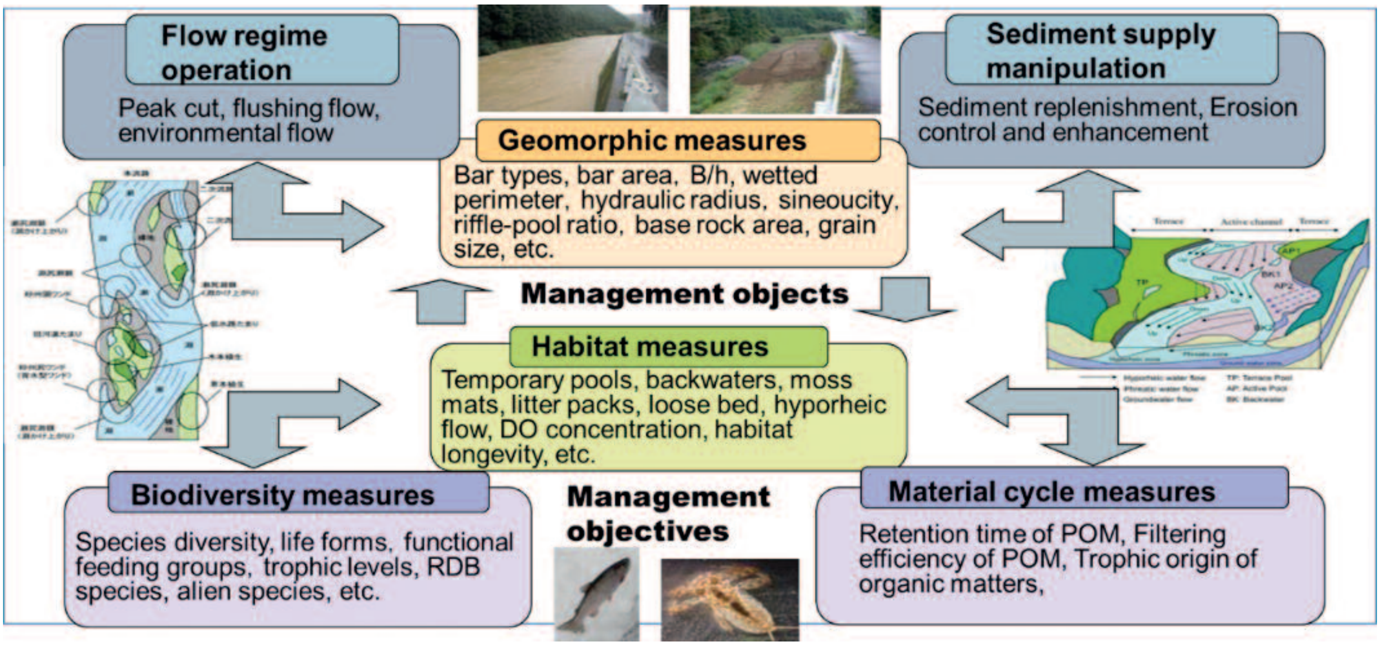

Figure 10. Conceptual figure for bridging between hydraulics, sediment, geomorphology, and biodiversity to achieve restoration of downstream river conditions (B/h: Channel width- flow depth ratio, RDB: Red Data Book, POM: Particle Organic Matter)[9]

Detailed monitoring of pre- and post-sediment supply is carried out to analyze the impact of such sediment augmentation on the riverbed dynamics, benthic organisms, and algae. Some of the sediment replenishment projects have had positive impacts when supplied sediments were redistributed during high flows. More details are given by Kantoush *et al*.[12,14].

Future directions

In Japan, plenty of dams are facing the problem of sedimentation in the deep, middle, and upstream tail-water parts of their reservoirs. Different sediment management methods may be suitable for each part of the reservoir, such as excavating, dredging, bypassing, flushing and sluicing. The present article highlighted the need for retrofitting and upgrading aged dams, planning adequately flushing and sluicing operations and adding sediment to the channel downstream of dams.

Reservoir sedimentation management in Japan is entering a new era, although there are still technical problems to be solved. The Ministry of Land, Infrastructure, Transport and Tourism of Japan[15] has released “The New Vision for Upgrading under Dam Operation”. This initiative encourages sediment management projects and contributes to international technical cooperation projects based on the experiences and lessons learned in Japan.

A new concept and methodology should be conceived *a priori* to design an intergenerational, sustainable, self-supporting rehabilitation system for river basins with reservoirs. For a complete analysis, all relevant benefits and costs must be measured. Further research is required to guide the future management of aging Japanese dams and to support the huge investment that will be required. Important research areas include reservoir service life issues and the necessity for upgrading and retrofitting aging dams. The present research areas should be extended to include a thorough assessment of the climate change impact and determination of the ecosystem response to sediment trapping in reservoirs. A critical study of the social dimension and effects of interventions is also essential for adequate sediment management.

To achieve reservoir sustainability and downstream environmental improvements, various disciplines should be involved in the restoration project. Modification of flow and sediment transport downstream of dams alters the geomorphic patterns which are cross relating to habitat degradation. It is important to better understand the interactive processes between input changes on flow regime and sediment supply and the output consequences of these changes on the biodiversity and material cycles. Figure 10 brings these factors together to clarify the river management objectives. For the purpose of river restoration, suitable habitat and translated geomorphic patterns fitting the management objectives should be defined. ■

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RESEARCH PROJECTS ON RESERVOIR SEDIMENTATION AND SEDIMENT ROUTING AT VAW, ETH ZURICH, SWITZERLAND

BY ISMAIL ALBAYRAK, DAVID FELIX, LUKAS SCHMOCKER AND ROBERT M. BOES

Reservoir sedimentation is a global concern and is expected to aggravate in the near future due to climate change and the linked increase in sediment availability below retreating glaciers. There is an increasing need for efficient sediment management to maintain the active storage volumes in reservoirs and to improve the continuity of sediment transport along rivers from upstream to downstream of dams. The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, Switzerland, has conducted several basic and applied research projects on reservoir sedimentation and possible countermeasures (*e.g.* sediment bypass tunnels and increased fine sediment transport through power waterways).

Figure 1. Griessee Reservoir with retreating glacier in the background, leading to higher sediment yield. (Photograph: D. Ehrbar, VAW, ETH Zurich)

Introduction

Hydropower is the most important source of renewable energy in Switzerland and constitutes the backbone of the Swiss electricity generation portfolio. Many reservoirs are located in the periglacial environment, *i.e.* in catchment areas of which at least 30 % is glacierized[1]. Climate change and the envisaged transition to a more sustainable energy supply system according to the 'Swiss Energy Strategy 2050' will challenge the existing infrastructure. The retreat of many glaciers in Switzerland may have significant impacts on water resources, but it may also provide opportunities such as new sites for hydropower reservoirs. New natural proglacial lakes have recently started to form at the termini of a number of retreating glaciers in the Swiss Alps. These reservoirs partly form naturally at rock rims after glacier retreat, yet some need a man-made dam to ensure their long-term stability.

However, the sediment yield and discharge downstream of retreating glaciers tend to increase, resulting in higher reservoir sedimentation. For sustainable reservoir operations, it is imperative to consider reservoir sedimentation and to plan and implement effective countermeasures. A number of field, laboratory as well as numerical research projects at VAW of ETH Zurich deal with reservoir sedimentation and associated countermeasures. They are briefly described hereafter.

Hydropower Potential and Reservoir Sedimentation in the Periglacial Environment Under Climate Change

The goal of this project was to better understand the effects of climate change on reservoir sedimentation and hydropower development in the Swiss periglacial environment. The study was divided into three parts, namely a systematic investigation of the hydropower potential in Swiss periglacial catchments, a field investigation of sediment fluxes into and inside periglacial reservoirs, and the numerical investigation of long-term sedimentation processes and patterns in such reservoirs.

In the first part, a framework based on an evaluation matrix with 16 economical, environ-

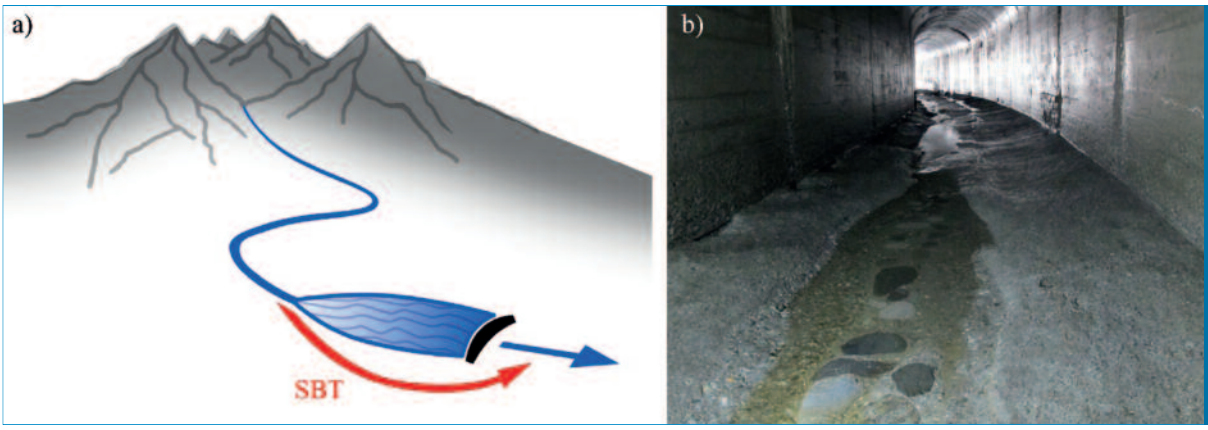

Figure 2. (a) Schematic view of an in-stream reservoir with sediment bypassing[7] and (b) abraded concrete invert of the Runcahez SBT, Switzerland (Photograph: M. Müller-Hagmann, VAW, ETH Zurich)

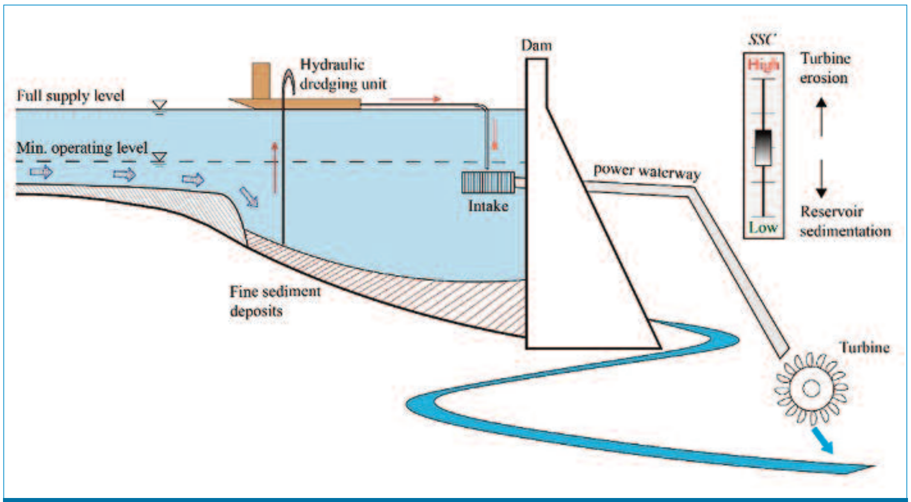

Figure 3. Increasing suspended sediment concentration (SSC) in turbine water as a countermeasure to reservoir sedimentation

mental and social criteria for consistent rating of all potential Swiss sites was developed and applied[2,3]. These criteria include the long-term run-off evolution, natural hazards, sediment continuity, protected areas, the visibility of new dams from populated places and effects on tourism. Seven suitable reservoir sites for new potential hydropower plants (HPPs) were retained, which are estimated to add 1.1 TWh of electricity per year[3]. With these new reservoirs, the intermediate goal of the Swiss Energy Strategy for hydro-electricity in 2035, *i.e*. 37.4 TWh/a, can be met. The infill time of all seven reservoir is 500 years or more, although it highly depends on the future retreat of glaciers. In the second part of the project, suspended sediment concentration (SSC), particle size distribution, bathymetry and flow velocity were investigated in the three Swiss periglacial reservoirs Griessee (Fig. 1), Gebidem and Lac de Mauvoisin with infill times between roughly 30 and 1000 years, to better understand sedimentation processes and delta formation[3]. All three reservoirs suffers from sedimentation problem and countermeasures are needed for their sustainable operation. A combination of water sample analysis, laser *in-situ* scattering and transmissometry (LISST) and Acoustic Doppler Current Profiler (ADCP) was applied in the field measurements. In the last part, a 1-D numerical model was implemented using the software BASEMENT[4] to simulate both the delta formation of coarse sediments and the lake-wide sedimentation from non-stratified (homopycnal) flows. The model was validated with data from the Gebidem Reservoir and then applied to a potential future periglacial reservoir[2,3]. Based on the project findings, implications on future reservoir operations, considering climate change, were discussed[2,3].

Hydroabrasion in high speed flow at sediment bypass tunnels

Sediment bypass tunnels (SBTs) are an effective routing technique to reduce reservoir sedimentation, diverting sediment-laden flow around the dam, thus allowing the re-establishment of the natural sediment continuity along the river (Figure 2a). Moreover, SBTs enhance the operating safety of dams by increasing the outflow capacity, which is not sufficient anymore at many schemes[5,6,7]. Despite these advantages, no guideline for the design and operation of SBTs is available and many SBTs face severe invert abrasion due to high-speed sediment-laden flows, putting SBT operation at risk and causing high maintenance costs (Figure 2b). To address these problems, four research projects have been conducted at VAW. The first project focused on flow characteristics, particle motion, particle and invert material properties, which are governing parameters of hydro-abrasion[6,8,9,10]. The study was conducted in a Froude-scaled laboratory flume modeling the physical processes present in a straight section of SBTs. The findings contributed to a better understanding of the physical processes underpinning hydro-abrasion of SBTs, and led to the modification of an abrasion prediction model[10]. A second and complementary *in-situ* investigation was conducted at three Swiss SBTs[7]. Various invert materials were tested and the obtained data were used to calibrate the above-mentioned abrasion model. Furthermore, the field data contributed to improve and optimize the bypass design and reservoir operations for better bypass efficiency [7]. The findings of both studies led to initiate the third and on-going research project entitled "Hydro-abrasion at hydraulic structures and steep bedrock rivers"[11]. The focus of this project is to investigate the effects of low aspect ratios of channel width to water depth and of sediment hardness and shape on sediment transport and hydro-abrasion in a laboratory flume, mimicking SBTs and high-gradient mountain streams. The fourth project dealt with the morphological effects of SBT operation on downstream river reaches by means of a field study at the Solis SBT in the Canton of Grisons, Switzerland, and by systematic numerical modelling of the SBT sediment pulses and their downstream effects in terms of both bed slope development and bed material composition[12]. The outputs of these projects contribute to establish a general guideline for sustainable and efficient design and operation of SBTs and other hydraulic/civil structures exposed to hydro-abrasion[5,13].

Reduction of reservoir sedimentation by increasing fine sediment transport through turbines

Sediment flushing through dam bottom outlets with water level drawdown is a technique to manage sedimentation problems in small reservoirs. However, this is rarely feasible for large reservoirs due to important water losses. In addition, environmental regulations may limit the admissible suspended sediment concentration (SSC) downstream of dams, or request that sediment transport is not hindered significantly by dams. An option to reduce sedimentation in HPP reservoirs in compliance with such environmental requirements is to increase the transport of fine sediments through power waterways – and hence the turbines – to the downstream river reach[14] (Figure 3). This has the advantages that (i) the SSC downstream of dams and powerhouses is low compared to those during occasional reservoir flushing operations, and (ii) no flushing water is lost for electricity generation. The disadvantage of this option is that turbines are exposed to higher sediment loads which may intensify hydro-abrasive wear. Turbine wear can be mitigated by appropriate turbine design and coatings as well as by limiting the SSC and particle sizes in the turbine water.

