Feedbacks from Asia and Europe for designing sediment passing facilities in hydropower dam projects

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Introduction

Dam outlets are commonly designed and used to ensure the water passage during high flow and flood conditions. For such hydrological situations, solid concentrations and fluxes flowing in the river channel are significantly increased according to various processes. Those processes are mainly a function of particle size, stream velocity and flow turbulence. In most cases, coarse and fine particles supplied from the riverbed erosion, which correspond mainly to gravel and sand, are transported as bed-load and graded suspension respectively. Very fine particles washed out from hillslopes, which are commonly named as wash-load and correspond mainly to silt and clay, are generally transported by uniform suspension. The relative importance of each process is determined by many factors such as the catchment size, the stream slope, the sediment sources (and in particular their nature, extension and location), the hydrological and sediment regimes of the catchment and the possible existence of upstream reservoirs.

The trapping efficiency of reservoirs regarding solid fluxes depends on many factors such as the dam height, reservoir depth and width, ratio between the mean annual discharge and storage capacity of the impoundment, size of the solid fraction considered, position and capacity of the different dam outlets… For instance, large dams and reservoirs allowing a seasonal regulation of water inflows are likely to trap a wide variety of sediments ranging from very fine to very coarse particles, while barrages or low head run-of-river dams (i.e. below 20 meters approximately) might affect the coarsest sediment fractions transported by the river only.

Assessing properly the sediment regime of a basin where a reservoir is planned is an essential prerequisite so as to (1) design a dam that allows sediment continuity to be maintained for a wide range of particles and hydrological situations, and (2) define operation rules likely to limit as much as possible sedimentation processes within the reservoir. For dam operators, such requirements are indeed of utmost importance for achieving in particular following objectives: (1) conserve as long as possible the storage capacity of the reservoir, (2) limit maintenance costs due to dredging needs and turbines refurbishment, and (3) prevent deposition and erosion issues likely to occur upstream, within and downstream reservoirs. Among those concerns, sediment starvation possibly induced in downstream reaches is a critical one. It is indeed clearly known now that the sediment supply and renewal due to river dynamics processes contributes to the good ecological health of river-systems and provides numerous environmental benefits such as soil fertilization, shoreline and riverbed stability, nutrients supply, habitats and spawning areas for the aquatic fauna…

A wise management of sediment fluxes flowing to and from reservoirs is thus essential, especially for maintaining the status of hydropower generation as a renewable energy. Strategies available are numerous and in this paper, a particular emphasis is put on two options which appear to be very cost effective. The first one consist in preventing sedimentation processes by sluicing (or routing) inflowing sediments and the second one is based on a remobilization of previously deposited sediments according to an eco-friendly flushing principle. Through two examples from Japan (Mimikawa River basin) and France (Rhône River basin), the purpose of this communication is first to present case studies for which successful strategies have been applied either from the very beginning of the design stage of the project or after several years of operation in the frame of retrofitting operations. In the final part, recommendations are formulated based on the experience acquired from these two examples, especially concerning the main factors to take into account for designing appropriate operation rules and optimizing the vertical distribution of hydraulic facilities contributing to pass sediment-laden flows.

1 Mimikawa River case study

1.1 Overview of geographical context

The Mimikawa River is located in the Miyazaki Prefecture, in the southeast of Kyushu, Japan. This torrential river is flowing from a mountainous area into the Pacific Ocean and is draining a catchment area of approximately 884 km². Making use of an abundant volume of water and large water head, 7 dams and hydropower stations were developed between the 1920's and 1960's (Fig. 1). Those developments have currently a combined generating power of 340 MW, and an output of 900 million kWh, making it one of the most important areas in the Kyushu region for hydropower production.

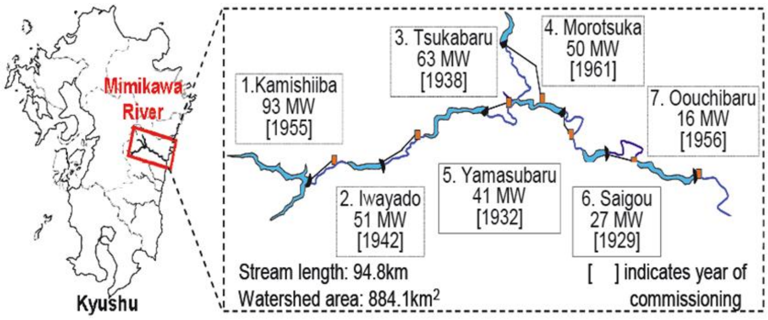

Fig. 1. Mimikawa river basin, dams and power plants features.

In the period from summer to fall, the river is regularly subject to flood events due to the occurrence of typhoons moving from the southern seas towards north. In September 2005, Typhoon Nabi hit Japan, causing heavy precipitations and large scale damages in various parts of Japan, including the Miyazaki Prefecture. In the Mimikawa River Basin, the maximum discharge ever recorded was exceeded, as well as the design flood of dams. Consequently, the Kamishiiba, Tsukabaru, Yamasubaru and Saigou power plants were flooded, leading to an interruption of power generation [1]. Inundations were extensive in the central area of Morotsuka village, which is located on the upstream edge of the Yamasubaru dam. Flood damages were amplified by diffuse mountain slope failures that occurred in approximately 500 locations (Fig. 2 and Fig. 3). Those erosion processes supplied a huge amount of sediments and woody debris into the channel of the Mimikawa River. Sedimentation within the dam-regulating reservoirs induced extra-flood hazards due to bed aggradation. Reservoir deposits totalized a volume of 5.2 Mm^3, corresponding approximately to half of the inflowing solid fluxes. The sediment stock available in the river basin after this event represents an additional volume of 26.4 Mm^3. As it may be remobilized and transported to the reservoirs during further typhoons, the basin management authority had to seriously address this pending threat.

