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River Morphology and Sediment Management Strategies for Sustainable Reservoir in Japan and European Alps

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Synopsis

Sustainability of Alpine reservoirs is severely threatened by sedimentation resulting from natural geomorphologic processes. Management of sedimentation in Alpine reservoirs cannot be apprehended by a standard generalized rule or procedure. The paper aims at identifying, measuring technique to assess the risk of reservoir siltation with and without countermeasures in Japanese and European Alps. Furthermore, analyzing how human interventions and climate changes may alter sediment fluxes, morphological patterns and in river basin system. Maintaining the “Healthy Life of the River Basin” is the ultimate goal of the paper by applies integrated sediment management, to realize the sustainable utilization of water resources and ecological environment protection, and achieve harmony between humans and nature. The results show that, the successful reservoir sediment management proceeds from a permanent change in river management. This may involve strategies to enhance water and sediment release by a combination of several countermeasures. In big Alpine reservoirs, turbidity currents are often the governing process in reservoir sedimentation by transporting fine materials in high concentrations.

Keywords: Alpine reservoirs, reservoir sedimentation, sediment management in reservoir, sediment control strategies, sustainable reservoir, dam impacts

1. Introduction

Sediment transport and deposition in alpine rivers is responsible for numerous problems related to reservoir sedimentation, river training and flood protections. Dams and their reservoirs are constructed and operated for multipurpose including power generation, flood protection, drinking water, agricultural water supply, recreation, fishing, and others. Until now the common engineering practice has been to design and operate reservoirs to fill with sediment. With such an approach, the consequences of sedimentation and project abandonment are left to be taken care of by future generations. For many dams this future has already arrived. Therefore we need to develop ingenious solutions for integrated sediment and water management; unless we will lose the struggle to enhance the available water resources and ecological environment.

Necessary elements of sediment management strategies for sustainable reservoirs are to collect enough data of deposited sediment for evaluation and select a suitable management technique for case by case. Furthermore, it is important to establish techniques for redeveloping existing dams, by construction of sediment bypass, and to develop environmental impact assessment approaches. These techniques minimize the minus impacts such as water quality change, and maximize the plus impacts such as the recovery of sediment routing.

Considering a sediment movement zone from alpine mountainous regions through coastal areas, a comprehensive approach has already been started in

Japan to recover a sound sediment circulation in the sediment transport system. Reservoir sedimentation management is placed as one of the top priorities; therefore, the meaning of reservoir sedimentation management should be widely shown.

Reservoir sedimentation problems are common in all countries, whether they are developed or developing countries. Therefore, it is necessary to exchange knowledge and collaboratively work for a solution with countries having the same problems. Schleiss et al., (2008) presented the reasons, problems of reservoir sedimentation, and possible measures against sedimentation. Putting its experience to use, Japan intends to make great international contributions to the promotion of reservoir sedimentation management in the field of technological development in future.

1.1 Alpine region conditions

Alpine environment are characterized by high energy potential and characteristic landform elements, high elevations, steep slopes, rocks, and availability of snow and ice (Barsch and Caine, 1984). In respect of sediment transport processes the specific hydrologic, geomorphologic, and climatic conditions of alpine regions are regarded as the major driving forces.

Japan has geologically young mountains, steep and short rivers with flashy flow regimes, and densely populated floodplains (Oguchi et al., 2001). Generally, the Pacific side of Japan has heavy rain in June and July (rainy season) and between August and October (Typhoons) (Matsumoto, 1993). The combination of steep catchments and heavy storms results in widespread hill slope failures and landslides and extensive flood discharges (Oguchi, 1996). On the other hand, from a topographical point of view, many rivers in Japan are very steep which run down over a short distance from mountains of 2,000 to 3,000 meters above sea level to lowland areas (Fig.1). This figure illustrates the relative steepness of Japanese rivers. Although the Shinano River (Fig.1) is the longest river in Japan, its gradient is still greater than most of the rivers in other countries. The annual average precipitation is approximately 1,700 mm, and, sometimes, intensive rainfall such as 100 mm in an hour or 200 to 500 mm in a day can be recorded. These topographical, geological and hydrological conditions have great impacts on sediment yield in river basins, and consequently reservoir sedimentation has been accelerated especially in Chubu and Hokuriku region which is located in the center of the main island.