The topic of turbine erosion and its negative effects (*e.g.* reduced turbine efficiency, production losses, increased maintenance costs) have been investigated since 2012 in the scope of an interdisciplinary research project at the high-head HPP Fieschertal in the Swiss periglacial environment. Various techniques for monitoring of suspended sediment load, turbine erosion and efficiency changes were tested and further developed [15,16]. Based on the acquired data, an analytical erosion model[17] was adapted and calibrated for coated Pelton buckets[15]. This model can be used to estimate acceptable SSCs and particle sizes for the option of increasing the fine sediment transport through power waterways and turbines. By this way, the negative effects of reservoir sedimentation and turbine erosion can be balanced in order to maximize the profitability and maintain the operational flexibility of storage hydropower schemes.

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Dr. David Felix joined the VAW of ETH Zurich as a teaching assistant and scientific collaborator in 2010. From 2012 to 2017 he focused on the PhD-project on turbine erosion described in the present article. He continues working on suspended sediment and turbine erosion as a postdoctoral researcher.

Dr. Lukas Schmocker joined the hydropower team of the Swiss Competence Centre of Energy Research – Supply of Electricity (SCCER-SoE) in 2014 with a research focus on hydropower production and infrastructure adaption. In parallel, he is working as a project manager in flood management at the consulting company Basler & Hofmann.

Dr. Robert M. Boes is Professor of hydraulic structures and Director of the VAW at ETH Zurich. His research works focus on sustainable hydropower, reservoir sedimentation and flood propagation, among others. He was formally the head of the Dam Construction Group at TIWAG-Tiroler Wasserkraft AG, an Austrian utility.

The sediment load in the power waterway may be increased by hydraulic dredging (pumping) of previously settled fine sediment in the vicinity of the turbine water intakes (Figure 3). The flow rate in the dredging pipe is regulated in such a way that the SSC in the turbine water is acceptably low. The particle size may be limited by the suitable selection of dredging area (sufficiently distant from the reservoir inflow), as well as by screens or settling tanks on the dredging boat.

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RESERVOIR SEDIMENTATION MANAGEMENT IN TAIWAN

BY HSIAO-WEN WANG AND WEI-CHENG KUO

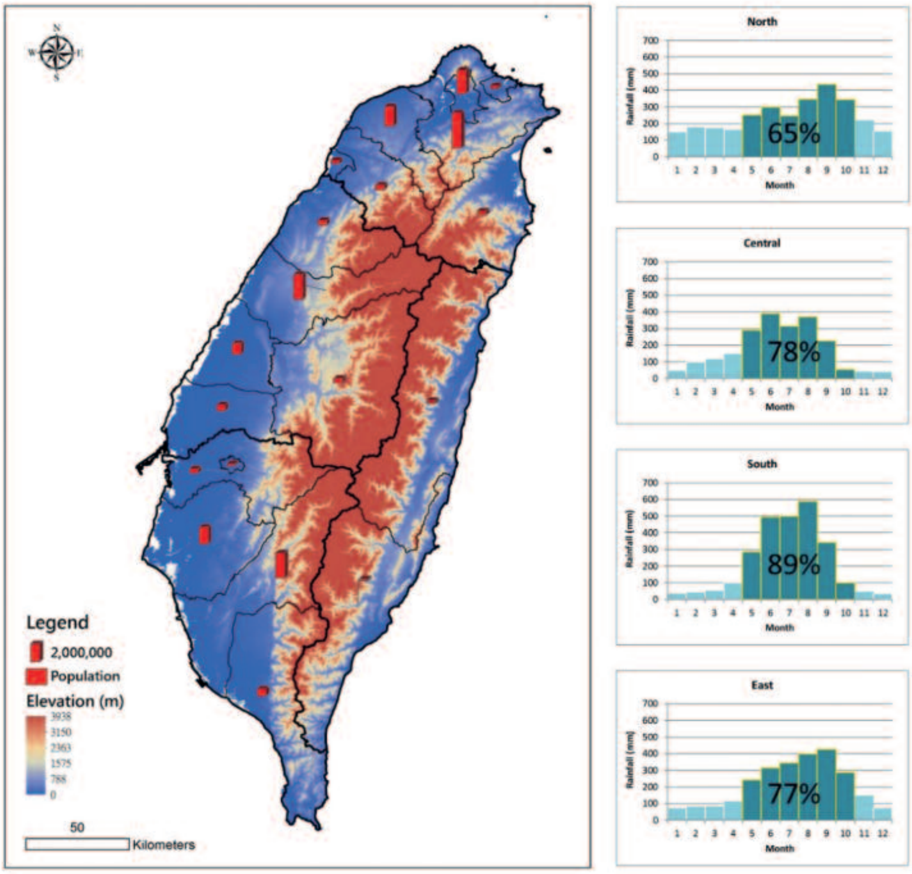
With many dams reaching the end of their design life, sediment accumulation has become an increasingly important stake in reservoir management. Feasibility studies conducted for existing reservoirs did not address the costs of dam decommissioning and sediment management at the end of the design life, but these costs are substantial, as has been demonstrated for more than 1000 dam removals[1]. The potential benefits of managing sediment to maintain the storage capacity of reservoirs has widely been recognized[2], but to date it has been implemented at relatively few sites. This article summarizes sediment management strategies in Taiwan, providing lessons to help guide planning and design of new dams, and establish design standards for sustainable reservoir management. This article is complementary to other articles in this and the previous issue of Hydrolink on reservoir sedimentation, such as those by Kondolf and Schmitt, Annandale *et al*., Kantoush and Sumi, Lyoudi *et al*. who present diverse experiences and policies in managing reservoir sedimentation worldwide.

Background

The island of Taiwan (36000 km^2) supplies the Pacific Ocean with 384 million tonnes of suspended sediment per year (Figure 1), which means that 1.9% of the global fluvial suspended sediment discharge is derived from only 0.024% of Earth's subaerial surface[3]. Tectonically subduction zones, rapid uplifts, intense monsoon and typhoonal rains generate rapid erosion rates that make Taiwan's sediment yield to be among the highest in the world.

Taiwan counts 61 major reservoirs which impound a total initial storage capacity of 2,200 Mm^3 of water for domestic, industrial, agricultural and hydropower needs. However, with its highly seasonal precipitation and erodible landscapes, the ability to store water is seriously threatened by sedimentation, calling therefore for the implementation of sustainable sediment management strategies[4]. The annual capacity loss due to sedimentation of reservoirs in Taiwan is 22 Mm^3. By 2011, almost 30% of the total initial capacity of reservoirs had been lost according to the Water Resources Agency, with some reservoirs having lost more than 80% of their initial volumes. Figure 2 shows a selection of reservoirs in Taiwan, and their corresponding sediment management strategies.

Figure 1. (a) Map of Taiwan and general information, (b) Monthly average rainfall from 1949 to 2017. Data courtesy of National Development Council Government Website Open Information Announcement and Central Weather Bureau



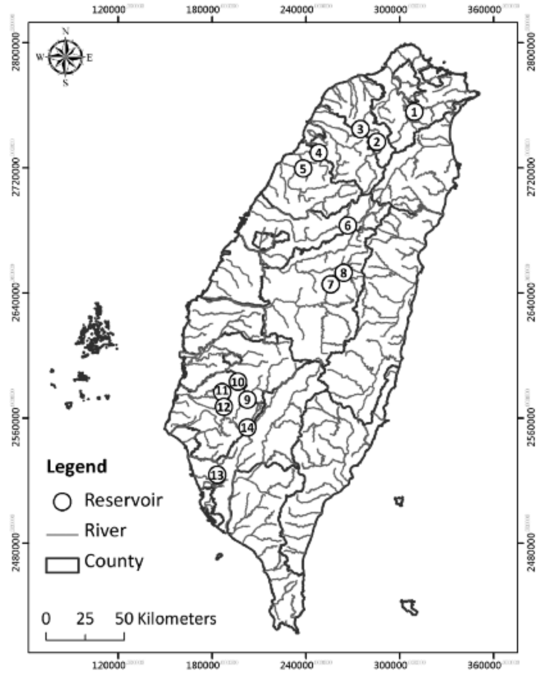
For the benefit of gathering helpful information for existing and future reservoir sediment management, six cases, spanning a range of river and dam sizes, geographical contexts, and management objectives, have been examined[5] (Figures 2). These reservoirs, Shihmen, Zengwen, Ronghua, Wujie, Agongdian and Jensanpei, are facing severe sedimentation problems (Table 1 and Figure 3), thereby requiring extensive interventions for maintaining/restoring the reservoir storage capacity and dam functions.

SEDIMENT MANAGEMENT STRATEGIES

Examining the selected six reservoirs, through the perspective of sediment management framework described by Annandale *et al*. (*cf*. first Hydrolink issue on reservoir sedimentation), some strategies were more commonly applied (Figure 2), such as reducing sediment yield from the catchment, trapping sediment above the reservoir by check dams (*i.e*. *Sabo* dams, Figure 4a), modifying dam operating rules, and hydraulic dredging of accumulated sediment near the dam. However, these practices represent the 'low-hanging fruit', generally characterized by low capital costs but also have limited effectiveness in maintaining and/or restoring the reservoir capacity.

Table 1. Overview of case studies. Reservoir purposes are Municipal and Industrial (M&I), Irrigation (IR), Industrial (ID), Hydropower Generation (HP), Recreation (R), Sediment Control (SC), and Flood Control (FC). (data

Figure 2. Selected reservoirs and associated sediment management strategies in Taiwan[5]. The study cases are 2: Ronghua, 3: Shihmen, 7: Wujie, 11: Jensanpei, and 13: Zengwen. (data courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation) (data courtesy of Water Resources Agency (WRA), Taipower Company, Taiwan Sugar Corporation, and Taiwan Water Corporation)



Strategies associated with each reservoirs

1 Feitsui: AF, ME
2 Ronghua: AF
3 Shihmen: AF, HD, ME, SL, VT, DT
4 Tapu: AF, EF, HD
5 Minte: AF, HD
6 Techi: AF, ME
7 Wujie: AF, DF
8 Wusheh: AF, ME
9 Zengwen: AF, HD, ME, OS, SL, (SB), VT
10 Paiho: AF, HD, ME, (SL), (SB)
11 Jensanpei: AF, EF, ME
12 Wusantou: AF, HD
13 Agongdian: AF, EF, ME
14 Nanhua: AF, ME, HD, VT

Description

AF: AFforestation
DF: Drawdown Flushing
DT: Desilting Tunnel
EF: Empty Flushing
HD: Hydraulic Dredging
ME: Mechanical Excavation
OS: routing Off-Stream reservoir
SL: Sluicing
SB: Sediment Bypass
VT: routing Venting Turbidity currents

Table 1. Overview of case studies. Reservoir purposes are Municipal and Industrial (M&I), Irrigation (IR), Industrial (ID), Hydropower Generation (HP), Recreation (R), Sediment Control (SC), and Flood Control (FC). (data courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation)

Reservoir (River)	Service year	Reservoir purposes	Initial Storage Capacity (Mm^3)	Live storage (Mm^3)	Mean annual runoff(Mm^3)	Mean Annual inflow Sediment (Mm^3)
Shihmen (Dahan)	1964	M&I, IR, HP, FC, R	309	208.3	1,468 (1964–2015)	3.5
Ronghua (Dahan)	1984	HP, SC	12.4	0.9	1086 (2001–2015)	2.8
Wujie (Jhuoshuei)	1934	HP	14	0.7	1,279 (2001–2015)	1.7
Jensanpi (Chiesui)	1938	IR, ID; after 2001, only R	8.1	1.5	7 (2001–2015)	0.25
Agongdian (Agongdian)	1953 2005	FC, IR, M&I (2011~)	36,700 18,370	17.2 16.3	54 (2001–2015)	0.38
Zengwen (Zengwen)	1973	M&I, IR, HP, R, FC	748,400	468	1,153 (1975–2015)	5.60

courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation)

In lieu of the aforementioned techniques, more efficient approaches requiring larger up-front capital investments are available. Dredging is relatively easy to implement, has low capital investment requirements, and offers potential value added from selling coarse aggregate for use in construction (when there is demand for such material). However, the effectiveness of dredging for maintaining the reservoir capacity relative to the annual sediment inflow is very low. For instance, in the multipurpose Shihmen Reservoir, approximately US$160 million was spent on hydraulic dredging operations over 31 years (1985 to 2015, Figure 4b), resulting in removal of only 8.1 Mm^3 of sediment at a unit cost of approximately US$20/m^3. In contrast, turbidity current venting and sediment sluicing through the renovated power plant penstocks, the renovated low-level Permanent River Outlet (PRO), which releases downstream water supply during power plant failures, and the spillway tunnel renovation projects (Figure 4c) effectively resulted in the removal of 12.6 Mm^3 of sediment in a period of 10 years (2005-2015), with a total initial engineering cost of about US$67 million, for a unit cost of approximately US$5/m^3. Thus, the infrastructure retrofits had a much higher economic efficiency than the hydraulic dredging.

The time horizon of sediment management is an important metric in comparing sediment management strategies. At the Shihmen Reservoir, dredging over 31 years removed the same amount of sediment as the PRO, turbidity venting, and spillway tunnel did in only 8 years. The cost of the power plant modifications (US$29 million) at Shihmen to facilitate turbidity current venting and sluicing, calculated over a 25-year design life of the tunnel, yielded a smaller unit cost for sediment removal (US$3/m^3) than did hydraulic dredging (US$20/m^3). Desilting tunnels are a high economically efficient technique compared to traditional dredging. The planned Amuping Desilting Tunnel will require an initial investment of US$133 million, and is expected to remove 0.64 Mm^3/year for a duration of 25 years of the dam operation[6]. Its total cost is therefore US$33 million less than the hydraulic dredging induced cost to remove the same material volume.

Some of the most effective sediment management strategies (*i.e.* sediment bypass, sediment pass-through) were implemented at only two sites, Shihmen Reservoir and Agongdian Reservoir. Sluicing, turbidity venting and flushing in Taiwan's reservoirs have been shown to discharge only 30 to 40% of the incoming sediment, calling for the use of other complementary methods. Thus, dredging continues to be an essential component of efforts to prolong reservoir life.