Fig. 2. Flooding in central area of the Morotsuka village.

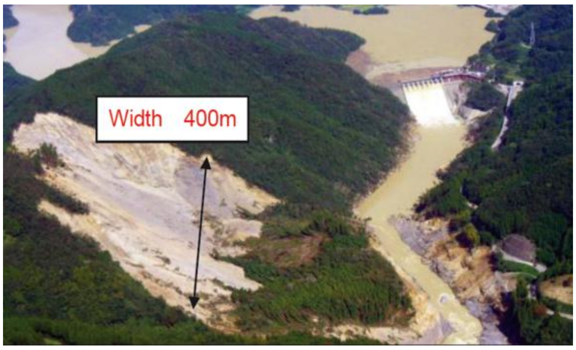

Fig. 3. Large landslide downstream of the Tsukabaru dam.

1.2 Sediment management scheme performed after 2005 typhoon

Finally a "Basin Integrated Sediment Flow Management Plan for the Mimikawa River" has been established in October 2011 by the Miyazaki Prefecture, which is the river administrator. This document was performed through regular discussions between stakeholders involved in the river basin management. Rather than focusing on each problem separately, the prefecture came to a proper understanding of these various sediment-related issues over the entire river basin, including the mountainous and coastal areas, the river system itself and the dam cascade operation. The main concerns regarding sediment issues in the basin were synthetized as well as possible approaches to solve these problems while balancing flood control, water usage and environmental conservation [2]. The role and objectives of each stakeholder were also defined so as to resolve comprehensively the sediment-related issues raised by this event [3].

As part of the Management Plan, the Kyushu Electric Power Company (KEPCO), which is responsible for the dam cascade operation, is aiming to restore the original sediment flow trapped in reservoirs until now. The definition of adequate measures for achieving such ambitious objective requires a sound understanding of the sediment dynamics in the river basin. For this reason, a combination of studies including numerical simulations and laboratory experiments using small scale physical models have been performed to evaluate different management scenarios.

Sediment sluicing operation at Yamasubaru, Saigou and Oouchibaru dams has finally appeared to be the most relevant option [4]. As a reminder, sediment sluicing (or routing) consists in a temporary lowering of the water level at dam site during flood situations so as to recover natural-like flow conditions and transfer inflowing sediments throughout the reservoir [5].

The surveys performed in the frame of this project provide also detailed specifications regarding following issues: (1) dam retrofitting works and innovative techniques required for performing sediment sluicing operation, (2) assessment of environmental impacts possibly induced below dams and (3) definition of complementary actions for managing sediment flows preliminary to sluicing operation. It has been also confirmed that as a result of this new sediment management scheme, a lower equilibrium profile would be obtained in the reservoirs and particles previously accumulated upstream dams, such as sand and gravel, would be effectively released further downstream. The numerous benefits provided by the restoration of the sediment continuity through the reservoirs were evaluated and the major ones can be summarized as follows: (1) extension of reservoir time life thanks to the limitation of sedimentation processes, (2) mitigation of extra-flood hazards possibly induced by the bed aggradation at reservoir inlet during flood events and (3) restoration of a healthier ecological state for the aquatic eco-systems, in particular through the diversification of riverbed materials and forms in the lower regions of the basin.

1.3 Definition of retrofitting scenarios for managing sediment supply to and from reservoirs

As already mentioned previously, the water level at dam has to be lowered sufficiently during flood conditions so as to recover favourable hydraulic conditions throughout the reservoir for sediment sluicing (or routing). If a too high water level is maintained, the flow velocity will be indeed too low and the inflowing sediments are likely to be massively deposited into the reservoir (Fig. 4).

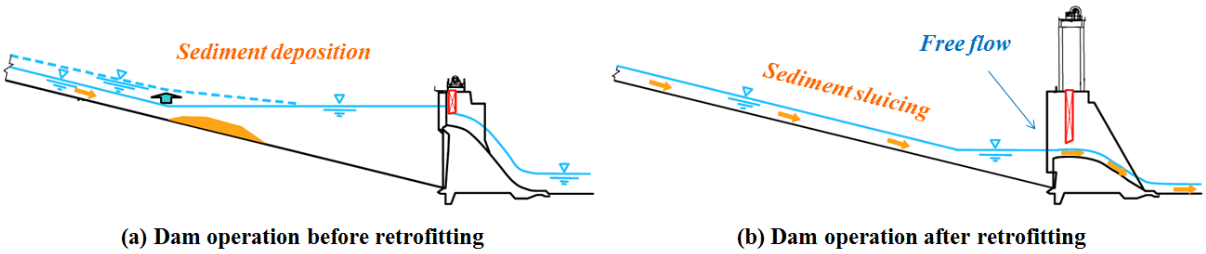

Fig. 4. Comparison of dam layout, reservoir operation and sediment dynamics before and after retrofitting.