For the European Alps the annual precipitation can reach values of more than 3.000 mm in high ranges while transpiration may drop to 100 mm over snow covered areas. Significantly higher values for precipitation of 6.000 mm per year or even more are reported from gauging stations from other parts of the world (Schaedler and Bigler, 1992). While the intensity of rain-/ snowfall together with the presence and condition of snowfields mainly affects the short-term run-off, seasonal changes of storage or release of water from snowfields affects the annual discharge.

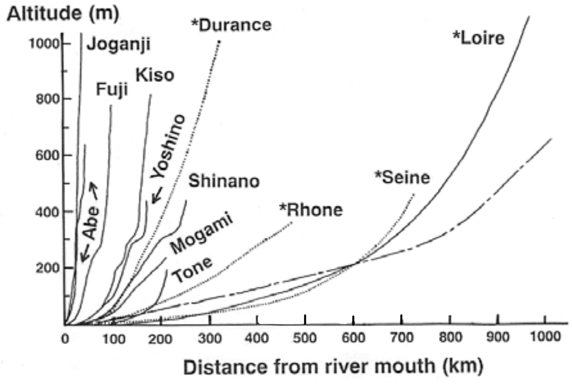

Fig. 1 Longitudinal profiles of Japanese and European rivers (Takahashi and Sakaguchi, 1976)

1.2 Dam impacts

Regardless of their purpose, all multipurpose dams trap sediment and inevitably lead to physical and ecological changes downstream of the reservoir site, as well as in the reservoir itself, and in some cases also upstream. Kondolf (1997) has described that, by changing flow regime and sediment load, dams can produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads. Downstream impacts develop through discontinuity in downstream gradients, e.g., sediment supply, water quality, temperature, flow and sediment regimes. Sediment deficit is not only an environmental issue but also a socio-economic problem, for instance due to loss of reservoir capacity (e.g., Fan and Springer, 1993; Morris and Fan, 1998). In addition, dams alter the downstream flow regime of rivers (Williams and Wolman, 1984), which controls many physical and ecological aspects of river form and processes, including sediment transport and nutrient exchange (Poff et al., 1997).

Morphological effects on the river channel (e.g., Kondolf and Matthews, 1993; Kantoush et al., 2010) that includes riverbed incision, riverbank instability, upstream erosion in tributaries, groundwater over drafting, damage to bridges, embankments and levees (e.g., Kondolf, 1997; Batalla, 2003), and changes in channel width. Hydrological effects caused by dams include changes in flood frequency and magnitude, reduction in overall flows, changes in seasonal flows, and altered timing of releases.

2. Sediment rates

Today's worldwide annual mean loss of storage capacity due to sedimentation is already higher than the increase of the capacity by construction of new reservoirs (Boillat et al., 2003). Thus, sustainable use of the reservoirs is not guaranteed on the long term. The time evolution over the last century of the water storage capacity and volume losses due to reservoir sedimentation in Japan, Switzerland and France are presented in Fig.2. To maintain the existing dams and their facilities over the long term becomes an essential policy issue.

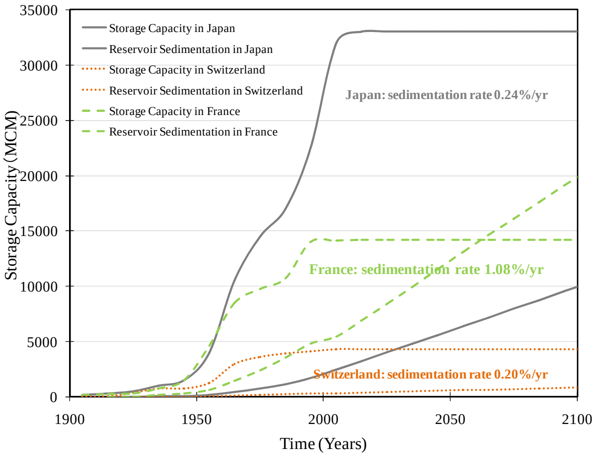

Fig. 2 Development and estimated evolution of installed water storage capacity and volumes lost due to reservoir sedimentation in Japanese and European countries.