The lack of sediment management plans and monitoring for most of the reservoir sites is striking. While intakes and hydraulic structures have been refitted for the Shihmen, Zengwen, and Agongdian reservoirs, or are under consideration for modification for the Ronghua Reservoir, only the Shihmen and Zengwen reservoirs have comprehensive plans placing these renovations within the longer-term context of sediment management. For instance, a comprehensive plan at Shihmen Reservoir (Figure 5) was developed to identify the management strategies that may be used over time to combat sedimentation. In addition to the current practices, the design of desilting tunnels from the reservoir itself is ongoing[7,8]. A desilting tunnel (Amuping) will divert discharge and sediment from the midpoint of the reservoir into a 3.7 km-long tunnel with a gradient of 2.86% to transport 0.084–0.104 mm sized sediment[6]. After completing the Amuping desilting tunnel in 2021, there are plans to construct the Dawanping desilting tunnel to vent turbidity currents through two 10-m-diameter steel pipes via an intake structure, a 0.9-km tunnel, and two outlets, rejoining the river 1 km downstream of

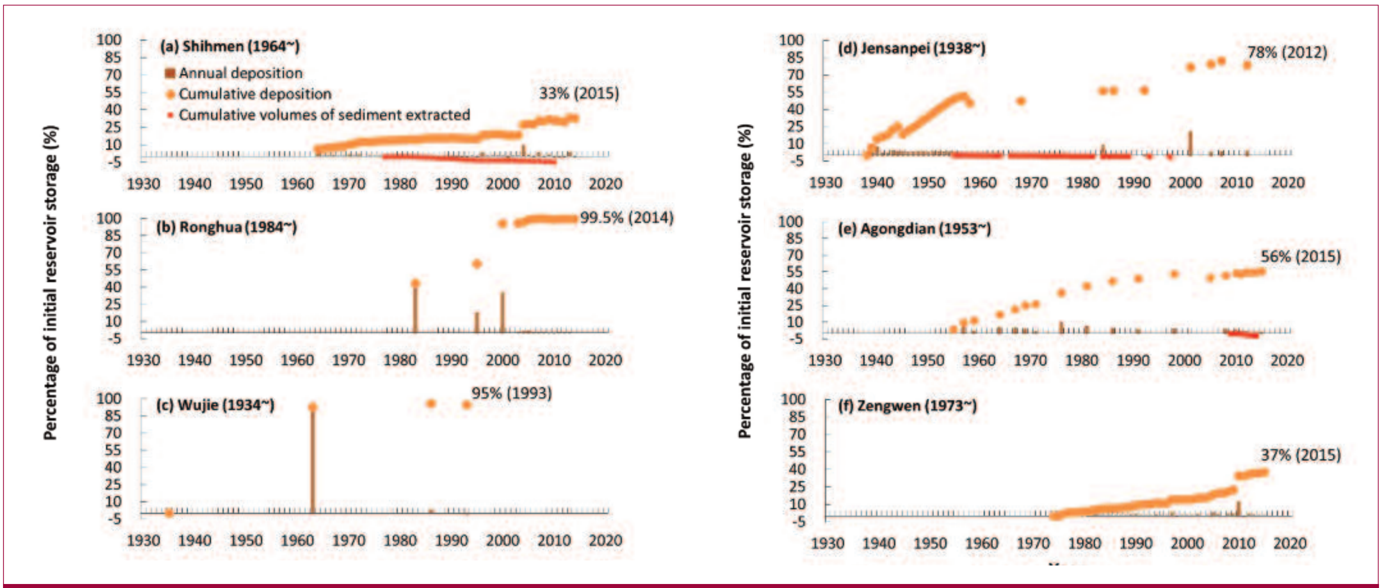


Figure 3. Reservoir sedimentation and material extraction over time[5]. The capacity loss due to sedimentation is reported along with the year of last reservoir survey on each plot (e.g. 33% and 2015, respectively, for Shihmen Reservoir). (a) Shihmen Reservoir; (b) Ronghua Reservoir; (c) Wujie Reservoir; (d) Jensanpei Reservoir; (f) Zengwen Reservoir. (data courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation). Most important events include Typhoon Gloria in 1963, Typhoon Herb in 1996, Typhoon Mindulle and Typhoon Aere in 2004, and Typhoon Morakot in 2009. Due to the high sediment yield, the Wuji reservoir was almost filled six years after its completion in 1934

the dam. The two tunnels are expected to remove approximately 1.35 M tonnes/year, representing 39% of the mean annual sediment inflow.

Suitability of sediment management techniques

The characteristics of a site can strongly influence the suitability of different sediment management techniques. For example, despite its effectiveness, drawdown flushing has been conducted during floods in the Wujie (Figure 4d), Agongdian and Jensanpei reservoirs. Drawdown sediment flushing during the non-flood season is limited to hydrologically small reservoirs, where the residence time (*i.e.* ratio of storage capacity to mean annual runoff) does not exceed a certain value[13]. Different values for the residence time for characterizing a reservoir as small have been proposed in the literature, ranging from 0.04[14] to 0.3[15]. In hydrologically "large" reservoirs, where drawdown is not an option, major infrastructure modifications may be needed to manage sediment by venting turbidity currents or bypassing incoming sediment.

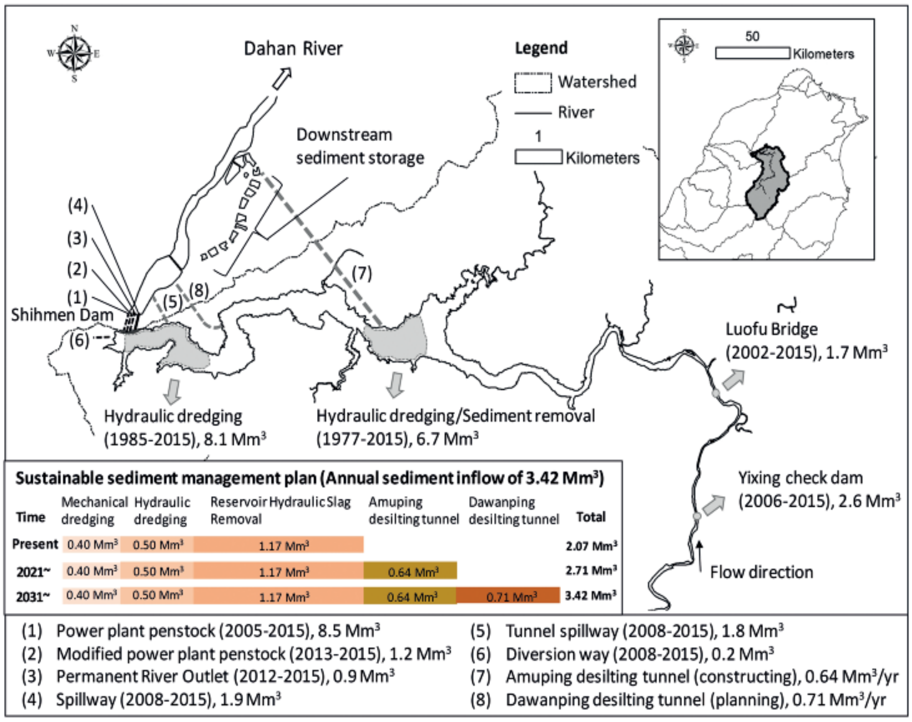
Similarly, bypass tunnels are best-adapted to situations where the geometry of the river and reservoir make possible a steeper short-cut route for the tunnel, such as where the reservoir occupies a river bend. A feasibility study at the Zengwen Reservoir proved that the unfavorable geometry, the high construction cost, and the engineering difficulty make the construction of a sediment bypass tunnel unlikely[16]. Furthermore, understanding the interactions between flow and sediment in sediment bypass tunnels is needed to avoid the need for frequent maintenance as bedload induces abrasion of the tunnel concrete bed (*cf.* Albayrak *et al.*'s article in the current issue).

Needs for and barriers to sustainable reservoirs

Sustainable reservoirs, from a sediment management perspective, have been defined as those a) whose life and reservoir capacity is maintained indefinitely, b) whose economic value is positive when taking a full life cycle approach that considers dam decommissioning and sediment management at the end of the project life, and c) provide intergenerational equity by not burdening future generations with the social, environmental, or economic costs of natural resources use by previous generations[13]. All these three concepts, either directly or indirectly, support the need for managing sediment throughout the reservoir life.

Shihmen and Zengwen are the most important reservoirs of Taiwan, supplying more than 25% and 40% of the water demand for the northern and southern regions, respectively. However, sedimentation was not taken seriously in these reservoirs until they lost a large portion of their respective capacity during a single typhoon event (*i.e.* 9% of initial storage capacity lost due to Typhoon Aere in 2004 for Shihmen Reservoir, 12% of initial storage capacity lost due to Typhoon Morakot in 2009 for Zengwen Reservoir). For Ronghua and Wujie, the two reservoirs with almost no remaining storage capacity, the originally stated design lives were short. For instance, the Ronghua Reservoir was commissioned in 1984 on the Dahan River with design life of only 25 years, as one of the 120 sediment-control dams (*i.e. Sabo*) reducing the sediment inflow to the Shihmen Reservoir. As of

Figure 4. Sediment management strategies in Taiwan[5]: (a) mechanical dredging from a sabo dam in Yixing, Shihmen basin, (b) hydraulic dredging at Shihmen reservoir (photo courtesy of WRA), (c) Sluicing at Shihmen Reservoir during Typhoon Soulik in 2013 (WRA), (d) Drawdown flushing at Wujie Reservoir

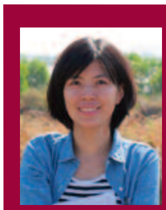


Sustainable sediment management plan (Annual sediment inflow of 3.42 Mm³)

Time	Mechanical dredging	Hydraulic dredging	Reservoir Hydraulic Slag Removal	Amuping desilting tunnel	Dawanping desilting tunnel	Total
Present	0.40 Mm³	0.50 Mm³	1.17 Mm³			2.07 Mm³
2021~	0.40 Mm³	0.50 Mm³	1.17 Mm³	0.64 Mm³		2.71 Mm³
2031~	0.40 Mm³	0.50 Mm³	1.17 Mm³	0.64 Mm³	0.71 Mm³	3.42 Mm³

(1) Power plant penstock (2005-2015), 8.5 Mm³
(2) Modified power plant penstock (2013-2015), 1.2 Mm³
(3) Permanent River Outlet (2012-2015), 0.9 Mm³
(4) Spillway (2008-2015), 1.9 Mm³
(5) Tunnel spillway (2008-2015), 1.8 Mm³
(6) Diversion way (2008-2015), 0.2 Mm³
(7) Amuping desilting tunnel (constructing), 0.64 Mm³/yr
(8) Dawanping desilting tunnel (planning), 0.71 Mm³/yr

Figure 5. Diagrammatic map showing management strategies at Shihmen Reservoir[5]. Data are from WRA[9-12]



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2003, the reservoir was almost filled with sediment and its remaining capacity as of 2014 was less than 1% (Figure 3b). For dams whose primary objective was sediment retention, the expected timeframe for their benefit has been short. Moreover, sediment-filled dams can either fail catastrophically[17] or become expensive engineering problems upon decommissioning[18], creating hazards and burdens for future generations. Reservoir sedimentation demonstrates the critical need to take a full life cycle approach during design and construction of any dam, accounting for decommissioning and sediment management at the end of the project life.

For Agongdian and Jensanpei, the two reservoirs where drawdown flushing operations are conducted, conflicts with the competing use the reservoirs for recreation led managers to decide against emptying them. Public education on the importance of sediment flushing may help reduce conflicts between recreational and sedimentation operations. However, this must be complemented by strong leadership from reservoir managers and politicians to ensure that the key benefits of flood regulation and water supply are not compromised by the promotion of tourism and recreational activities.

Classifying the conflicts associated with sustainable sediment management in the Taiwan case studies highlights how social, technical, environmental, and economic barriers all inhibit effectively addressing reservoir sedimentation. Social barriers can be local (*e.g*. traffic concerns, tourism impacts, flood hazards) to global (*e.g*. design-life engineering paradigm, disregarding intergenerational equity). Among them, social concern about increased flood hazard risk due to aggradation downstream of the dam is also a technical issue. While the evaluation of increased sediment concentrations and aggradation of the bed downstream due to sediment passed through the bypass and desilting tunnels were conducted for Shihmen Reservoir[7,8], few such systematic evaluations exist for other sites.

A variety of technical concerns may emerge in any individual project. The methodological and financial challenges associated with monitoring sediment inflows has been the most common technical barrier, though methods for monitoring sediment are well established[19]. The loss of water supply associated with sediment flushing and sediment pass-through has also been a common technical barrier across our case studies. The primary environmental impact of sediment management is associated with high turbidity, even though it was identified as a concern at only two of the sites, Shihmen and Zengwen, and the literature on this impact is still immature. For instance, large pulse releases of sediment during flushing operations can impact downstream aquatic organisms through abrasion, burial, and in cases of organic sediments, anoxia[20]. Besides, dredging is known to impact aquatic organisms in the reservoirs in a variety of adverse ways[21] that range from direct mortality over the short term to transgenerational effects over the long term. Engineering and ecological research could evaluate operational and mechanical sediment management based on deviations from background concentrations, or behavioral or toxicity thresholds for aquatic organisms[22]. The most obvious economic impacts are associated with the capital costs of modifying water infrastructure to accommodate sediment pass-through, but ancillary impacts, such as foregone hydropower revenue, may also pose real barriers to implementing some of the most sustainable sediment management solutions. It is worth noting that the most commonly identified conflicts (*e.g*. design-life, capital costs, monitoring, impacts to water supply) tend to be addressed by more short-term strategies (*e.g*. mechanical dredging, check dams) instead of implementing long-term solutions (*e.g*. infrastructure retrofits).

Conclusion

Given the high sediment yield, several strategies for managing reservoir sedimentation have been implemented in Taiwan, offering insights into their effectiveness, tradeoffs, and barriers.-The selected case studies highlight the social barriers to reservoir sustainability, including the crisis-response approach to addressing sedimentation and the low priority for sediment

Continues in page 117

SUSTAINABLE MANAGEMENT OF SEDIMENT FLUXES IN THE RHÔNE RIVER CASCADE

BY CHRISTOPHE PETEUIL

The Rhône is one of the major river systems of Europe. Originating in the Swiss Alps, it flows mainly through France to the Mediterranean Sea. At the catchment outlet, the mean annual discharge is approximately 1,700 m^3/s for a basin area of 95,500 km^2. Compared to similar catchments, the Rhône River is quite steep and its flow discharge is significant. A powerful waterway, the Rhône River is not only a source for hydropower generation but also a carrier of sediment.

