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Innovative strategies for managing reservoir sedimentation in Japan

Hydrolink

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.

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

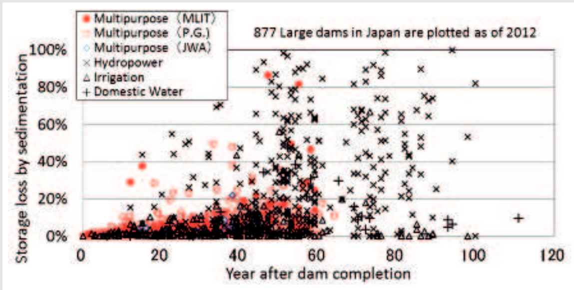


Figure 1. Evolution of the reservoir sedimentation rate over dam's age. (MLIT: Ministry of Land, Infrastructure, Transport and Tourism, P.G.: Prefectural Government, JWA: Japan Water Agency)

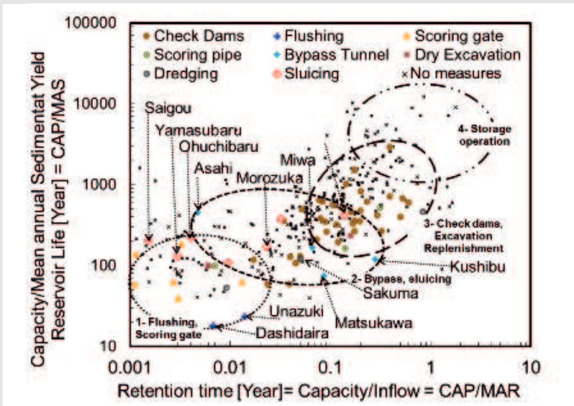


Figure 2. Plot of projects in Japan with different sediment management strategies. Reservoir life is indicated by the ratio between the reservoir storage capacity and the mean annual inflow sediment to the reservoir (CAP/MAS). The residence time of water (called also retention time, impoundment ratio)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

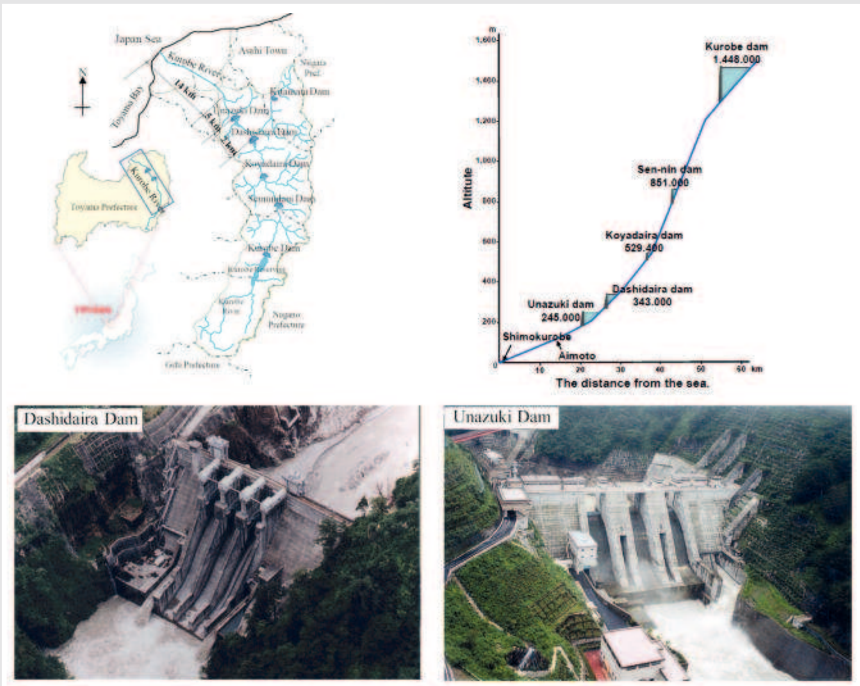


Figure 3. Location map of the Dashidaira Dam (high: 76.7 m, initial storage capacity: 9 Mm^3, annual sediment inflow: 0.62 Mm^3) and the Unzauki Dam (high: 97 m, initial storage capacity: 24.7 Mm^3, annual sediment inflow: 0.96 Mm^3). Photos show the two dams during a coordinated sediment flushing operation