Because of the following reasons: sedimentation is proceeding more than expected in many dams; the share of the dams having a design life of more than 50 years, such as multi-purpose dams where maintaining storage capacity is absolutely necessary, will rapidly increase in the future; and due to social changes in environment-conscious trend and an era of low-growth economy. Figure 2 shows the relationship between the changes in the reservoir storage capacity and the storage capacity loss due to sedimentation in Japan. While the storage capacity is being increased by the construction of new dams, it is being lost by an average rate of 0.24 %/year. The figure shows that the average in Switzerland about 0.2% of the storage capacity and in France is 1.08%. The evolution in Switzerland of the water-storage volumes lost due to reservoir sedimentation, and that of the installed water-storage capacity over the last century with the estimated future development are also presented in the same Fig.2. The lower sedimentation rate in Switzerland is due to the geologic characteristics, mainly rocky mountains, of the catchment areas at high altitudes.

There are no accurate data on the rates of reservoir sedimentation worldwide, but it is commonly accepted that about 1–2% of the worldwide storage capacity is lost annually (Jacobsen, 1999). A detailed collection of sedimentation rates in regions all over the world can be found in Fig.3. The volumes of water-storage capacity lost due to reservoir sedimentation and the volumes of installed water-storage capacity in the world are presented in Fig.3. The graph shows the evolution over the last century, and the predicted future development.

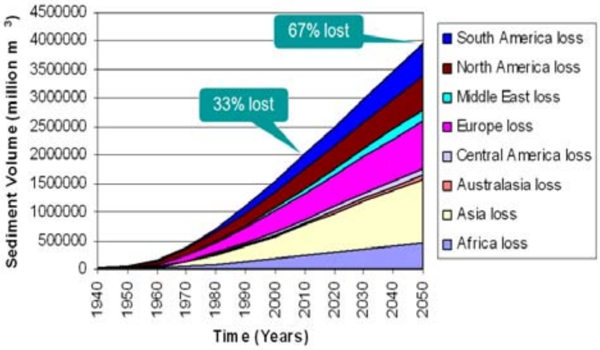

Fig. 3 Global reservoir sedimentation rates (Basson, G. 2009).

3. Sustainability of reservoirs

The concept of sustainability applied to agriculture developed, ground water development, and road engineering. The optimization of sediment removal methods as a dam group is inexpensive if a dam group was linked with each other for sediment management. The essential concept of sustainable development is that the welfare of future generation should logically figure into the project decision-making (Morris et al., 2008). Reservoirs arguably represent today's class of non-sustainable infrastructure. The objective of management is to minimize the adverse effect that deposition in a reservoir has on its operations. The sustainability of reservoir should seek to balance sediment inflow and outflow across the reservoir while maximize the long-term benefits, the concept of sustainability is shown in Fig.4.

This may involve strategies to minimize sediment inflow, enhance sediment release, or combination of several countermeasures for coarse and fine sediments. Examples of each facilities and proper maintenance sustainable reservoir management under the limited budget are presented. Technically, efficient economically and environmentally countermeasures, the coordinating sediment management of multiple reservoirs in a river basin, are discussed. The main development patterns for reservoirs and sustainable development are summarized in Fig.4. Several methods for sediment management are available and have been implemented in practice.

Fig. 4 Concept of a sustainable alpine reservoir.

The latter essentially implies that the current generation uses resources in a consumptive manner, leaving the problems of dealing with its remains to future generations without providing resources to do so. The ultimate objective is to achieve a master plan for sustainable countermeasures for sedimentation in reservoir, integrated strategy for management assessment, and stochastic sediment inflow, which includes variable levels of social, environmental and climatic impacts on river basin system management. Integrated models of sediment flow and morphological dynamics in both regulated and free flowing rivers are necessary. Integration of different skills and approaches through provision of effective reservoir sediment management system to prolong the reservoir lifetime as illustrated in Fig.5, should allow the research to obtain some significant advances in the understanding of dam impacts.