In the case of the Oouchibaru dam, the current layout of spillway gates is already suitable to perform sediment sluicing. For this dam, which is the furthest downstream development, the operation rules only will be changed, in particular by lowering the operating level during flood conditions by 7 meters at minimum. Concerning the Yamasubaru and Saigou dams, a sufficient drawdown of the reservoir water level cannot be obtained for sediment sluicing with the initial structures. This limitation is due to the current spillway feature, which is characterized by a too high crest elevation and a too low discharge capacity. To achieve suitable conditions for sediment transportation at dam site, the spillway crest has to be lowered by cutting down partially the weir section (Fig. 5). In the particular case of the Yamasubaru dam, retrofitting will be carried out by removing the existing two central spillway gates, cutting down spillway crest height by approximately 9.3 m, and implementing a single large spillway gate. With such scheme, it has been demonstrated that the sediment transport capacity of the flow will be comparable to the one obtained by a dam removal, and that the cost for managing sediment fluxes will be minimised. For Saigou dam, the optimal scenario consists in removing the four central spillway gates and cutting down the spillway crest height by approximately 4.3 m. It is interesting to note that in the cases presented, sediment sluicing appears feasible as soon as the ratio between the gate height and dam head exceeds 60 to 70% or as soon as the ratio between gate and dam heights is approximately above 50% (Tab. *1*).

Tab. 1. Dam and gates characteristics before and after retrofitting.

Project		Yamasubaru dam	Saigou dam	Oouchibaru dam
Dam height (m)		29.4	20.0	25.5
Dam head (m)		23.0	16.0	19.0
Size (HxL) of initial gates (m)		6.4x7.6	5.8x8.7	13.1x14.0
Size (HxL) of retrofitted gates (m)		15.5x13.6	10.2x17.6	-
Ratio between gate height and dam head	Initial	28%	36%	69%
	Retrofitted	67%	64%	-
Ratio between gate and dam heights	Initial	16%	29%	51%
	Retrofitted	53%	51%	-

Fig. 5. Current state and retrofitting scheme of Yamasubaru and Saigou dams on left and right side pictures respectively.

1.4 Implementation of retrofitting scheme in the field

Retrofitting works on Yamasubaru and Saigou dams have started in November 2011. In Japan, it will be the first time that an existing dam will be modified by the addition of a new sluicing function 80 years after its commissioning. Cutting down the weir of a dam is obviously a challenging operation that has to be performed without causing structural damage. It requires in particular the installation of a large-scale coffer dam for diverting temporarily the river flow through a headrace to maintain power generation. In addition, field works are limited to a period extending from November to May when the river is statistically less subject to flood events. For managing flood hazards and discharging safely water from dams while retrofitting work is still in progress, a 4 m high steel-rubber gate (SR gate) has been also installed in the upper part of the temporary cofferdam. Finally, sediment sluicing operations are planned to effectively start at Saigou and Oouchibaru dams in 2017 and at Yamasubaru dam in 2021.

1.5 Understanding environmental changes induced by sediment sluicing at dams

Sediment sluicing at dams will be increasing the solid fluxes released from reservoirs and is likely to induce morphological changes in the river environment. Assessing the impact of such measure prior to its implementation is therefore necessary. To achieve this objective and better define the current state of the Mimikawa River in terms of sediment dynamics, a survey is being carried out, covering issues such as water quality, bed-materials characteristics, river channel morphology, as well as aquatic fauna and flora.

It has to be noted that due to the ongoing retrofitting works, changes have been already experienced regarding the quantity of sediments passing through the reservoirs. In the particular case of the Saigou dam, a very significant intensification of coarse sediment fluxes has been observed since the beginning of the works as a result of the water depth drop and flow velocity increase. Those preliminary field evidences are very encouraging and demonstrate that sediment sluicing is a promising measure for restoring the sediment continuity throughout the river system for a wide range of particles. Field monitoring appears to be an essential management tool and is thus scheduled to continue for understanding and quantifying the impact of sediment sluicing operations performed at dams on the river environment.

2 Rhône River case study

2.1 Overview of geographical context

The Rhône River originates from the Swiss Alps and flows through the South-East part of the French territory down to the Mediterranean Sea (Fig. 6 left). The river drains a total area of 95,500 km² at the outlet of its catchment and figures prominently among the largest rivers of Western Europe. In its upper part, the Rhône River flows into the Geneva Lake. As almost all inflowing solid particles settle into this very large water impoundment, the major part of the sediment input downstream Genova Lake is actually provided by the Arve River, a left bank torrential tributary flowing from the Mont Blanc mountainous range (Fig. 6 right).