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

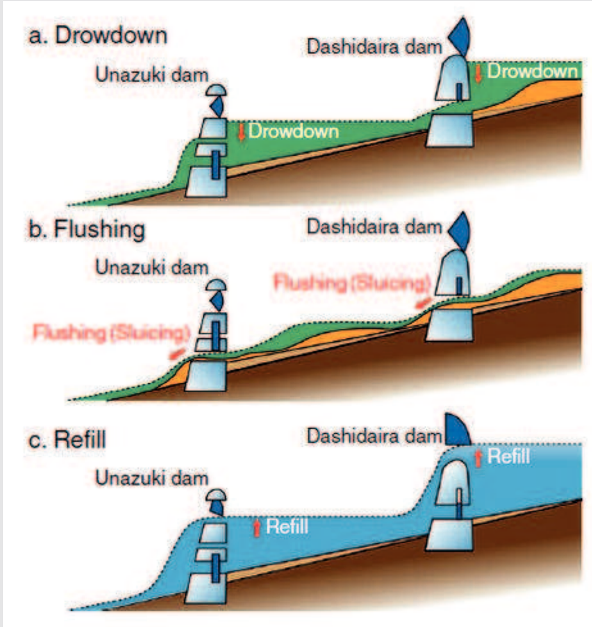
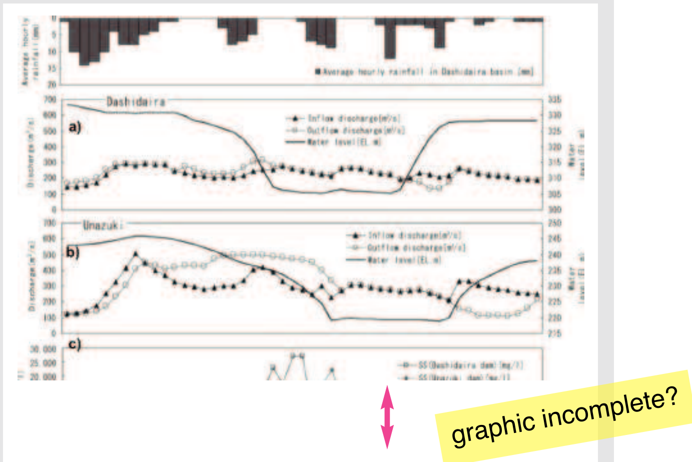


Figure 5. Coordinated flushing at reservoirs in the Kurobe River, 1–3 July 2006[6]. Inflow and outflow hydrographs and reservoir stage for (a) Dashidaira and (b) Unazuki dams. (c) resultant suspended sediment (SS) concentrations. Shimokurobe is near the river outlet at Japan Sea



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

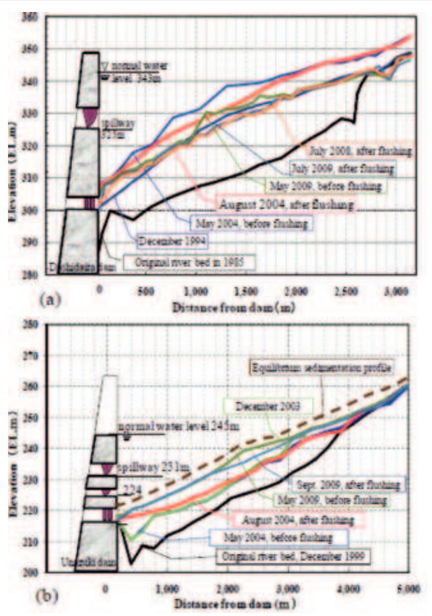
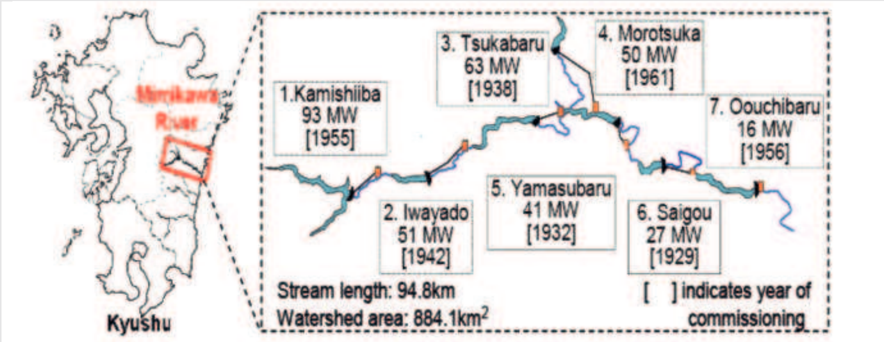


Figure 6. Measured longitudinal profiles before and after flushing operations[7]. (a) Dashidaira Reservoir, (b) Unazuki Reservoir