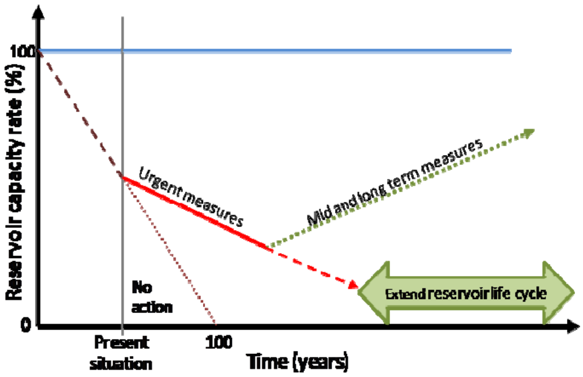

Fig. 5 Illustration of prolongation of the reservoir lifetime.

Definitions of sustainable development have proliferated, but the following basic concepts are most relevant from the standpoint of water resources infrastructure:

[1] Guaranty security and acceptable functioning of the infrastructure for its purposes (drinking water, irrigation, energy production, etc);

[2] Today's patterns of infrastructure development should preserve the capacity of the reservoir and maximum possible time of functioning. Not compromise the ability of future generations to access these same resources;

[3] Produce minimum impact to the environment and maintain biological diversity;

[4] Minimize the potential for catastrophic disasters resulting from infrastructure failure;

[5] Avoid activities that create a legacy of

environmental restoration or infrastructure rehabilitation obligations that disproportional on future generation;

[6] Take into account all processes: hydrological regime (floods and drags), soil erosion, climate change, environment and associated ecosystems, water & sediment continuity.

Requiring a reservoir life measured in terms of thousands years instead of decades will demand new methods of analyzing costs and benefits. For all these reasons, developing new techniques to evacuate the fine and coarse sediment to maintain the functionality, and at the same time ecologically rehabilitating the involved landscape would be economically and environmentally beneficial for all types of reservoirs.

4. Sediment management of alpine reservoirs

According to the time scale of sediment management, we can distinguish three phases: (1) short term phase requiring immediate corrective actions to improve conditions that are getting worse (Corrective management), (2) medium term phase with management direct at prevention of creation of problems (Preventive management), (re-suspend the sediment and optimal reservoir geometry), and (3) long-term phase that include accountability for future generations sustainable management.

Among the several methods hypothesized for maintaining water reservoir volumes and for keeping satisfactory levels of functionality, the periodical removal of sediments is one of the most common engineering techniques.

4.1 Why sediment management is needed?

The need for the reservoir sediment management in Japan can be summarized into the following three points:

[1] To prevent the siltation of intake facilities and aggradations of upstream river bed, accompanied by the sedimentation process in reservoirs, in order to secure the safety of dam and river channel;

[2] To maintain storage function of reservoirs, and realize sustainable water resources management for the next generation;

[3] From a perspective on comprehensive sediment management in a sediment transport system, to release sediment from dams.

The point in [1], as stated above, became major concerns in the middle-scale hydroelectric dams constructed in early years and the following measures were then taken: to install sediment scouring gates and locally discharge sediment accumulated in front of the intake facilities, or to use spillway to accelerate traction and discharge of sediment deposited at the end of reservoir.

The point in [2] is an important issue in the future. As shown in Figs.2 and 3, the reservoirs in Japan are now facing a critical question of sedimentation. The point in [3] represents a new policy in Japan. The amount of sediment supplied from rivers to coasts was radically reduced with construction of erosion control dams or storage dams in mountain areas and acceleration of the aggregate excavation from riverbed after World War II.

As a result, various problems rose up including riverbed degradation at downstream, oversimplification of river channel, and retreat of shoreline due to the decrease in sediment supply to the coast. The sediment budget throughout Japan is outlined in Fig.6. Sediment of approximately 200 million m^3 (MCM) is produced from mountain areas every year. A volume of 100 MCM is deposited in reservoir or others, and the remaining 100 million m^3 is discharged into downstream rivers. In the latter, 4 MCM is allocated for gravel excavation.