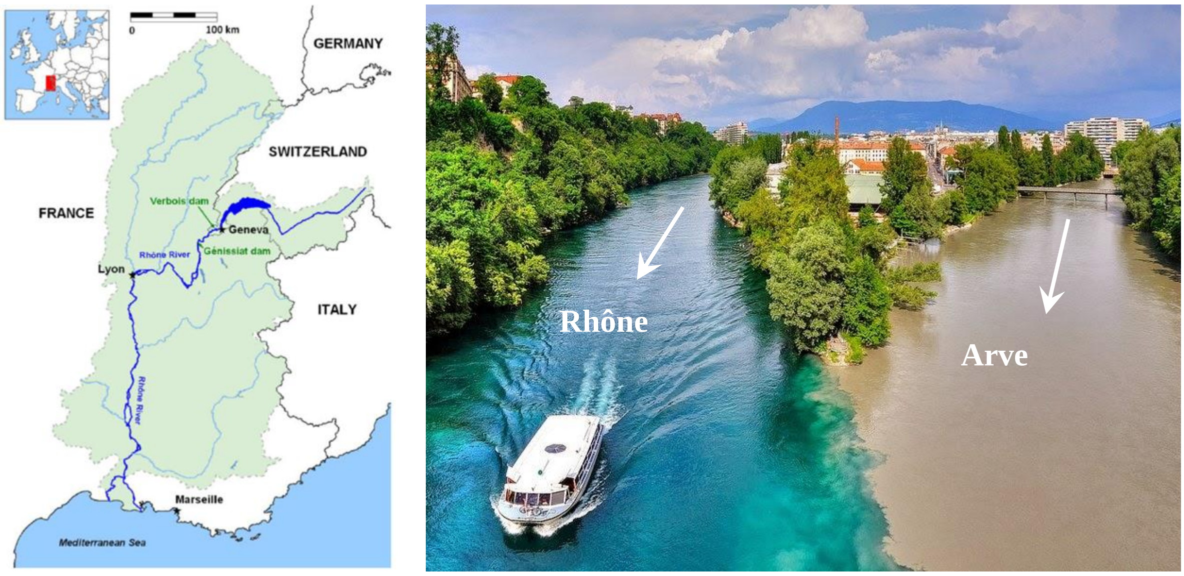

Fig. 6. Rhône River Basin (left) and confluence between Rhône and Arve rivers (right). Source of picture: feel-planet.com.

2.2 Principle of eco-friendly flushing performed downstream Génissiat dam

A significant amount of the Arve River sediments (Fig. 6 right) is regularly trapped upstream of the Verbois and Chancy-Pougny dams which are located in Switzerland and operated by Swiss operators. Due to a significant bed aggradation at Verbois reservoir, extra-flooding hazards are likely to be induced for the riverine people of Geneva city. As a result, Swiss operators have been used to organize regular flushing operations usually every 3 years until 2012. During the Swiss reservoirs emptying required by those operations, uncontrolled releases of fine suspended sediments reaching up to 40 g/l caused huge damages to the aquatic ecosystems (e.g. high fish mortality) and led to adverse impacts on river-related developments.

On the French side of the Rhône River basin, Compagnie Nationale du Rhône (CNR) has been granted the Rhône River concession since 1933 to build and operate a cascade of 19 hydropower developments from the Swiss border to the Mediterranean Sea (installed capacity over 3000 MW). The 65 meter head Génissiat dam is the largest and the furthest upstream development operated by CNR. During the flushing operations organized at the request of Swiss operators, CNR has to deal with all river-connected issues including mainly the preservation of (1) natural sections of the Rhône River recently restored by CNR for environmental purposes, (2) water intakes for nuclear plant as well as for well-fields dedicated to drinking water and (3) reservoirs managed by CNR likely to be exposed to siltation. So as to maintain acceptable conditions for the river eco-system and the riparian interests located further downstream, solid fluxes released from Swiss dams during flushing are significantly regulated by CNR into the Génissiat reservoir. As a reminder, the average solid concentration released downstream Génissiat dam throughout the 10 days of operation has not to exceed 5 g/l according to French regulations. It has also to remain below 10 and 15 g/l in average for continuous periods of 6 hours and 30 minutes running, respectively (Fig. 7).

To perform such kind of eco-friendly flushing operation [6], the water level of Génissiat reservoir is slowly lowered at given and precise elevations so as to remobilize carefully the sediments previously deposited and ensure the routing (or sluicing) of inflowing sediments released from Swiss dams (Fig. 7). As the Génissiat dam is equipped with 3 gates located a 3 different vertical positions, a suitable solid concentration is obtained further downstream by an appropriate gate opening and by mixing the sediment laden flows released by each hydraulic facility thanks to a real time monitoring. The flow being characterized by a vertical gradient of concentration for suspended sediments, the low level outlet discharges highly concentrated water, the intermediate level outlet releases less concentrated flows and the high level outlet passes even more clear water (Fig. 8). In downstream CNR run-of-river developments, the sediments fluxes routing is ensured by increasing the flow velocity thanks to a lowering of the water level at dams. As a result of those supporting operations, the Génissiat reservoir as well as the lower CNR developments in a lesser extent have experienced a steady sedimentation that could impair their sustainability in the long run despite operation rules defined to mitigate as much as possible such processes. Moreover, environmental hazards possibly induced by this kind of operation could engage CNR responsibility through prosecution procedures.