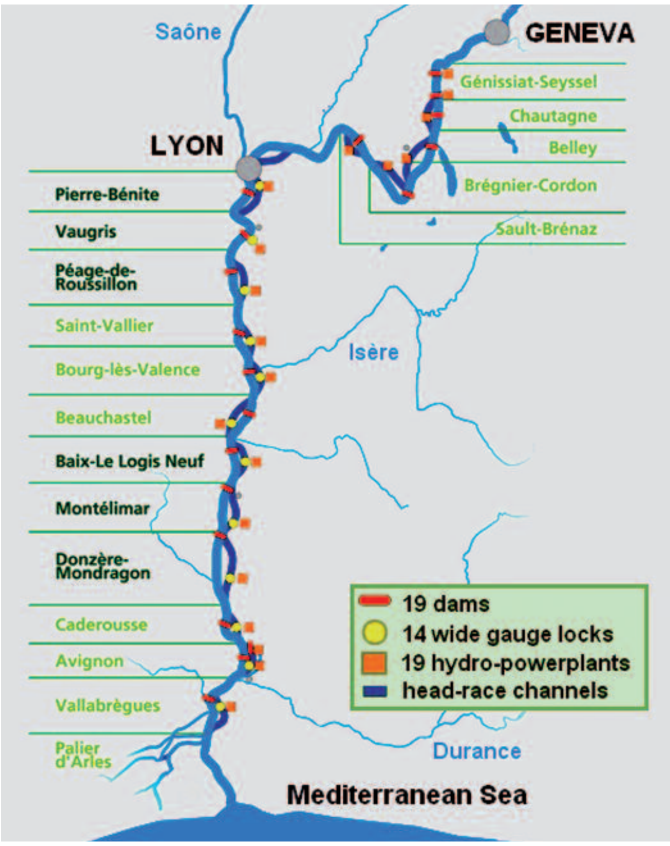
The Rhône River cascade: background and challenges

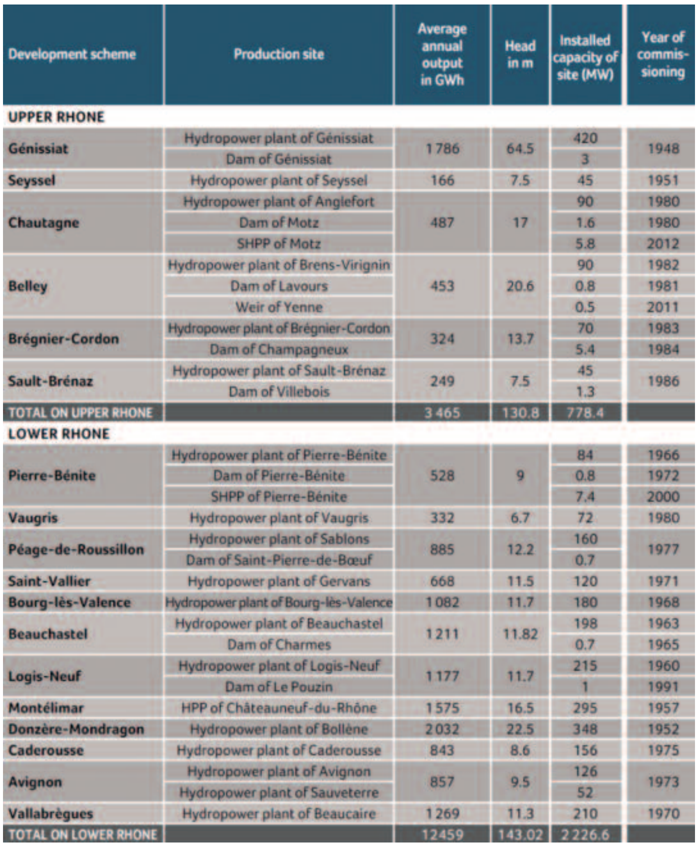
The French State entrusted the concession of the Rhône River in 1934 to Compagnie Nationale du Rhône (CNR) to fulfil three objectives for the benefits of the national community: hydroelectricity production, navigation development and management, and irrigation. CNR is France's leading producer of 100 % renewable energy (water, wind, sun), with a total installed capacity of approximately 3,700 MW including a cascade of nineteen (19) dams and hydropower plants from the Swiss border to the Mediterranean Sea (Figure 1). The company produces 25% of France's hydroelectricity, and manages a concession covering 27,000 hectares in the Rhône Valley and 330 km of wide-gauge navigable waterways. CNR has conceived a redistributive business model based on the River Rhône management whereby green electricity production is combined with territorial development[1].

Except for three dams including the Génissiat dam on the French Upper Rhône (*i.e.* between Swiss border and the city of Lyon), all hydropower developments operated by CNR are run of the-river short-circuiting the natural river course through a side canal[2] (Figure 2). Typically, run of the river facilities include a barrage built across the river mainstream that diverts the major portion of the flow through a headrace canal towards the power plant. To maintain suitable conditions for aquatic life, an ecological flow discharge is released into the natural river course through one of the dam outlets. The reservoir storage capacity of run-of-the-river dams is negligible compared to river flow volumes, especially during flood conditions. Neither inter-annual nor seasonal regulation is thus possible because the water outflow is very close to the water inflow.

On the Rhône River cascade, CNR has to cope with several sedimentation-related constraints, among them the facilitation of sediment routing loads arriving at inlets of reservoirs. Significant quantities of sediments are supplied to reservoirs during flood periods or flushing events

Figure 1. Map of CNR hydraulic assets in and outside of the Rhône River valley (left) and general information on CNR mainstream dams (right)





Development scheme	Production site	Average annual output in GWh	Head in m	Installed capacity of site (MW)	Year of commis-sioning
UPPER RHONE					
Génissiat	Hydropower plant of Génissiat	1 786	64.5	420	1948
	Dam of Génissiat			3	
Seyssel	Hydropower plant of Seyssel	166	7.5	45	1951
Chautagne	Hydropower plant of Anglefort	487	17	90	1980
	Dam of Motz			1.6	1980
	SHPP of Motz			5.8	2012
Belley	Hydropower plant of Brens-Virignin	453	20.6	90	1982
	Dam of Lavours			0.8	1981
	Weir of Yenne			0.5	2011
Brégnier-Cordon	Hydropower plant of Brégnier-Cordon	324	13.7	70	1983
	Dam of Champagneux			5.4	1984
Sault-Brénaz	Hydropower plant of Sault-Brénaz	249	7.5	45	1986
	Dam of Villebois			1.3	
TOTAL ON UPPER RHONE		3 465	130.8	778.4	
LOWER RHONE					
Pierre-Bénite	Hydropower plant of Pierre-Bénite	528	9	84	1966
	Dam of Pierre-Bénite			0.8	1972
	SHPP of Pierre-Bénite			7.4	2000
Vaugris	Hydropower plant of Vaugris	332	6.7	72	1980
Péage-de-Roussillon	Hydropower plant of Sablons	885	12.2	160	1977
	Dam of Saint-Pierre-de-Bœuf			0.7	
Saint-Vallier	Hydropower plant of Gervans	668	11.5	120	1971
Bourg-lès-Valence	Hydropower plant of Bourg-lès-Valence	1 082	11.7	180	1968
Beauchastel	Hydropower plant of Beauchastel	1 211	11.82	198	1963
	Dam of Charmes			0.7	1965
Logis-Neuf	Hydropower plant of Logis-Neuf	1 177	11.7	215	1960
	Dam of Le Pouzin			1	1991
Montélimar	HPP of Châteauneuf-du-Rhône	1 575	16.5	295	1957
Donzère-Mondragon	Hydropower plant of Bollène	2 032	22.5	348	1952
Caderousse	Hydropower plant of Caderousse	843	8.6	156	1975
Avignon	Hydropower plant of Avignon	857	9.5	126	1973
	Hydropower plant of Sauveterre			52	
Vallabrègues	Hydropower plant of Beaucaire	1 269	11.3	210	1970
TOTAL ON LOWER RHONE		12459	143.02	2 226.6	

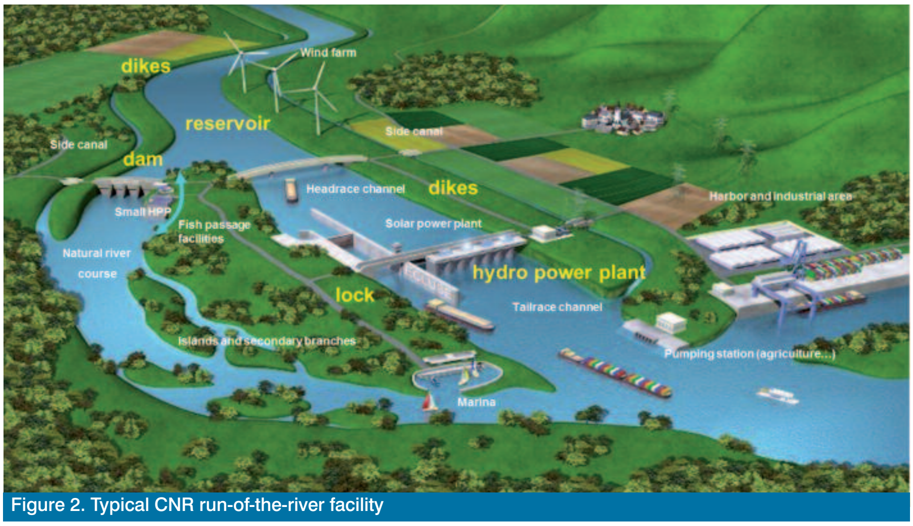


Figure 2. Typical CNR run-of-the-river facility

initiated by dam operators in the upper Swiss Rhône and the French Rhône tributaries. At the same time, it is crucial to keep the fine suspended sediment concentrations downstream of the dams low enough for several river uses, such as supporting aquatic life, and the operation of intakes for cooling systems of nuclear power plants, well-fields for drinking water supply and bathing areas. Moreover, floodwater routing must be ensured by guaranteeing adequate hydraulic capacity of channels and by avoiding adverse obstructions of dam spillways, possibly resulting from sediment deposits. Good navigation conditions have also to be maintained through regular monitoring and maintenance of the riverbed. To deal with these requirements, CNR has adopted an overall sediment management program established under the supervision of the French authorities. Complementary to this masterplan, "environmentally friendly flushing" operations are also regularly conducted at the Génissiat dam as a result of the historical transboundary issues of the Rhône River.

"Environmentally friendly flushing" concept from the Génissiat Dam

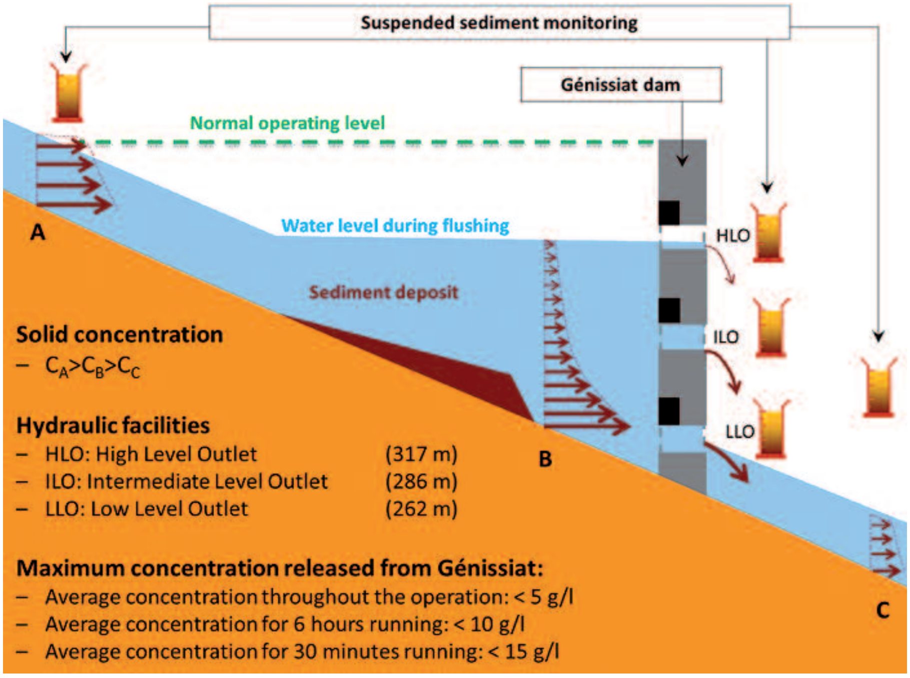
Since the completion of the Verbois dam (located near Geneva, upstream of the Génissiat dam) in 1942, the Swiss operator SIG has been initiating full drawdown flushing events every three years to prevent increased-flood hazards that may be caused by sedimentation in the Verbois reservoir. Before 2016, Swiss reservoirs had used to be completely emptied during these operations, leading to very efficient remobilization rates but also to lethal effects on the aquatic fauna due to suspended sediment concentrations reaching up 40 g/l.

On the contrary, the sediment release downstream of the Génissiat dam (104 m high, commissioned in 1948) has been conducted under strict restrictions, especially since 1980 as a result of a progressively increasing understanding of sensitive issues on the French Rhône River. In particular, the suspended sediment concentrations released from the Génissiat reservoir have not to exceed 5 g/l on average over the entire operation, 10 g/l on average over any 6 hours period, and 15 g/l over any 30 minutes period. Respecting those limits allows maintaining bearable life conditions for the aquatic fauna and preventing efficiently adverse effects. To achieve this objective, routing and regulation of fine suspended sediment concentrations discharged from the upper Swiss reservoirs are performed by CNR in the Génissiat reservoir (23 km long, storage capacity of 56 Mm^3) where the dam is equipped with three outlets (Figure 3): a bottom gate (LLO), an outlet at halfway up the dam (ILO), and a surface spillway (HLO).

First, the water surface in the Génissiat reservoir is lowered at specific levels in order to remobilize the sediments previously deposited and to ensure the routing of inflowing sediments discharged from the upper Swiss reservoirs. Inflowing sediments could entirely settle if the water level in the reservoir is too high, while huge sediment concentrations may be released downstream of the dam if the water level is too low. Secondly, an appropriate gate opening program and mixing of the sediment-laden flows released by each of the three outlets (*i.e.* mixing water with high sediment concentrations from the bottom of the water column with enough "cleaner" water from higher in the water column) are performed to stay within the required concentrations further downstream. The Low Level Outlet (LLO) discharges highly concentrated water, the Intermediate Level Outlet (ILO) releases less concentrated flows and the High Level Outlet (HLO) discharges clear water (Figure 3). The efficiency of such program is controlled with the benefit of real-time sediment concentration monitoring implemented at the dam site and in downstream stations.

All other CNR hydropower facilities operated downstream of the Génissiat dam are low head run-of-the-river systems. For normal operating

Figure 3. Management of the Génissiat reservoir during flushing sediment operations



conditions, the reservoir water level upstream of each dam is more or less horizontal. During high flows or flood conditions, the spillway gates are progressively opened to decrease the water level upstream of the dam and to increase the waterline slope throughout the reservoir. This situation avoids extra-flood hazards for riverine people and allows the recovery of natural-like flow conditions in the whole reservoir. The routing (or sluicing) of inflowing sediments throughout the reservoir is thus facilitated and previously deposited sediments are more easily remobilized. The sediment transport through CNR dams is also eased because the crest of the spillway weir is practically at the same elevation as the river bottom prior to dam construction and because the heights of the spillway gate and dam are very similar.

Lessons learned

The efficiency of such a gate arrangement and the operation rules associated with its configuration has been demonstrated for decades and makes possible the sustainable management of sediment fluxes with a very limited impact on the aquatic life and river users. Since the beginning of 1990's, the operation rules have been continuously optimized. The annual sedimentation rate in the Génissiat reservoir has been consequently reduced by half, and for the 1993-2018 period, the yearly rate of sediments passing through the dam outlets has increased up to 85% on the average, *i.e.* only 15% of the inflowing suspended sediment flux have been trapped into the reservoir (Figure 4).

Additional gains are expected in the near term as Swiss and French operators have to comply with the same restrictions on suspended sediment concentrations released from dams since 2016. This evolution results from a cooperative work performed between 2012 and 2016 by the operators and the regulatory authorities from both countries with the objective of ensuring a consistent and sustainable management of sediment fluxes throughout the whole river cascade. The benefits of this new operating scheme have been demonstrated during the 2016 event, allowing an adequate balance of the sediment fluxes flowing to the Génissiat reservoir and from the dam outlets. The downstream sediment transfer throughout the CNR run-of-river facilities has been also increased by 50% compared to previous events. Such operation is however costly to CNR, which engages a staff of 400 people 24 hours a day over approximately 10 days, at a cost of about 6 to 8 million euros (based on the 2012 and 2016 flushing). With the benefit of such design and operation patterns, the impact on sediment fluxes is significantly minimized. Locally, some sediment deposits may, however, occur, especially in areas where the flow velocity is very low, such as navigation lock garages, harbors, and the Rhône-tributary confluence zones. In the Lower Rhône River (downstream of the city of Lyon) the average volume of deposits in the river system represents 0.04% to 5% of the annual inflowing suspended sediment fluxes (Figure 4). These changes have been observed during the continuous monitoring of the river and hydraulic structures performed by CNR with a fleet of hydrographic boats. A comprehensive update of the bathymetric state of the river is carried out with a minimum frequency of 5 years or after significant floods.