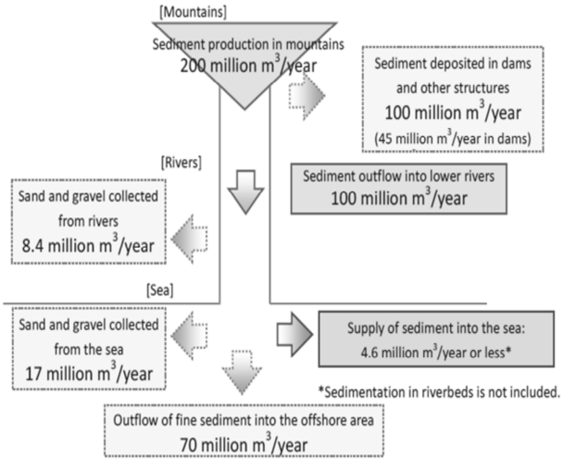

Fig. 6 Sediment budget in Japan (Sumi 2003).

In the years from 1950 to 1960, however, a considerable amount of aggregate was taken, so that the amount of sediment supplied to coasts through estuaries was remarkably reduced. Regarding the sediment budget for the sand fraction which constitutes coasts, erosion (350 thousand m^3) surpasses deposition (250 thousand m^3) and therefore coastal erosion is still proceeding. At present, it is said that eroded coasts account for approximately 60 % of the Japanese shoreline of about 34 thousand km.

Furthermore, approximately 40 % of that erosion is involved in the decrease in the amount of sediment supplied from rivers, including reservoir sedimentation. A sediment transport system represents a target region for management, in which attention is focused on the movement of sediment in the range form mountainous region to coastal region, compared to a water system representing the conventional movement of water. The need for management of sediment, which covers from the sediment supply mountain through the downstream river and coastal region, has been growing.

4.2 Strategies of sediment control

Controlling reservoir sedimentations means in fact the control of sediment deposition in reservoir. It consists of three basic strategies:

[1] *Sediment yield reduction*: to reduce sediment inflow to reservoirs. Apply erosion control techniques to reduce sediment yield from tributary catchments. These techniques will typically focus primarily on soil stabilization, and revegetation.

[2] *Sediment routing*: to pass sediment inflow around or through the reservoir so as not to accumulate in reservoirs, by employing techniques such as drawdown flushing and turbidity release.

[3] *Sediment removal*: to remove sediment accumulated in reservoirs by dredging or excavation or hydraulically.

Fig.7 shows how sediment management is undertaken and classified. And some representative dams and examples from Europe and Japan, which exercise sediment management, are listed. Further studies needed for the improvement of reservoir sediment management (De Cesare & Lafitte, 2007).