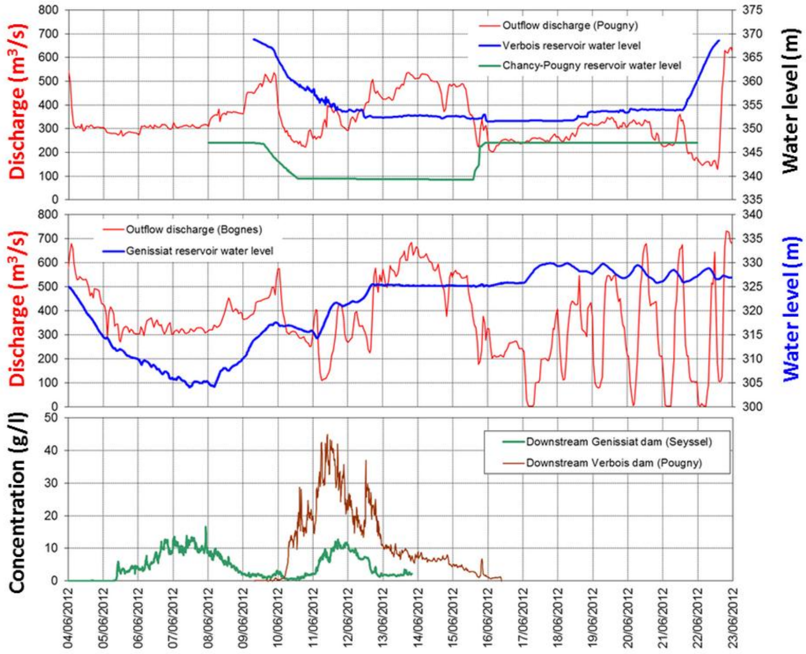

Fig. 7. Typical session corresponding to eco-friendly flushing performed downstream Génissiat dam for regulating sediments released from upper reservoirs (Verbois and Chancy-Pougny).

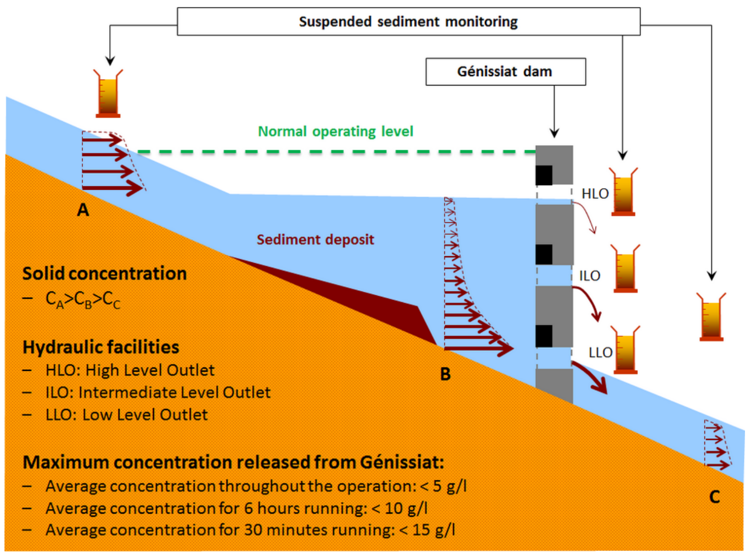

Fig. 8. Principle of suspended sediment regulation and dilution performed at Génissiat dam.

Following 2012 operation, discussions have been launched in 2013-2014 between the dam operators and the regulation authorities of both countries in order to account for all issues at stake from an equal and consistent manner on each side of the border [7] [8]. Those discussions have led finally to the definition of a transboundary integrated management scheme for sediment fluxes. Recommendations have been formulated after evaluating and comparing the impact of numerous options. This benchmarking approach has taken into account the following concerns: environmental impact compared to current management scheme, direct costs for operators, repercussions on social, ecological and industrial issues and technical feasibility. Following a broad consultation, the main conclusions are for both French and Swiss operators to favour 3 options combining (1) sediment routing (or sluicing) during flood conditions, (2) eco-friendly flushing with a 3 year frequency on the whole Upper Rhône River and (3) dredging. This mixed management scheme appears indeed to be the less impacting regarding all issues at stake. Sound surveys based on comprehensive field monitoring and hydraulic modelling have been conducted by dam operators and research institutes to better understand the sediment dynamics, confirm the feasibility of such approach and optimize the operational pattern of reservoirs [9] [10] [11]. In particular, a 1D numerical model including a specific module for the Genissiat dam gates located at various depths has been developed and validated [12]. Such a model can be used to simulate and test new strategies of eco-friendly flushing. The 3 new options previously mentioned have already started to be implemented and will be fully deployed for the next eco-friendly flushing operation planned in May 2016.

2.3 Water and sediment flows management through CNR run-of-river developments

All other CNR hydropower developments operated downstream Génissiat dam correspond to low head run-of-river schemes, i.e. between 6.7 and 22.5 meter high head. Those developments are typically composed of a barrage which is built across the mainstream of the river (Fig. 9). This barrage diverts the major part of the water flow through a headrace canal down to the power plant. For maintaining suitable conditions for the aquatic life, an ecological discharge is released in the natural course of the river through one of the barrage outlets. Another major point of such run-of-river concept is that the storage capacity of the reservoir is negligible compared to river flow volumes, especially during flood conditions. Neither inter-annual nor seasonal regulation is thus possible, such as water outflow is always equal to water inflow.