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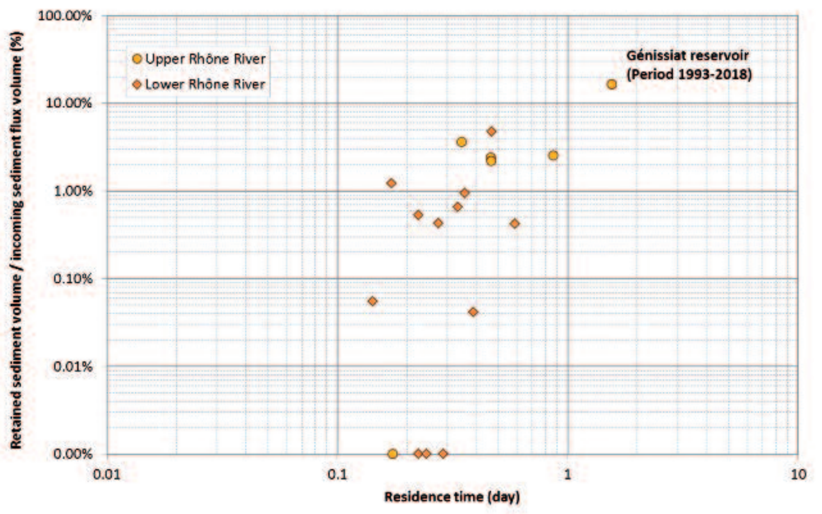
Figure 4. Sediment trapping rate at CNR reservoirs according to the residence time of water (reservoir capacity volume/mean annual river flow)



In order to keep adequate conditions for navigation, dam operation and hydraulic safety, maintenance works are also performed on sediment deposits and vegetation in the framework of a management plan established under the supervision of the French authorities. This plan is generally updated every 10 years. Ecological restoration works carried out by CNR on oxbows and alluvial margins represent also a noticeable part of these works. Considering dredging operations only, which represent in recent years an annual average volume of 0.54 Mm^3, the distribution of works relatively to the issues at stake is as follows: 41% for navigation safety, 41% for ensuring flood passage, 13% for dam operation and 5% for biodiversity restoration. For approximately a decade, extraction of sediment deposits in the channel has ceased. These deposits are instead artificially resuspended in the flow and reinjected in the riverbed further downstream, considering fine and coarse particles respectively. This requirement minimizes the potential disruption of sediment continuity down to the Rhône River Delta and contributes to prevent its erosion. The management scheme defined and implemented by CNR has demonstrated that achieving a sustainable management of sediment fluxes through hydropower cascades is possible. This program requires that several key factors are respected, namely adequate design and positioning of dam outlets, development of an operation pattern of the reservoir allowing the progressive recovery of natural flow conditions, regular monitoring of the river channel and hydraulic structures, and finally adaptive management of the river depending on a comparison of target states and observed evolutions. ■

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SILTING OF RECHARGE DAMS IN OMAN: PROBLEMS AND MANAGEMENT STRATEGIES

BY ALI AL-MAKTOUMI

In the Sultanate of Oman, 155 dams have been constructed as of 2018 for different purposes: flood protection (3 dams), recharge (46) and surface storage (106). Recharge reservoir dams are an effective measure to manage and augment water resources, especially groundwater aquifers, through making use of floodwater which is often lost to the sea and desert. These reservoir dams proved their efficiency, however (like elsewhere in the world) facing challenges that threaten their amenities. One of the most important issues to be countered is the silting of dams (i.e. reservoir sedimentation). The concerned water authorities along with academia are devoting many efforts to solve this problem.

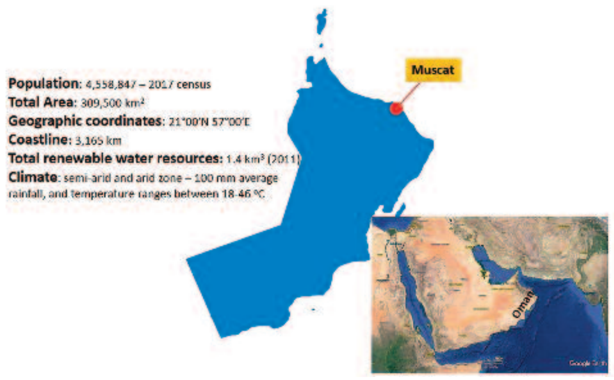

Figure 1. Map of Oman. Muscat is the capital of Oman

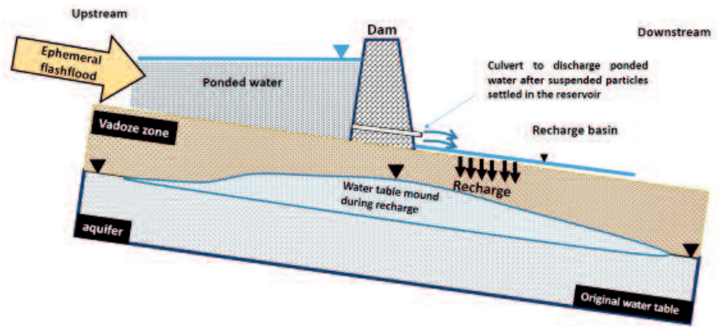

Figure 2. The concept of recharge dam reservoirs

Reharge reservoir dams in of oman: concept and role

The Sultanate of Oman is an arid country where drought conditions prevail and water is precious (Figure 1). Oman experiences a severe water shortage that threatens the national plans for development in all sectors (*e.g.* agriculture, tourism, industry). Government agencies and research institutions have been actively addressing different ways of augmenting water resources, mainly groundwater. Indeed, the water demand in Oman is mostly covered by groundwater withdrawal, supplying 87% of the demand, particularly for domestic and agriculture purposes. However, the intensive use of groundwater has led to the lowering of water tables and saltwater intrusion. One of the prudent measures to mitigate these problems is enhancing groundwater recharge (artificial recharge) by intercepting floodwaters (which are often wasted in the sea or in the desert) after rainfall events, storing them temporarily in reservoirs and down gradient infiltrating this water into the soil and aquifers (Figure 2).The water in the reservoirs is detained for about two weeks to avoid evaporation and health risks. Then the stored water is released slowly through culverts to the recharge basin which is located downstream of the dam. The recharge dam embankments are often made of soil, which is highly permeable, with a low-permeability clay core as the main seepage-checking component.

Forty-six (46) recharge dams have been constructed on alluvial valley wadis between 1970 and 2018 in Oman, with a total storage capacity of 101 Mm^3. While desalination provides a seemingly unlimited but costly water supply, recharge dams provide a limited water supply but relatively cheaply. Additional benefits of recharge dams are flood protection and deceleration or even reversing of seawater intrusion into coastal aquifers by creating groundwater mounds and, correspondingly, excess seaward oriented hydraulic slopes in these aquifers. Therefore, maintaining dam efficiency is necessary to achieve the optimum use of catchment-scale water resources.

Silting of reharge dams: problems and management starategies

Recharge dams in Oman are experiencing the problem of siltation, *i.e.* deposition of sediments

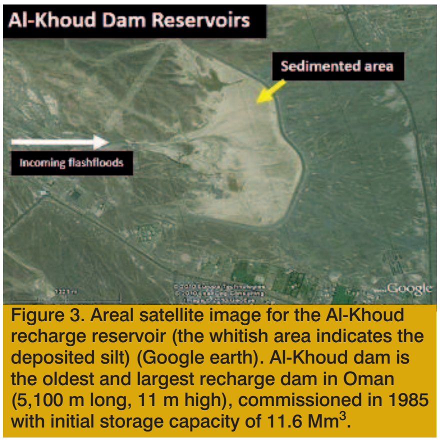

Figure 3. Areal satellite image for the Al-Khoud recharge reservoir (the whitish area indicates the deposited silt) (Google earth). Al-Khoud dam is the oldest and largest recharge dam in Oman (5,100 m long, 11 m high), commissioned in 1985 with initial storage capacity of 11.6 Mm^3.

brought by runoff water (Figures 3 and 4). This adversely affects the storage capacity of the reservoirs along with other problems (*e.g.* dam safety, water quality). Over time, layers of sediments from intercepted and detained water currents cover the entire reservoir area. Consequently, the water infiltration rate decreases, water loss via evaporation increases, and the reservoir volume is reduced. For example, about 3.4 Mm^3 of sediments have been deposited in the Al-Khoud reservoir since 1985[1]. Unfortunately, there is no detailed data on the silting rates of Omani dams, but a number of them have been recently equipped with gauging sticks to assess the volume of sedimentation. The use of low-cost multispectral satellite data for mapping the silting of dams has also been promoted[2].

As a common practice, the deposited material layer is removed to increase water infiltration and storage space of the reservoir, but this is not always possible or feasible. Another solution is building small check dams, or siltation ponds along the flashflood pathways to intercept most of the sediments within the catchment before they reach the reservoir. It is more practical and less costly to clean up the reservoirs of small dams. The trapped sediments are removed and used in the oasis clusters or scattered on the banks of the waterway.

Mechanical intervention (bulldozzing, drilling) greatly improves the ability of the reservoir area to act as a surface-to-subsurface hydrological sink. The responsible water authority in Oman excavates and scraps out the deposited sediments from the dam-beds and utilizes them in agricultural practices, with a plan to use these sediments also in the pottery and stoneware industry. However, mechanical removal of sediments remains costly (*e.g.* around US$ 250,000 for the Al-Khoud dam for basic cleaning of debris), it is tedious and requires recurring actions after each flood-deposition event. More importantly, part of the deposited fine particles is carried by water infiltrating vertically into the porous medium (Figure 5). Hence, the surface scraping cannot remove the clogging particles, which have already migrated deep into the parent bed material (commonly a coarse alluvium). Fine particles gradually change the physiochemical properties of the original subsurface porous medium. Understanding the behavior and patterns of the percolating soil particles and their effect on infiltration and aquifer recharge is of critical importance for better management strategies. This understanding will provide the foundation for future decision making by the Ministry of Regional Municipalities and Water Resources and other governmental agencies as related to future dam design and maintenance. Research has been done to gain more insight into the kinetics of filtration, surface-subsurface water dynamics, evolution of infiltration fronts, in essentially heterogeneous porous media of reservoir beds[1,3,4,5,6]. Analysis of the results revealed that the soil in reservoir areas is rapidly evolving because of intensive anthropogenic hydrologic impacts caused by periodic ponding, infiltration and desiccation. This results in complicated and dynamic heterogeneities as the more fine sediments are translocated vertically into the subsurface, altering therefore the hydrological properties of the substrate material[1,5].

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Along with the problem of the reduction in the reservoir storage capacity, the alteration of the soil properties are found to significantly affect the ponding time , and the infiltration patterns within the reservoir area. This increases the

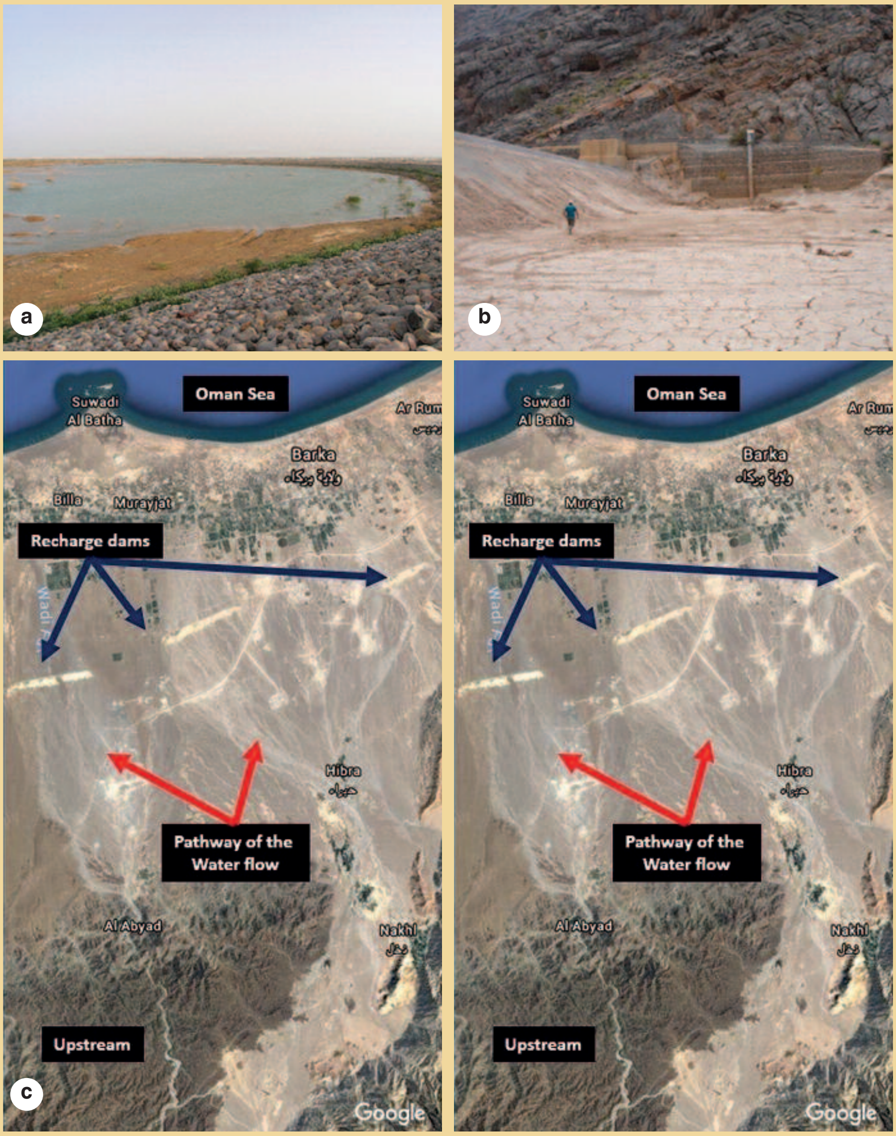

Figure 4. (a) Recharge dam in Oman after a flash flood, (b) Empty dam reservoir in Oman after long dry spell, (c) Satellite images of a number of recharge dams in North coastal line of Oman (left image), and Al-Khoud dam (right Image). Note: the whitish color in these images indicates the siltation patches. Excavations showed that the thickness of the deposited sediments exceeds 2-3 m.

potential hazards of flooding in the areas adjacent and downstream of the dam through over-spilling of ponded water. Zones located downstream of the dam, which are supposed to serve as recharge areas, receive pluses of reservoir water both from the dam's culverts and the spillways. This water is still rich in fine suspended particles which, similarly to what happens in the reservoir itself, in part translocate vertically into the subsurface, hydraulically impair it, *i.e.* adversely affect the recharge process. In addition, reduced infiltration through the recharge area downstream of the dam intensifies surface runoff and hence increases the loss of valuable fresh water resources to the sea or desert, jeopardizing any urbanized areas in its flow path by flooding.