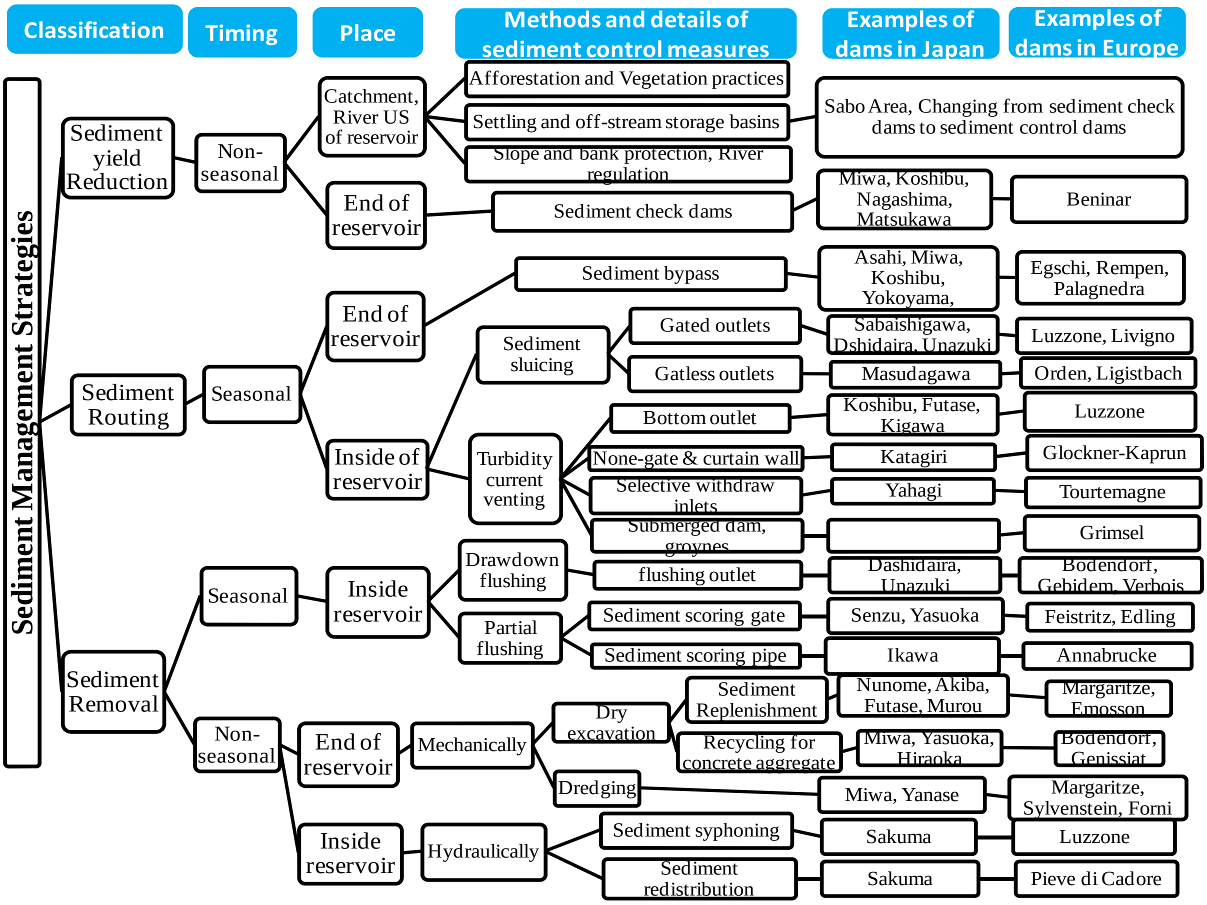

Fig. 7 Classification of strategies of sediment control in Japanese and European reservoirs.

(1) Sediment yield reduction into reservoirs

A reduction of sediment yield by soil stabilization in the catchment area can be very effective, and can solve the reservoir sedimentation problem in a sustainable way. Where the climatic conditions allow vegetation practices, the soil can be protected from erosion by afforestation or vegetation screens. In catchment areas without vegetation, as for example the high Alpine catchment areas, erosion protection can only be achieved with engineering measures such as gully control, as well as slope and bank protection works on rivers. If the reservoir is supplied by water diverted from neighboring catchments, careful attention will be needed to trap the sediment from the intake. This will include settling of coarse grain sizes in the impoundment by a diversion dam or weir and providing settling basins to remove suspended sediment (Boillat et al., 2003). One example of settling basins from Switzerland is shown in Fig.8.

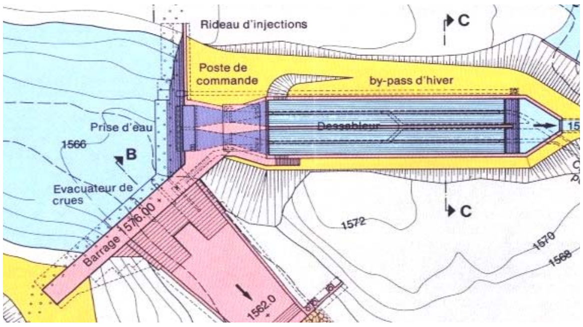

Fig. 8 Plan view of the water intake of La fouly, part of the hydroelectric scheme of Emosson (Switzerland) (Boillat et al. 2003)