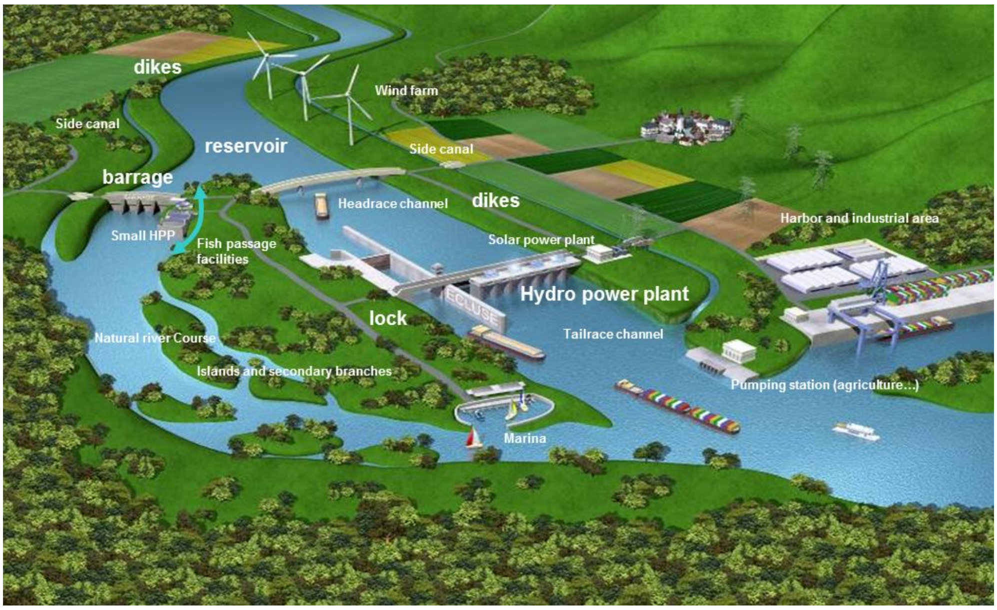

Fig. 9. Typical run-of-river scheme operated by CNR on the Rhône River.

For normal operating conditions, the reservoir water level upstream of each dam is very close to the horizontal. During high flows and flood conditions, the spillway gates are progressively opened so as to decrease the water level upstream of the dam, increase the waterline slope in the reservoir and avoid as a result extra-flooding hazards for riverine people. Thanks to those operations rules, natural-like flow conditions are gradually recovered in the whole reservoir. The routing (or sluicing) of inflowing sediments throughout the reservoir is thus facilitated and previously deposited particles are more easily remobilized. The passage of sediments through dams operated by CNR is moreover eased because (1) the crest of the spillway weir is practically at the same elevation as the river bottom before the dam construction and (2) the heights of spillway gate and dam are in general very similar (Fig. 10). Those gates are ranging between 7 and 14 meter high on CNR developments, but recent South-East Asia projects demonstrate that gates up to 25 meter high can be installed on dams.

Thanks to such dam design and reservoir operation pattern, the possible impacts on sediment fluxes are globally minimized. Locally, some sediment deposits may however occur, especially in sections where the flow velocity is very low, such as navigation lock garages, harbours, and tributary channels in confluences areas with the Rhône River. Considering for instance a given development, the volume of deposits corresponds on average to 3% of the suspended sediment fluxes flowing through the river channel. Those evolutions are highlighted thanks to a steady monitoring of the river and hydraulic structures conducted with a fleet of hydrographic boats. This work is done at the minimum every 5 years or after each significant flood (i.e. above a discharge of 5 to 10 year return period).

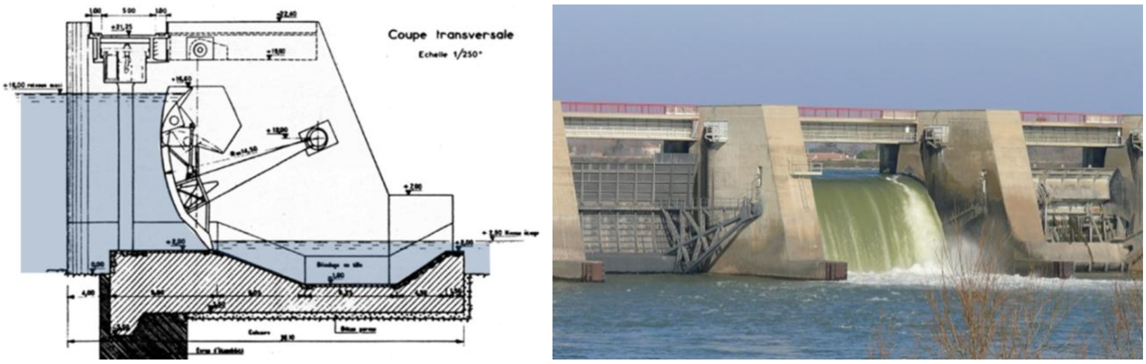

Fig. 10. Spillway layout (left) and downstream view (right) of Vallabrègues barrage on the Rhône River, France.

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 frame of a management plan established under the supervision of the French administration. This plan is generally updated every 10 years. Ecological restoration works carried out by CNR on secondary arms and alluvial margins represent also a significant part of the dredging works performed. In addition, it has to be noted that for a few decades, sediment deposits have not been definitely extracted from the river channel anymore, but have been put into suspension or artificially removed further downstream in order to minimize the potential disruption of sediment continuity down to the Rhône River Delta. As a reminder, 75% of deposits are composed of silt and sand while the remaining 25% correspond to gravel.