Reservoir sedimentation threatens the stability and safety of the dam due to hydro-ecological interplay[7]. The slopes of the embankment are supported with gabions (Figure 3a) that have large mesh openings, acting as corridors and hosting settled suspended soil particles after each reservoir filling. The gabion serves as a mulch which reduces evaporation from the very wet shoulder and clay core of the dam. Fine textured materials are characterized by high water-holding capacity that intercepts the ex-filtrating water[7], and hence serves as a supply water source that supports the growth of lush vegetation, which thrives in the embankment. A vegetation strip has been observed on the slopes of the embankment of a recharge dam in Oman that emerged after torrential rains and temporary filling of the dam reservoir (Figure 4a). The vegetation is interpreted as the footprint of temporary storage of water, which is a small-sized groundwater mound within the permeable shoulder of the embankment[7]. The responsible governmental entity set a monitoring program to uproot this vegetation from the dam wall and reinforce the core with a concrete wall to avoid possible damage to the dam structure. ■

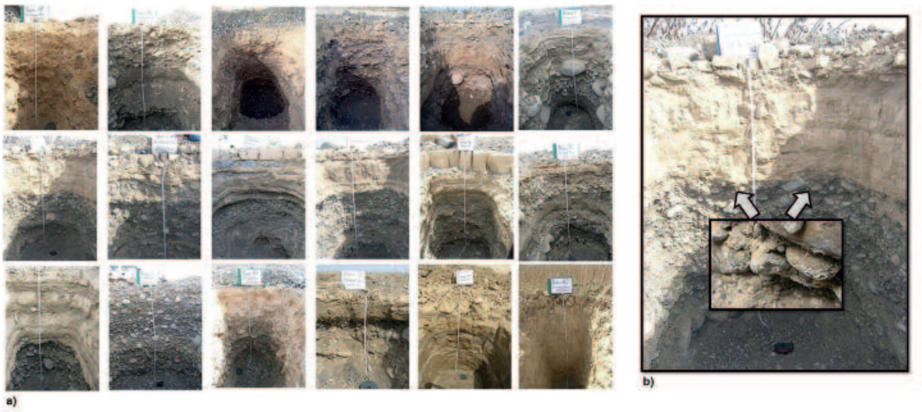

Figure 5. (a) Soil Pedons of the Al-Khoud dam bed, about thirty (30) years after the dam commission, (b) a typical soil profile illustrating the sedimentation in Al-Khoud reservoir and the deep percolation of fine particles into the original gravelly alluvium

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Continued from page 111

management vis-à-vis several competing objectives for the use of these reservoirs. Technical and economic barriers also exist, driven primarily by the engineering challenges and costs of retrofitting existing dams with new infrastructure to flush or bypass sediment. For new and existing dams, sediment management strategies should be evaluated on the basis of cost and efficiency rather than the continuing need for dredging. Finally, several site conditions, such as road access or valley geometry, may impact the suitability of any given sediment management practice at a site. A systematic approach for evaluating the social, economic, ecological, and engineering tradeoffs of sediment management could facilitate this critical aspect of sustainable water resources. Ultimately, for many areas of the world characterized by high sediment yields, a suite of sediment management practices may be necessary.

Acknowledgements

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SEDIMENTATION AND FLUSHING IN A RESERVOIR – THE PAUTE - CARDENILLO DAM IN ECUADOR

BY LUIS G. CASTILLO AND JOSÉ M. CARRILLO

Flushing is one possible solution to mitigate the impact of reservoir impounding on the sediment balance across a river. It prevents the blockage of safety works (*e.g.* bottom outlets) and the excessive sediment entrainment in the water withdrawal structures (*e.g.* power waterways). This study is focused on the morphological changes expected in the Paute River (Ecuador - South America) as a result of the future construction of the Paute - Cardenillo Dam.

Project Characteristics

The Paute River is in the southern Ecuador Andes. The river is a tributary of the Santiago River, which is a tributary of the Amazon River (Figure 1). Paute - Cardenillo (installed capacity of 596 MW) is the fourth stage of the Complete Paute Hydropower Project that includes the Mazar (170 MW), Daniel Palacios - Molino (1100 MW) and Sopladora (487 MW) plants (Figure 2).

The double-curvature Paute-Cardenillo Dam is located 23 km downstream from the Daniel Palacios Dam (Figure 3). The reservoir is 2.98 km long and the normal maximum water level is 924 m above sea level (MASL). The study drainage area is 275 km^2 and the mean riverbed slope is 0.05 m/m (Figure 2). The bed material is composed of fine and coarse sediments. The use of a point counting method allowed characterizing the coarsest bed material (diameters larger than 75 mm) (Figure 4). The estimated total bed load is 1.75 Mm^3/year and the maximum volume of the reservoir is 12.33 Mm^3.

In order to prevent the accumulation of sediment into the reservoir, the dam owner proposes periodic discharges of bottom outlets or flushing[1]. These operations should transport sediment far downstream, avoiding the advance of the delta from the tail of the reservoir. Reservoir sedimentation and flushing were investigated using empirical formulations as well as 1D, 2D and 3D numerical modelling.

Flow Resistance Coefficients

Estimation of the total resistance coefficients was carried out according to grain size distribution, sediment transport capacity rate and macro-roughness (*e.g.* cobbles, blocks)[2] (Figure 5). The flow resistance due to grain roughness (*i.e.* skin friction) was estimated by means of ten different empirical formulas. For each analyzed flow discharge, calculations were carried out by adjusting the hydraulic characteristics of the river reach (mean section and slope) and the mean roughness coefficients. To estimate the grain roughness, only formulae whose values fall in the range of the mean value - one standard deviation of the Manning resistance coefficient of all formulas were considered. The formulas that gave values out of this range were discarded. The process was repeated twice. It was observed that the mean grain roughness was between 0.045 and 0.038. Using measured water levels for flow discharges of 136 m^3/s, 540 m^3/s and 820 m^3/s, the floodplain and the main channel resistance coefficients were obtained through the calibration of the 1D HEC-RAS v4.1 code[3]. Figure 6 shows Manning's roughness coefficients for flow rates of different return periods, considering the blockage increment due to macro roughness.

According to the feasibility study[1], the minimum flow discharge evacuated by the bottom outlet to achieve an efficient flushing should be at least twice the annual mean flow (Q_{ma} = 136.3 m^3/s). The dam owner adopted a conservatively high flow of 409 m^3/s (» $3Q_{ma}$) for the design dimensions of the bottom outlet.

Reservoir Sedimentation

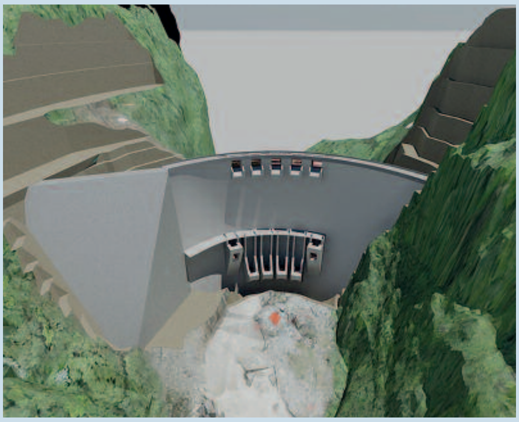
The time required for sediment deposition (bed load and suspended load) to reach the height of the bottom outlets (elevation 827 MASL) operating at reservoir levels was numerically investigated using the 1D HEC-RAS program[3]. The input flows were the annual mean flow (Q_{ma} = 136.3 m^3/s) equally distributed in the first 23.128 km and the annual mean flow discharge of the Sopladora hydroelectric power plant ($Q_{ma\text{-}sop}$ = 209 m^3/s). The Sopladora discharge comes from two dams located upstream. Sediment transport was computed using Meyer-Peter and Müller's formula corrected by Wong and Parker[4] or Yang's[5] formula. Figure 7 shows the initial and final states of the water surface and bed elevation. The suspended sediment concentration calculated numerically with HEC-RAS at the inlet section of the reservoir was 0.258 kg/m^3. This value takes into account the sediment transport from the upstream river and the annual mean sediment concentration from the Sopladora Hydroelectric Power Plant.

	Yang		Corrected Meyer-Peter & Müller	
Reservoir elevation (MASL)	Required time (years)	Sediment volume (hm^3)	Required time (years)	Sediment volume (hm^3)
860	**0.35**	**0.65**	**0.32**	**1.47**
892	5.10	2.77	2.58	3.86
918	12.90	6.07	8.80	7.34
920	13.60	6.33	9.50	7.64
924	14.80	6.62	10.90	8.97

Table 1. Sediment deposition volume in the reservoir and the time required to reach the bottom outlets. Results are presented for two sediment transport capacity formulas

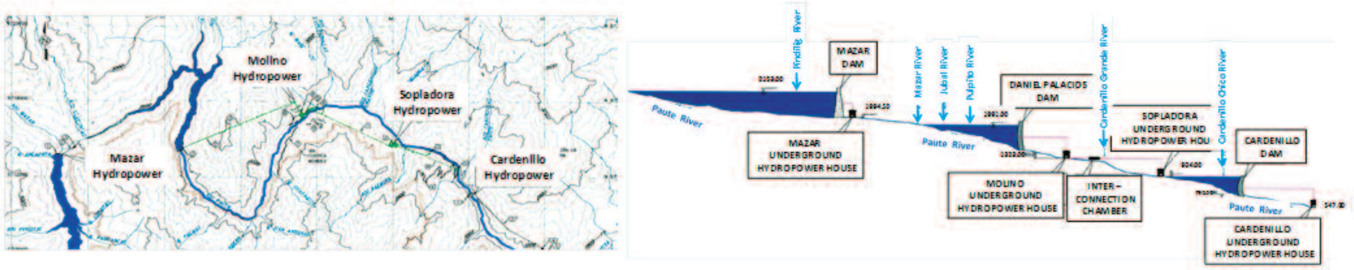
Table 1 shows the total volume of sediment deposited in the reservoir and the time required to reach the bottom outlets (827 MASL). Several water levels in the reservoir based on future operations at the dam were considered, *e.g.*, 860 MASL which is the water level considered to operate the bottom outlets, 920 MASL the pondered average water level, and 924 MASL the normal upper storage level (Figure 8). Results show that the sedimentation volume in the reservoir increases with the water level in the reservoir, and requires a longer time to reach the bottom outlet elevation. Using the corrected Meyer-Peter and Müller formula, with the level of the reservoir being at 860 MASL, yields the largest sedimentation volume (1.47 hm^3) and the smallest time to reach the level of the bottom outlets (3 months and 27 days).

▲ Figure 1. Geographical situation of the Paute River (Ecuador - South America)

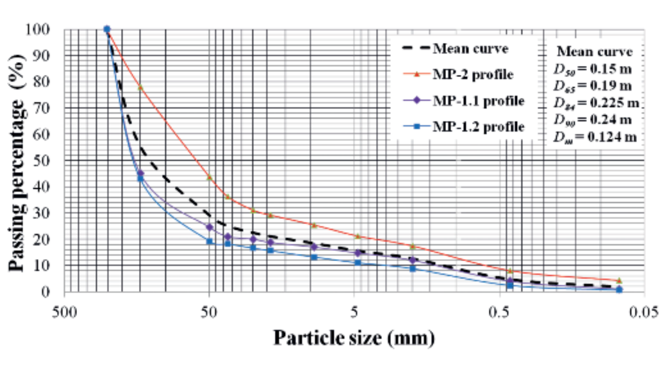


▲ Figure 3. Design of the Cardenillo Dam (maximum height of 136 m)

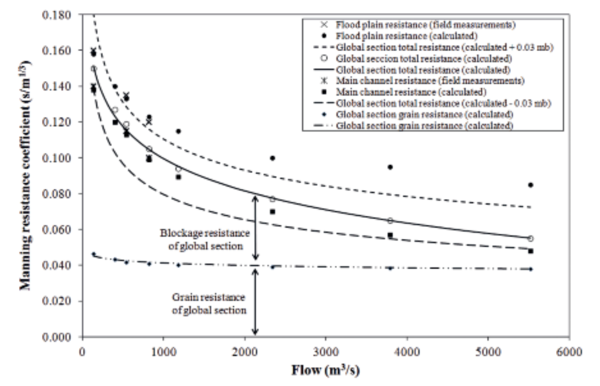
▲ Figure 5. Macro-roughness in Paute River at the Cardenillo Dam reach



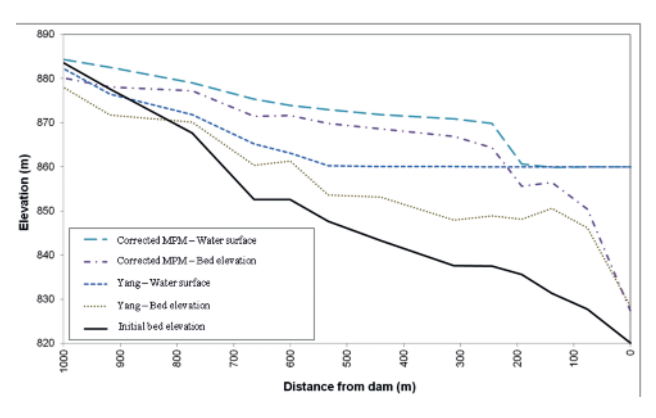
▲ Figure 2. Paute Hydropower Project: Mazar (170 MW), Daniel Palacios - Molino (1100 MW), Sopladora (487 MW) and Paute - Cardenillo (596 MW)



▲ Figure 4. Sieve curves of coarse bed material near Cardenillo dam

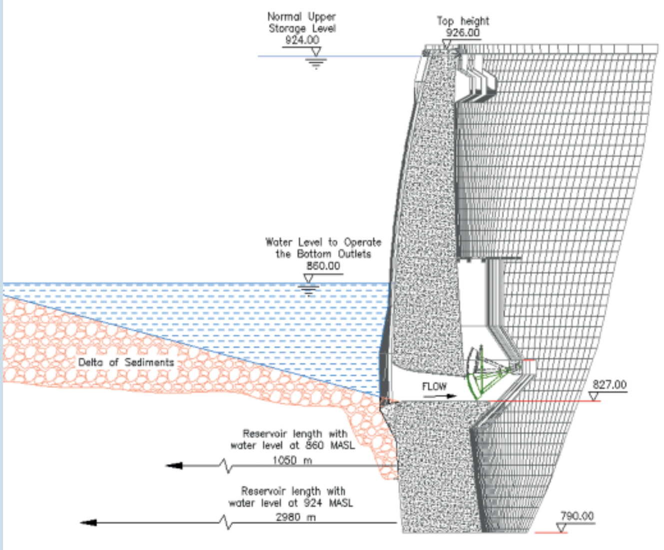


▲ Figure 6. Manning resistance coefficients in the main channel and flood-plain according to the flow discharge



▲ Figure 7. Bed and free surface profiles near the dam; the level of the bottom outlets is 827 MASL

Figure 8. Scheme of the dam, water levels and sediment delta in the initial condition of the flushing ▶



Flushing Simulations

The efficiency of the hydraulic flushing depends on the ratio between the storage volume of the reservoir and the annual amount of incoming runoff. Annandale[6] indicates that flushing is effective if this ratio is less than 0.02, whereas Basson and Rooseboom[7] raised this threshold to 0.05. The Cardenillo Reservoir ratio is about 0.003. Hence, an effective flushing process may be expected.