There are two techniques to reduce the amount of transported sediment: 1) countermeasure to control sediment discharge which covers entire basin including the construction of erosion control dams; and 2) countermeasure to forcibly trap sediment by constructing check dams at the end of reservoirs. Although the catchment areas of dams have high forest cover rates, a remarkable amount of sediment is produced in the watershed where landslides frequently occur due to the topographical and geological conditions. When sediment yield is also expected from side slopes surrounding dam reservoirs, a project to buy and preserve a certain plot of forest as a greenbelt has been implemented by dam administrator itself. On the other hand, check dam is effective to stop sediment and prevent from sediment disasters downstream. Open check dams can be divided into two categories, beam dam and slit dams characterized by a different management of sediment transport: beam dams are characterized by wide openings.

To be more precise, the erosion control dams in the upstream region are planned to be converted to slit dams with notches, which are so designed as to pass, not to trap, as much fine sediment carrying less risk of sediment disaster as possible. Photo 1 shows the upstream check dam of Koshibu reservoir, which was constructed in 1978. The sediment deposited at check dams should be excavated and disposed regularly (Sumi 2000). Open check dams assembled from steel pipes (Photo 2) or concrete dams having slit are built to stop sediment only at times when sediment outflow is great and to let sediment rundown into lower basins when water and sediment outflow is small. The accumulated sediment can be excavated on land except for flood time, and the removed sediment is utilized effectively as concrete aggregate.

Photo 1 Upstream check dam of Koshibu dam Japan (Sumi et al., 2006)

Photo 2 Slit check dam from steel pipes
http://www.dpri.kyoto-u.ac.jp/rcfcd/sabo/index.htm

A private plant for taking aggregate is shown in Photo 2. Securing of both a financial source and a disposal method becomes absolutely necessary in order for check dams to fulfill their primary function in a sustainable way.

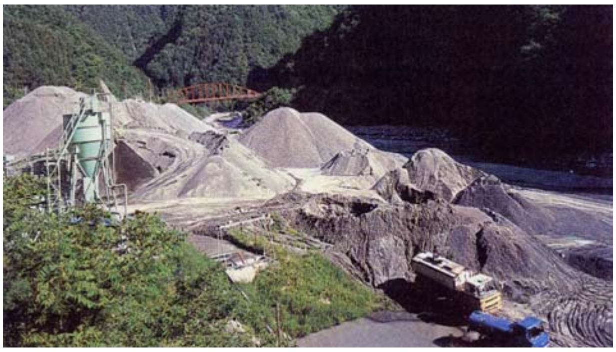

Photo 3 Private plant for taking aggregate (Japan)

(2) Sediment routing in reservoirs

Another possible approach to sediment management, next to the reduction of sediment inflow itself, is to route sediment inflow so as not to allow it to accumulate in reservoirs. In Japan and Europe the following techniques are adopted: 1) sediment bypass by directly diverting sediment transport flow, and 2) turbidity current venting by using a nature of high-concentration sediment transport flow.

In Japan, it is sediment bypass tunnels that have been studied most exhaustively. Although this technique involves high cost caused by tunnel construction, it is also applicable to existing dams; it does not involve drawdown of reservoir level and therefore no storage capacity loss; and it has relatively small impact on environment because sediment is discharged not so rapidly as sediment flushing, which is described later. The subjects of designing sediment bypass tunnels are to secure the safety of sediment transport flow inside tunnels and to take countermeasures for abrasion damages on the channel bed surface. Among factors that significantly relate to these problems are grain size, tunnel’s cross-sectional area, channel slope, and design velocity.

Table 1 shows some examples of existing sediment bypass tunnels and the ones under construction and study. It should be understood that design condition becomes increasingly hard if higher velocity and larger grain size will be expected. Density current venting, on the other hand, is a technique to use a nature of high-concentration sediment transport flow, which runs through relatively deep reservoir with original channel bed of steep slope as a density current with less diffusion, and to discharge it effectively through outlets in timing of reaching dam. In both techniques, the main target is fine-grained sediment such as suspended sediment and wash load. In the multiple-purpose dams in Japan that usually have high-pressure bottom outlets for flood control; the effective operation of these facilities during flood season can increase a chance to actively discharge fine-grained sediment.