3. Recommendations and guidance for project design and management

An essential output from the case studies presented previously is that outlets controlling the release of water and sediment from a dam should be positioned, sized and operated so as to enable recovering natural-like flow conditions in the major parts of the reservoir. To satisfy such conditions, low level outlets should be located as low as possible, sized as large as possible and incorporated in sufficient number in the dam design (Fig. 11 left). The best scheme is the one minimizing the head loss for the widest range of discharges, i.e. case C in Fig. 11 left. For maximizing sediment sluicing (or routing) through the reservoir, free flow state conditions have to be progressively recovered as soon as hydrological conditions lead to significant sediment laden flows (Fig. 11 right). In many large tropical rivers, such situations correspond at minimum to high flows and as a result to quite frequent discharge values (i.e. 100 to 150 days per year). In a context of smaller catchments and more temperate environment, sediment transportation is generally more occasional as erosion processes occur mainly during significant flood events.

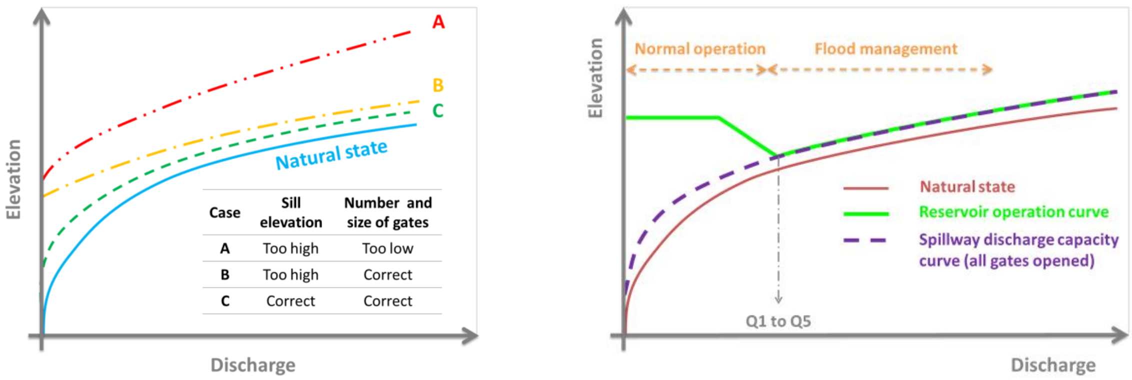

Fig. 11. Comparison between natural rating curve of a river with discharge capacity curves corresponding to different gate arrangements at a proposed dam site (left) and example of spillway capacity and reservoir operating curves allowing successful sediment sluicing as soon as hydrological conditions lead to significant sediment laden flows (right).

Lowering as much as possible the spillway elevation for recovering natural-like flow conditions in a reservoir during flood situations presents a twofold advantage (Fig. 12). First, it prevents the deposition of inflowing sediment fluxes and ensure a transfer of particles through reservoir and dam. Second, it permits a more efficient remobilization of sediments previously deposited in the reservoir, particularly in the case of flushing operations. In Fig. 12, a higher remobilization of previously deposited sediments is indeed obtained in the lower reservoir compared to the upper reservoir. The lower elevation of the outlet sill in the case of the lower reservoir allows free flow conditions to be better recovered and avoid the permanent blockage of sediments just upstream of the dam.

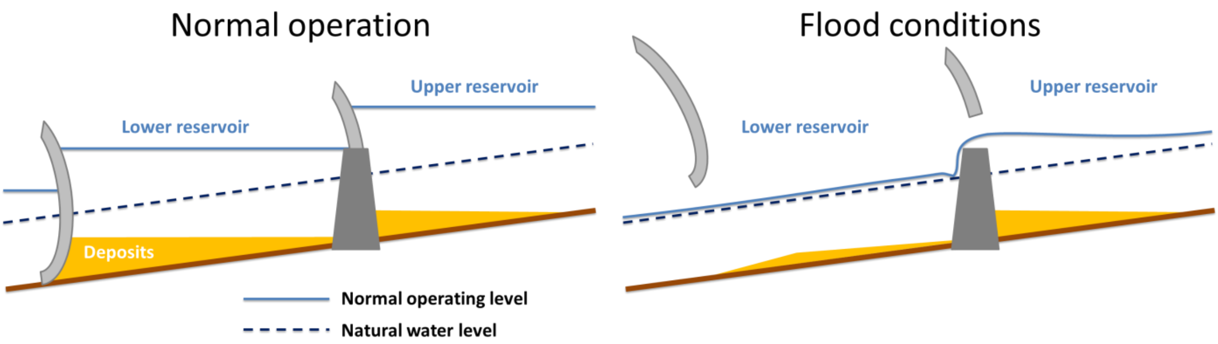

Fig. 12. Efficiency of reservoir deposits erosion during flood conditions depending on the low level outlet elevation.

In the case of run-of-river dams below 20 meter high, including gates as high as the barrage height will be often the best option regarding sediment issues. This limit is fully consistent with the technical solutions currently available worldwide. For higher dams, multiple-level intake structures should be systematically considered at design stage. As a preliminary approach, it is recommended that dams higher than 40 meters include outlets located at low, intermediate, and high levels, while for dams between 20 and 40 meter high, outlets could be positioned at low and high levels only. Even if each project is obviously unique, the examples presented in this paper as well as recent projects developed in south-east Asia prove that such recommendations can be successfully applied whatever the catchment size, river slope, sediment regime, reservoir volume or dam height.