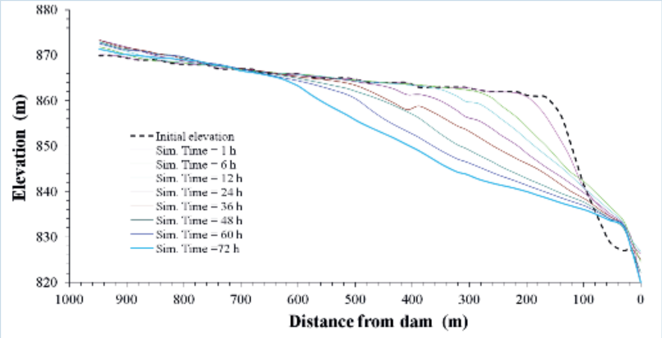
2-D numerical runs

The flushing process was analyzed using the 2D depth-averaged, finite volume Iber v1.9 program[8]. The sediment transport rate was calculated by the corrected Meyer-Peter and Müller formula[4]. The evolution of the flushing over a continuous period of 72 h was studied, according to the operational rules at the Paute-Cardenillo Dam. The initial conditions for the sedimentation profile (the lower level of the bottom outlet) was 1.47 hm^3 of sediment deposited in the reservoir. The suspended sediment concentration at the inlet section was 0.258 kg/m^3. In accordance with the future dam operations, the initial water level at the reservoir was set at 860 MASL. Figure 9 shows the time evolution of bed elevation during the flushing operation. After a flushing period of 72 hours, the sediment volume transported through the bottom outlets is 1.77 hm^3. This volume is due to the regressive erosion of the delta of sediment (1.47 hm^3) which is almost removed in its entirety during the flushing operation, and to the erosion of prior deposits accumulated at the reservoir entry (due to the inlet suspended load) during the first times of flushing.

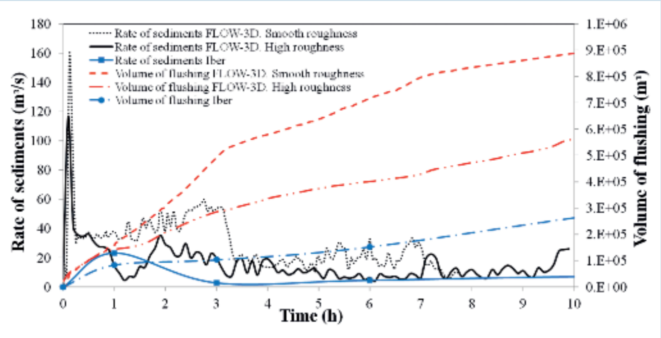
Figure 10 depicts the transversal profiles of the reservoir bottom before and after the flushing operation. Lai and Shen[9] proposed a geometrical relationship calculating the flushing channel width (in m) as 11 to 12 times the square root of the bankfull discharge (in m^3/s) inside the flushing channel. In the present study, the mean width of the flushing channel is 220 m, which is about 11 times the square root of the flushing discharge.

3-D numerical runs

Two-dimensional simulation might not properly simulate the instabilities of the delta of sediment that could block the bottom outlets. A 3D simulation could clarify the uncertainly during the first steps of the flushing operation. The computational fluid dynamics (CFD) simulations were performed with FLOW-3D v11.0 program[10]. The code solves the Navier - Stokes equations discretized by a finite difference scheme. The bed load transport was calculated using the corrected Meyer-Peter and Müller formula[4]. The closure of the Navier-Stokes equations was the Re-Normalisation Group (RNG) *k-epsilon* turbulence model[11]. The study focused on the first ten hours. The initial profile of the sediment delta was the deposition calculated by the 1D HEC-RAS code. As in the 2D simulation, the water level in the reservoir was 860 MASL. Due to the high concentration of sediment passing through the bottom outlets, the variation of the roughness in the bottom outlets was

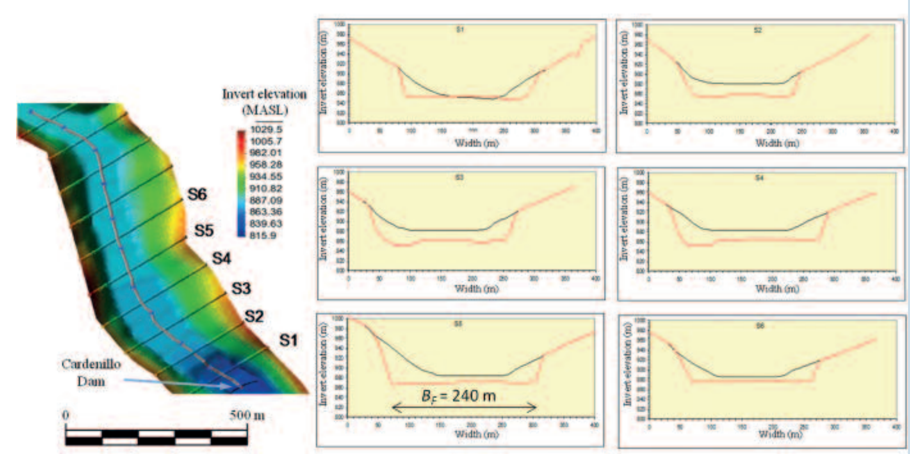


▲ Figure 9. Bed profile evolution during the flushing period of 72 h



▲ Figure 11. Comparison of the flushing operations simulated with 2D and 3D codes

Figure 10. Sediment deposition before and after a flushing period of 72 hours. B_F is the flushing channel width ▶



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considered. The Nalluri and Kithsiri formula[12] was used to estimate the hyperconcentrated flow resistance coefficient on rigid bed (bottom outlets).

Figure 11 shows the volume of sediment flushed and the transient sediment transport during the first few hours of the flushing operation. There is a maximum of 117 m^3/s of sediment for an associated flow of 650 m^3/s (volumetric sediment concentration of 0.180), at the initial times for the high roughness 3D simulation. Later, the sediment transport rate tends to decrease to values similar to those obtained with the 2D model. The total volume of sediment calculated by FLOW-3D is higher than with the Iber program. The 2D simulations considered that all the total volume of sediment (1.47 hm^3) may be removed in 60 hours. Considering that sediment transport would continue during the entire flushing operation, the 3D simulation with high roughness would require 54 hours to remove all the sediments. A more detailed analysis is given by Castillo *et al*.[13].

Principal conclusions

Empirical formulas and 1D simulations are used to estimate sedimentation in the reservoir. Two-dimensional simulations allow the analysis of a flushing operation in the reservoir. Three-dimensional simulations show details of the sediment transport through the bottom outlets, where the effect of increasing the roughness due to the sediment transport through the bottom outlets was considered. The results demonstrate the utility of using and comparing different methods to achieve adequate resolution in the calculation of sedimentation and flushing operations in reservoirs. Suspended fine sediments in the reservoir may result in certain cohesion of the deposited sediments, which might influence the flushing procedure. Carrying out a flushing operation every four months, the cohesion effect in increasing the shear stress can be avoided.

Designers must take into account the high degrees of uncertainty inherent in sediment transport (numerical modeling and empirical formulae). Sensitivity analysis must be performed to prove the models are robust to various inputs and not limited to only a single scenario. ■

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XXVIII LAD Congress 2020
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BUILDING RESERVOIR SEDIMENT MODELING CAPABILITIES WITH THE LAO PDR MINISTRY OF ENERGY AND MINES

BY JOHN SHELLEY, PAUL BOYD, STANFORD GIBSON, DANIEL PRIDAL AND TRAVIS DAHL

Background

Over the past several years the Mekong River Basin has experienced rapid development of new hydropower dams. Eleven (11) proposed dams on the main-stem of the Lower Mekong River (six are wholly within the Lao People's Democratic Republic (Lao PDR), two are on the Lao PDR-Thailand shared border, one on the Lao PDR-Cambodia border, and two are wholly within Cambodia), and numerous additional dams on tributaries, have the potential to significantly reduce the sediment input to the downstream channel (Figure 1). The sediment continuity in the Mekong basin is vital to maintaining the fisheries that over 50 million residents rely on according to National Geographic. There is an increased need to understand and minimize the impacts of reservoir sedimentation.

In 2013, the Government of Lao PDR requested, through the U.S. Embassy in Vientiane, specific assistance in hydraulic and sediment transport modeling for several key dam projects. Since 2014, reservoir sedimentation experts from the U.S. Army Corps of Engineers (USACE) have interfaced in a series of technical exchanges with the Ministry of Energy and Mines Department of Energy Policy and Planning (MEM-DEPP). The overall goal of these exchanges is to equip MEM with the technical oversight and review skills to improve the environmental and social sustainability of hydropower development in the Mekong River Basin. Proper planning and oversight can limit the impacts of dam building on the aquatic ecosystem of the lower Mekong River and increase the long-term sustainability of all reservoir benefits, including hydropower dams in Lao PDR.

Sediment Properties and Transport Analysis Workshops

Since 2014, USACE experts have held several workshops on topics such as sediment properties, river geomorphology, watershed management, and dam safety considerations. A set of three workshops in 2015 in Luang Prabang, Paksan, and Pakse, introduced nearly 80 MEM-DEPP engineers and technical staff to the physical processes that transport and deposit sediment in reservoirs, and methods to estimate the volume of sediment that has or would deposit in a reservoir (Figures 2 and 3). In 2016, a subsequent pair of workshops introduced river and reservoir sediment management methods as well as an initial exposure to sediment transport numerical modeling.

Collaborative Numerical Modeling Workshops

In 2017, USACE personnel held a hands-on reservoir sediment modeling workshop with

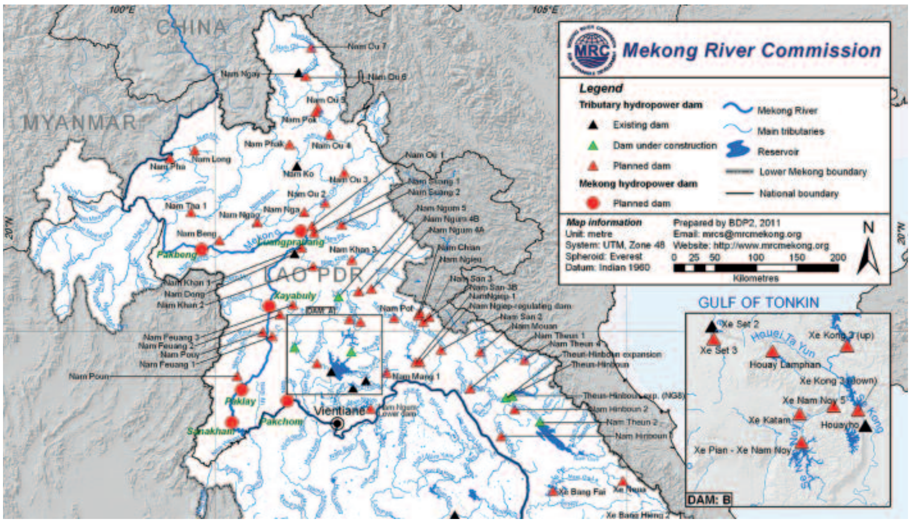

Figure 1. Excerpt from "Existing and Planned Hydropower Projects in Lao PDR"[2]

Figure 2. Dr. Paul Boyd and Mr. Daniel Pridal with MEM-DEPP engineers at Nam Khan 3 dam site

Dr. John Shelley is a hydraulic engineer and sedimentation specialist for U.S. Army Corps of Engineers, Kansas City District, River Engineering and Restoration Section, where he specializes in sedimentation analysis and modeling for rivers and reservoirs. Dr. Shelley received his BS degree in Civil Engineering from Brigham Young University and his Ph.D. in Civil Engineering from the University of Kansas.

MEM-DEPP engineers. The workshop included presentations by USACE experts interspersed with hands-on collaborative modeling exercises conducted jointly by USACE and Lao PDR engineers. These modeling exercises utilized the Hydrologic Engineering Center River Analysis System (HEC-RAS) version 5.0.3[1], which combines hydraulic modeling, sediment modeling, and reservoir gate operations. During the workshop, MEM-DEPP engineers built models using data from Lao watersheds and existing or proposed dams. These models allow for evaluating changes in management and infrastructure, and how those can affect the projected reservoir sedimentation. MEM-DEPP engineers modeled changes in reservoir pool level management that resulted in increased sediment transport to the river below the dams. Also tested was the effectiveness of drawdown flushing with and without low-level outlets. Over time these actions can reduce the environmental impact of dams on the downstream channel and prolong the useful life of the dams and hydropower infrastructure.

The workshop also included a visit to the Nam Mang 1 dam (Figure 4). The original construction of the dam included a sediment bypass tunnel. In most years, the heavily-forested watershed does not contribute significant quantities of sediment. However, wildfires, landslides, major storms, and other disturbances have the potential to introduce significant quantities of sediment in a short time frame. The inclusion of the sediment bypass tunnel allows flexibility in future operations to handle these eventualities.

Figure 3. Mr. Vithounlabandid THOUMMABOUT leads a team of MEM-DEPP engineers learning to estimate bed material size with a gravelometer (March 2015)

Figure 4. Nam Mang 1 Outlet Channel and Sediment Bypass Tunnel

Not all current designs for dams include active sediment management infrastructure. MEM intends to use the sediment modeling skillset to ensure that the current and future designs meet the sustainability goals that the Government of Lao PDR has set forth for hydropower development.

Future

USACE is continually expanding the sustainable reservoir management knowledge base, and will hold future workshops with MEM under a train-the-trainer framework. In the future, MEM-DEPP engineers who have developed the sediment modeling skillset will partner in delivering workshops to a larger group of MEM engineers, ensuring that knowledge effectively transfers to MEM staff located in provincial offices. Future workshops will use HEC-RAS v.5.0.5, which will bring increased geospatial functionality and independence without the need for integration with licensed software.

This ongoing effort is supported by the United States Agency for International Development (USAID) through the Smart Infrastructure for the Mekong (SIM) program, and the USACE. The SIM program is a collaborative effort supported by an inter-agency agreement between USAID and the US Department of the Interior.

Acknowledgements

The USACE technical team and authors would like to express their gratitude to the leadership within the MEM for their continued engagement and efforts to increase sustainability within their hydropower development program. Specifically, Dr. Daovong PHONEKEO, Permanent Secretary MEM, Mr. Khamso KOUPHOKHAM, Acting Director General DL-MEM, and Mr. Vithounlabandid THOUMMABOUT, Deputy Director General DEPP-MEM, have assisted in engaging MEM engineers, coordinating engagements, and providing resources for this effort. ■

References

[1] Brunner, G.W. (2016). HEC-RAS, River Analysis System Hydraulic Reference Manual. U.S. Army Corps of Engineers, Davis, CA.
[2] MRC Planning Atlas of the Mower Mekong River Basin. (2011). www.mrcmekong.org/assets/Publications/basin-reports/BDP-Atlas-Final-2011.pdf.

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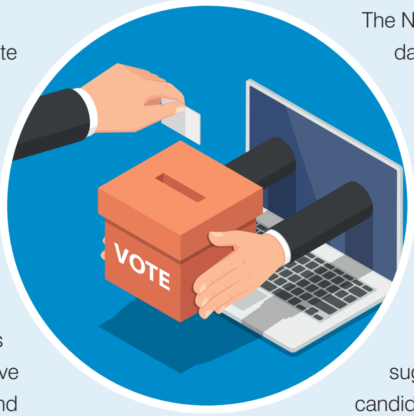
COUNCIL ELECTION 2019 – 2021

Nominating Committee 2019

At its meeting in Lyon, France, in September 2018 the IAHR Council has identified a Nominating Committee (NC 2019) for the next Council election ahead of the next World Congress in Panama, 1-6 September 2019. The Nominating Committee will be chaired by Roger Falconer (UK), former President of IAHR, and comprises Julio Kuroiwa (Peru), Ana Maria da Silva (Canada), Arthur Mynett (The Netherlands), Jose M. Carrillo (Spain), Angelos Findikakis (USA), Yoshiaki Kuriyama (Japan) and Farhard Yazdandoost (Iran). IAHR President Peter Goodwin (USA) will serve as the Council contact person.