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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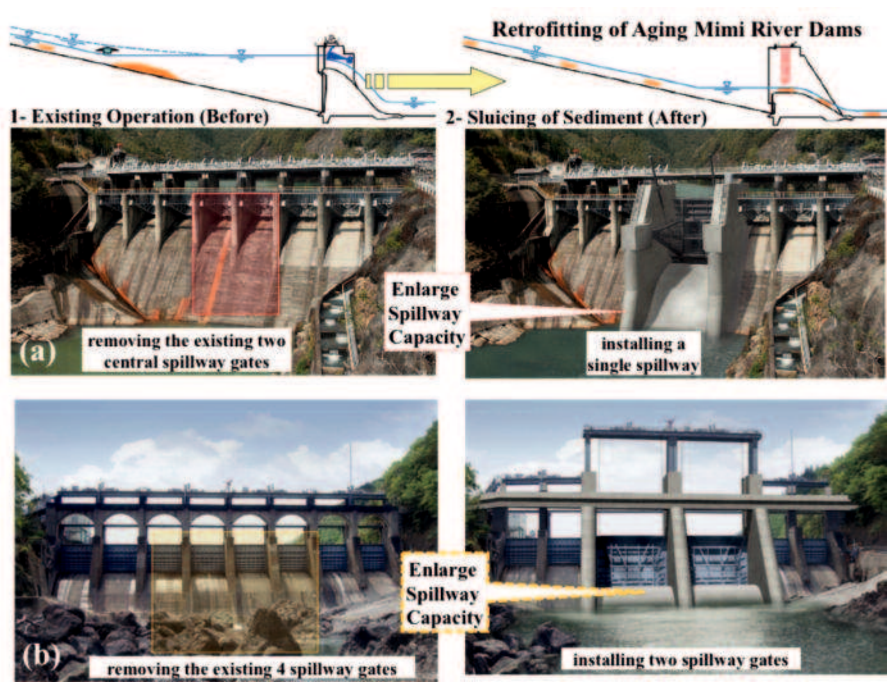

Figure 8. Existing and upgraded states by cutting down the crest of spillways of (a) Yamasubaru dam (two spillways retrofitted into one) and (b) Saigou Dam (four spillways retrofitted into two)[11]

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).

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

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).

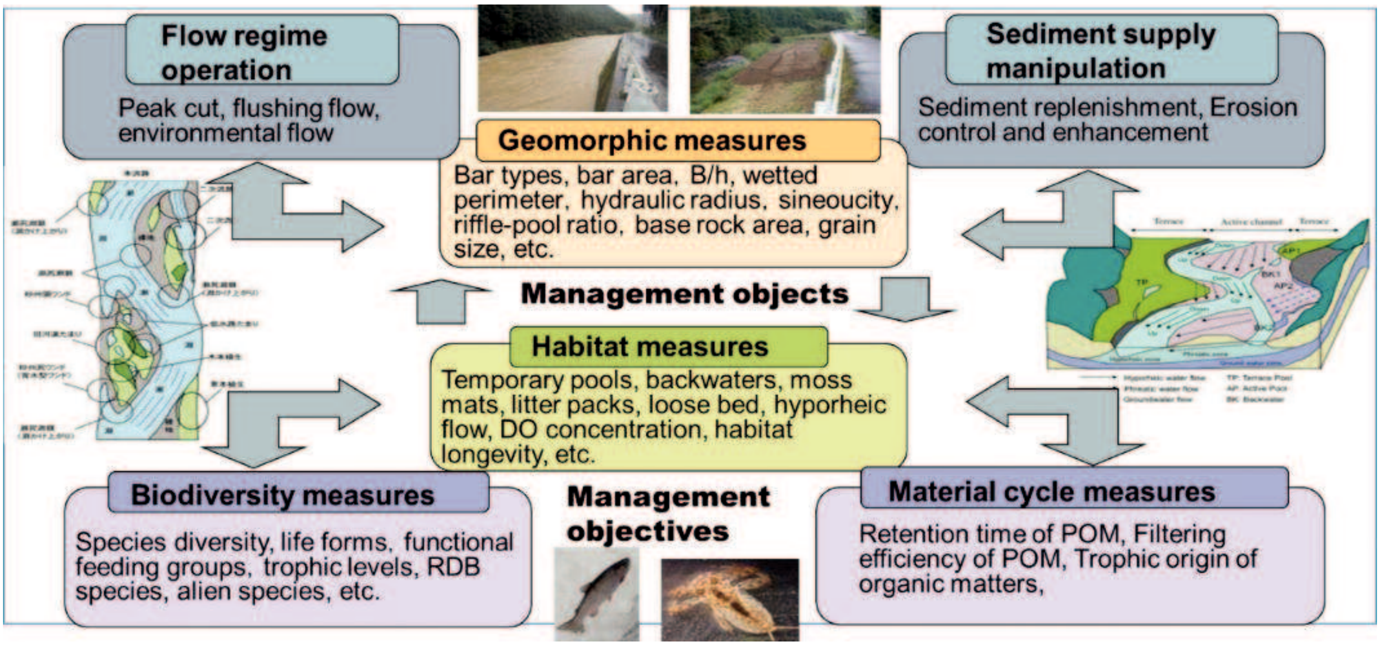

Figure 10. Conceptual figure for bridging between hydraulics, sediment, geomorphology, and biodiversity to achieve restoration of downstream river conditions (B/h: Channel width- flow depth ratio, RDB: Red Data Book, POM: Particle Organic Matter)[9]

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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