Referring to the Génissiat dam example, it has been also demonstrated in this paper that such original arrangement provides another essential advantage. This concerns especially the case of reservoirs for which a panel of particles ranging from very fine to very coarse sediments is likely to experience settling processes due to high water depths and low flow velocities. Controlling the quantity and quality of sediment fractions released downstream of this kind of reservoirs, and especially the finest ones, is indeed essential to prevent adverse impacts on aquatic life and human activities connected to the river system. Such requirement is fully made possible thanks to a selective withdrawal of more or less turbid water flowing from intake structures located at different depths. The scheme (C) in Fig. 13 is the preferred one because it allows: (1) both bed-load and suspended solids to pass the dam when favourable flow conditions are recovered in the reservoir, and (2) to control the nature and concentration of solid flows released downstream of the reservoir. Dasidaira and Unazuki dams in the Kurobe River Basin (Japan), as well as Sanmenxia dam in the Yellow River Basin (China), correspond also to relevant references of high dams using bottom outlets for sediment flushing and sluicing [13] [14] [15].

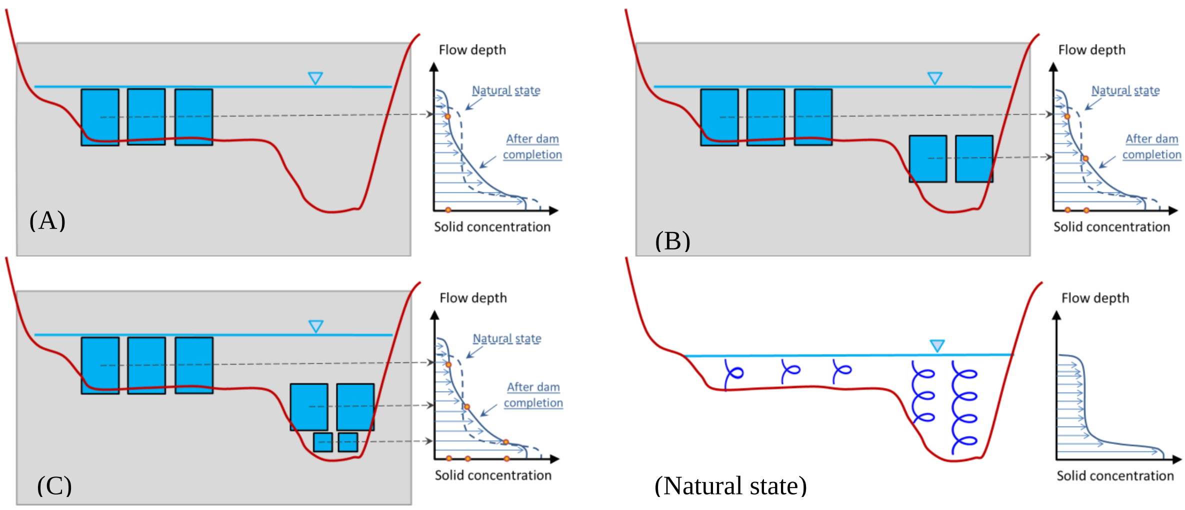

Fig. 13. Possibilities offered by different gate arrangements for obtaining a selective withdrawal of waters corresponding to different flow depths and solid concentrations.

Japanese examples provided in this paper, as well as Chinese experience existing in particular in the Yellow River Basin at Sanmenxia dam, show that project retrofitting after construction is at best very difficult and expensive, but could be even impossible at worst. As a result, the strategy consisting in building now and adapting later should be avoided as much as possible in every emerging dam projects. Collecting a comprehensive set of site specific data is on the contrary the best way for establishing a relevant baseline situation regarding sediment dynamics, as well as for managing properly sediment fluxes in hydropower projects design and operation [16]. In that sense, defining the relative importance of each transportation process (i.e. bed-load, graded suspension and uniform suspension) with appropriate methods is an essential prerequisite as each plays a specific role in river systems and as their susceptibility to being trapped by reservoirs is radically different. It has also to be kept in mind that sediment fluxes management through a reservoir should never rely on a unique solution. All suitable and cost effective options should be considered, combined and implemented for minimizing the impact of a project. Mutualizing the functions of a given facility, for instance by installing outlets dedicated to both flood passage and sediment routing, is also a relevant strategy that makes such option being more acceptable financially speaking. Bearing in mind that sediment sluicing allowed thanks to low level outlets could avoid costly dredging works into the reservoir and expensive mitigation measures further downstream is also a way of considering the implementation of such facility like a long run investment rather than an immediate cost.

Finally, for achieving an integrated, balanced and sustainable management of sediment fluxes through a cascade of reservoirs, the application of the following “5C” concept is suggested to regulation authorities, project developers and engineering designers dealing with hydropower cascade design and management:

1. Consultation with other public and private stakeholders for defining an integrated management scheme regarding sediment issues,
2. Continuity-friendly design of emerging projects (and possibly existing ones) regarding sediment transportation, and beyond fish migration, flood passage, navigation traffic…
3. Consistency of cascade design and reservoirs operating rules regarding previous issues,
4. Coordination between all operators,
5. Control of sediment fluxes, reservoir sedimentation and related impacts through field monitoring.

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