The NC collects proposals from individual and institute members, searches itself for candidates, and evaluates the performance of present Council members in view of their possible re-election. It must consider the alignment of candidates with Council composition requirements, including the question of progression of Council Members to Vice Presidential positions or to the Presidency.



It is the task of the NC to propose a list of candidates for the 2019 Council election, which includes Executive Committee positions (President, 3 Vice-Presidents and Secretary General) and regularly elected Council members. This list must reflect a balance between the possibly conflicting requirements of:

- world-wide representation of the IAHR membership and yet at the same time a small active group which is capable to lead the Association, and to fulfil Council assignments;
- continuous renewal through new members while assuring necessary continuity;
- adequate representation of hydro-environment engineering practice;
- IAHR's goal to increase gender diversity in its leadership team – particularly for the future

Invitation to the membership for nomination of candidates

The Nominating Committee hereby invites all IAHR members to submit suggestions regarding nomination of possible candidates for Council. Please make your suggestions of potential Council candidates to any member of the NC 2019 before January 31st, including a rationale for the suitability of the candidate proposed and an indication of the nominee's willingness to accept if elected. The Nominating Committee will give due consideration to all suggestions for Council Members.

NC 2019 slate of candidates

The Nominating Committee will evaluate all proposed nominations for Council Members with respect to their qualification for fulfilling the major tasks of the IAHR Council.

The IAHR Council has the task to promote the interests of the Association and co-ordinate the activities of its members serving the interests and needs of Hydro-environment Engineering and Research, both at global and at regional scale. This includes long-range planning for the biennial World Congresses as well as co-ordination and interlinkage of activities of Regional and Technical Divisions and Committees, *e.g.* conferences, IAHR publications and Awards and promotion of continuing education, student chapters and short courses. Membership promotion, finances, IAHR secretariat liaison and links with institute members, industry and the profession are also important tasks, as well as relations with government agencies and other professional/technical societies and international organisations.

The Nominating Committee will develop a slate of candidates, which must be published according to the By-Laws by March 1st. This slate may contain up to two candidates for each position.

Any member wishing to receive a printed list of the slate of candidates should contact the Secretariat after this date.

Nomination by petition

If the Nominating Committee has not included your suggestion in its slate or if you have another suitable candidate not hitherto considered, all members have the option to file a nomination by petition within two months after publication of the NC 2019 slate. The new election procedure gives any group of members in the Association, which feels that its interests are not properly taken into account by the NC 2019 slate, the chance to submit nominations by petition for any of the regular Council member positions. A valid petition requires signatures of 15 members from at least five countries or from a group of countries representing 10% of the IAHR membership. This assures that there is support for a candidate which goes beyond a personal or national interest. All valid nominations by petition will be included in the ballot.

Nominations by Petition must be submitted to the Secretariat within two months after publication of the NC slate of candidates with a statement from the candidate, that she or he is willing to accept the nomination, a resumé including professional career, involvement in IAHR, and a statement on the planned contribution as Council member.

Ballot

The NC will submit its list of candidates to the Secretariat for publication together with any candidates "by Petition", reaching members at least two months prior to the congress. Members will be invited to elect the new Council through written or electronic ballot before and at the Panama Congress, closing on Wednesday 4th September, 2019.

Contact:

NC 2019 Chair:
Prof. Roger A. Falconer, Former IAHR President
IAHR_Nom2019@iahr.org

IAHR AWARDS
CALL FOR NOMINATIONS 2019

Hosted by
Spain Water
and IWHR, China

IAHR members are invited to submit nominations for the Arthur Thomas Ippen Award, Harold Jan Schoemaker Award, and M. Selim Yalin Award. These awards will be presented at the 38th IAHR World Congress, Panama, September 1-6 2019.

IAHR Vice President Prof. Silke Wieprecht is co-ordinating nominations received for the 2019 Awards. The nominations should consist of a concise statement of the qualifications of the nominee, a listing of his/her outstanding accomplishments, pertinent biographical data, and a proposed statement of the endeavours for which the nominated awardee would be recognised. Each nomination should not be more than two typewritten pages in length.

IAHR is interested to increase the visibility of particularly qualified female researchers. Thus, we would appreciate efforts to identify qualified women. IAHR also attaches great importance to representing a complete cross-section of the regional distribution and subject area of its members. However, the scientific qualification is of primary importance for the awarding of the prize. Although, a balanced consideration of the diversity of our members is very important to us.

Nominations for the three awards must be sent by January 31st, 2019 using the standard nomination form at www.iahr.org / About IAHR / Awards

21st Arthur Thomas Ippen Award

For outstanding accomplishment in hydraulic engineering and research

The Founding Statement and the Rules for Administration of the Award are as follows:

Founding Statement

The Ippen Award was established by the IAHR Council in 1977 to memorialise Professor Ippen, IAHR President (1959-1963), IAHR Honorary Member (1963-1974), and for many decades an inspirational leader in fluids research, hydraulic engineering, and international co-operation and understanding. The Award is made biennially by IAHR to one of its members who has demonstrated conspicuously outstanding ability, originality, and accomplishment in basic hydraulic research and/or applied hydraulic engineering, and who holds great promise for continuation of a high level of productivity in this profession. The awards are made at the biennial congresses of IAHR, where the most recent recipient delivers the Arthur Thomas Ippen Lecture. The Award fund, which was established by Professor Ippen's family, is authorised to receive contributions from association members and friends of Professor Ippen. The 2015 Award was made to Qiuwen Chen, China.

Rules for the administration of the award

1. The Arthur Thomas Ippen Award (hereinafter referred to as the Award) will be made biennially, in odd-numbered years, to a member of IAHR who has developed a conspicuously outstanding record of accomplishment as demonstrated by his research, publications and/or conception and design of significant engineering hydraulic works; and who holds great promise for a continuing level of productivity in the field of basic hydraulic research and/or applied hydraulic engineering.

2. Candidates must be under 45 years of age at the time of presentation of the Award in the Congress

3. Each awardee will be selected by the IAHR Council from a list of not more than three nominees submitted to the Council by a Committee (hereinafter referred to as the Awards Committee) composed of the Technical Division Secretaries and chaired by IAHR Vice President, Prof. Silke Wieprecht. The Awards Committee will actively seek nominations of awardees from the IAHR membership, and will publish at least annually in the IAHR Newsletter an advertisement, calling for nominations. The advertisement will include a brief description of the support material which is to accompany nominations.

4. The awardee for each year will be selected by the Council by mail ballot in January of the year of the Congress.

5. The award need not be made during any biennium in which the Council considers none of the nominees to be of sufficient high quality.

6. The awardee will present a lecture, to be known as the Ippen Lecture (hereinafter referred to as the Lecture), at the IAHR World Congress following his election. The subject of the Lecture will be agreed upon by the awardee and the IAHR President. The Lecture will be published in the Congress Proceedings. Public presentation of the Award will be made by the President during the opening ceremonies of the Congress.

7. The awardee will be given a suitable certificate which will state the purpose of the Award and indicate the specific contribution(s) of area(s) of endeavour for which the awardee is recognised. The awardee also will receive a monetary honorarium upon presentation of the Lecture. The terms of the honorarium will be published in the announcement of each biennial Award. The monetary honorarium for the Award is US$1,500.

8. Wide distribution of awardees among different countries and different areas of specialisation is to be sought by the Award Committee and by the Council.

9. No individual shall receive the Award more than once.

Previous Winners

Q. Chen, China (2017) in recognition of outstanding contributions in the field of environmental hydroinformatics and ecohydraulics.

D. Violeau, France (2015) for outstanding contributions in the field of fluid mechanics with special emphasis on turbulence modeling for addressing complex, real-life hydraulics problems.

G. Constantinescu, USA (2013) for outstanding contributions in the field of fluid mechanics and especially of turbulence modeling with applications to fluvial hydraulics and stratified flows.

X. Sanchez-Vila, Spain (2011) for his outstanding contributions in the field of groundwater flow and contaminant transport with application to flow modeling in heterogeneous porous media.

Y. Niño, Chile (2009) for his outstanding basic contributions in fluid mechanics with applications to sediment transport and environmental flow processes.

M. S. Ghidaoui, HK China (2007) for his outstanding contribution to research in environmental fluid mechanics.

A. M. Da Silva, Canada (2005) for her outstanding contributions in the area of fluvial processes and in particular, sediment transport.

21st Harold Jan Schoemaker Award

for the most outstanding paper in the Journal of Hydraulic Research

IAHR members are invited to submit candidates for nomination for the Harold Jan Schoemaker Award. This Award will be made for the 21st time at the 38th IAHR World Congress to the author(s) of the paper judged the most outstanding paper published in the IAHR Journal of Hydraulic Research in the issues, starting with Volume 54 (2016) no. 5 up to and including Vol. 56 (2018) no. 4. A proposal for nomination shall be completed with a clear argumentation (maximum one page) regarding its outstanding quality and why the paper is of such a specific quality that it outweighs the other papers of the considered series.

Founding Statement

The Schoemaker Award was established by the IAHR Council in 1980 to recognise the efforts made by Professor Schoemaker, Secretary (1960-1979), in guiding the Journal of Hydraulic Research in its formative years. The Award is made biennially by the IAHR to the author(s) of the paper judged the most outstanding paper published in the IAHR Journal.

Rules for the administration of the Award

1. The Harold Jan Schoemaker Award (hereinafter referred to as the Award) will be made at each biennial IAHR Congress, to the author(s) of the paper judged the most outstanding and published in the IAHR Journal during the preceding two-year period.

2. The awardee will be selected by the IAHR Council from a list of not more than three ranked nominees submitted to the Council by a Committee (hereinafter referred to as the Award Committee) composed of the Technical Division Secretaries and chaired by IAHR Vice President Prof. Silke Wieprecht. The Award Committee will actively seek nominations of awardees from the IAHR membership (also non-members whose employers are corporate members will be considered)

3. The awardee will be selected by the Council by ballot. The awardee(s) shall be notified immediately by the Executive Director.

4. An award need not be made during any biennium in which the Council considers none of the nominees to be of sufficient high quality.

5. The award will consist of a bronze medal and a certificate.

Previous Winners

B. Vowinckel, et al for the paper “Entrainment of single particles in a turbulent open-channel flow: a numerical study” (Vol. 54, 2016, Nº 2)
T. Stoesser (2015) for the paper “Large-eddy simulation in hydraulics: Quo Vadis?” (Vol. 52, 2014, Nº 4)
V. Heller (2013) for the paper “Scale effects in physical hydraulic engineering models” (Vol. 49, 2011, Nº 3)
H. Nepf (2013) for the paper “Hydrodynamics of vegetated channels” (Vol. 50, 2012, Nº 3)
U. Chandra Kothyari, H. Hashimoto and K. Hayashi (2011) for the paper “Effect of tall vegetation on sediment transport by channel flows” (Vol. 47, 2009, Nº 6)
H. Morvan, D.W.Knight, N.Wright, X.Tang (2009) for the paper “The Concept of Roughness in fluvial hydraulics and its formulation in 1D, 2D, and 3D numerical simulation models” (Vol. 46, 2008, Nº 2)
K.Blankaert and U.Lemmin (2007) for the paper “Means of noise reduction in acoustic turbulence measurements” (Vol. 44, 2006, Nº 1)
E.J. Wannamaker and E.E. Adams (2007) for the paper “Modelling descending carbon dioxide injections in the ocean” (Vol. 44, 2006, Nº 3)
A. Carrasco and C. A. Vionnet (2005) for the paper “Separation of Scales on a Broad Shallow Turbulent Flow” (Vol. 42, 2004, Nº 6)

7th M. Selim Yalin Award

for significant and enduring contributions to the understanding of the physics of phenomena and/or processes in hydraulic science or engineering, and demonstrated outstanding skills in graduate teaching and supervision

IAHR members are invited to submit candidates for nomination for the M.Selim Yalin Award. This Award will be made for the 6th time at the 37th IAHR World Congress. The Founding Statement and the Rules for Administration of the Award are as follows:

Founding Statement

The M. Selim Yalin Award was established by the IAHR Council in 2006 to honour the memory of Professor M. Selim Yalin, Honorary Member (1925-2007), and Fluvial Hydraulics Section Chairman (1986-1991). Professor Yalin is remembered for his prolific and pioneering research contributions in fluvial hydraulics and sediment transport, and for his inspirational mentoring of students and young researchers.

The Award is made biennially by IAHR to one of its members whose experimental, theoretical or numerical research has resulted in significant and enduring contributions to the understanding of the physics of phenomena and/or processes in hydraulic science or engineering and who demonstrated outstanding skills in graduate teaching and supervision. The awards consisting of a certificate and cash prize are presented during the IAHR World Congresses. The Award fund, which was established by the family and friends of Professor Yalin, is authorised to receive contributions from association members and friends of Professor Yalin.

Rules for the administration of the award

1. The IAHR M. Selim Yalin Award (hereinafter referred to as the Award) will be made biennially, in odd-numbered years, to a member of IAHR whose experimental, theoretical or numerical research has resulted in significant and enduring contributions to the understanding of the physics of phenomena and/or processes in hydraulic science or engineering and who has demonstrated outstanding skills in graduate teaching and supervision.

2. Each awardee will be selected by the IAHR Council from a list of not more than three nominees submitted to the Council by a Committee (hereinafter referred to as the Award Committee) composed of the Technical Division Secretaries and Chaired by a Council Member. The Award Committee will actively seek nomination of awardees from the IAHR membership, and will publish at least annually in the IAHR Newsletter an advertisement, calling for nominations. The advertisement will include a brief description of the support material which is to accompany nominations.

3. The awardee for each biennium will be selected by the Council either at its meeting during the preceding even-numbered year or by mail ballot in January of the year of the Congress.

4. The award need not be made during any biennium in which the Council considers none of the nominees to be of sufficient high quality.

5. Public presentation of the Award will be made by the President during a public ceremony taking place within the Congress.

6. The awardee will be given a suitable certificate which will state the purpose of the Award and indicate the specific contribution(s) of area(s) of endeavour for which the awardee is recognised. The awardee also will receive a monetary honorarium, the terms of which will be published in the announcement of each biennial Award.

7. Wide distribution of awardees among different areas of specialisation is to be sought by the Award Committee and by the Council. Efforts will also be made to ensure a wide geographical distribution.

8. No individual shall receive the Award more than once.

Previous Winners

M. H. García, USA (2017), in recognition of outstanding contributions in the field of numerical morphodynamics and specially in the excellence of his teaching and mentorship of young professionals as well as contribution to applied projects.
A. Armanini, Italy (2015), for enduring theoretical, experimental and modeling contributions to the understanding of sediment and debris transport processes and excellence in graduate teaching and advancement of academic programs in hydraulic engineering.
Y. Shimizu, Japan (2013), for outstanding science and excellence in teaching and mentorship of young professionals as well as contribution to applied projects.
Prof. Ian Wood (2011), for outstanding contributions in the field of hydraulic engineering and especially in the experimental research of hydraulic structures, as well as in the teaching and supervision of graduate students from around the world.
I.Nezu, Japan (2009), for his outstanding research contributuions in both fundamental hydroscience (in particular for his pioneering work in turbulanece measurements and analysis) and applied hydraulic engineering, and for his dedication to teaching and young professional mentoring
G. Parker, USA (2007)
for his outstanding achievements over thirty years in the field of sediment transport, river engineering, river morphodynamics and submarine sedimentation processes

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