Table 1 Comparison of sediment bypass tunnels in the Japan and Europe

Name of Dam	Country	Tunnel Completion	Tunnel Shape	Tunnel Cross Section (B×H(m)）	Tunnel Length (m)	General Slope（%）	Design Discharge (m^3/s）	Design Velocity (m/s)	Operation Frequency
Asahi	Japan	1998	Hood	3.8×3.8	2,350	2.9	140	11.4	13 times/yr
Miwa	Japan	Under construction	Horseshoe	2r = 7.8	4,300	1	300	10.8	-
Matsukawa	Japan	Planning	Hood	5.2×5.2	1,417	4	200	15	-
Egshi	Switzerland	1976	Circular	r = 2.8	360	2.6	74	9	10days/yr
Palagnedra	Switzerland	1974	Horseshoe	2r = 6.2	1,800	2	110	9	2～5days/yr
Pfaffensprung	Switzerland	1922	Horseshoe	A = 21.0m^2	280	3	220	10～15	～200days/yr
Rempen	Switzerland	1983	Horseshoe	3.5×3.3	450	4	80	～14	1～5days/yr
Runcahez	Switzerland	1961	Horseshoe	3.8×4.5	572	1.4	110	9	4days/yr

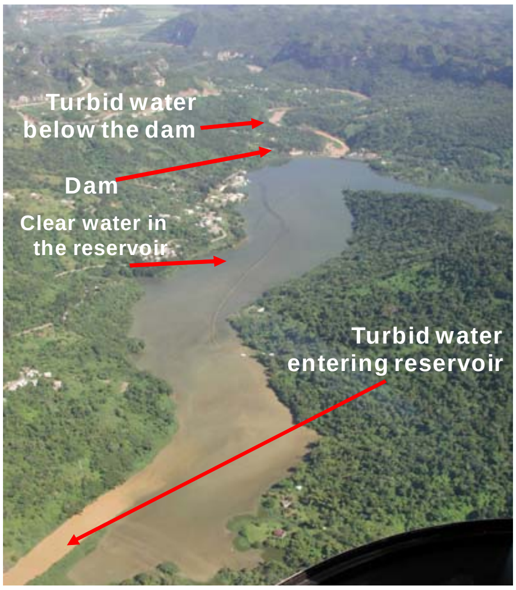

Photo 4 Turbidity current passing through (Morris and Fan, 1998)

In Grimsel reservoir (Photo 5), in Switzerland, an ongoing design project consists of heightening the two existing dams by 23 m (Spitallamm Arch Dam 114 m; Seeuferegg Gravity Dam 42 m). The excavation and demolition works necessary for the planned heightening generate approximately 150'000 m^3 of rock material. This large amount of materials has to be stored somewhere near the construction site. This led to the idea of building some kind of obstacle in the form of a submerged embankment dam to prevent sediment deposition due to the turbidity currents in the area near the intake structures. A case study is presented to investigate the occurrence and impact of turbidity currents on the reservoir sedimentation and to check the efficiency of such submerged obstacles to retain the sediments (Oehy 2003).

Photo 5 Grimsel reservoir (1909 m.a.s.l., 108 m^3) (Bühler, J., 2009)

The release of sediment laden water through power intakes and turbines is a promising possibility to manage the long term problem of the sedimentation process in reservoirs. In order to get the suspended sediments entrained into the power intake, they need to be in suspension right in front of the water intake. At Laboratory of Hydraulic Construction (LCH), Swiss Federal Institute of Technology (EPFL), Jenzer (2009), experimentally investigates an innovative technique to keep the turbid water in suspension (Fig.9). Therefore an upward flow to lift the sediments and to maintain them in suspension is required. Jenzer (2009) tested several series to provide attractive methods which allow these processes using a minimum of external energy by making use of the affluxes of water transfer tunnels feeding the reservoir. The water of the transfer tunnels is caught and introduced into jet nozzles fixed at a definite position in the reservoir close to the power intake.

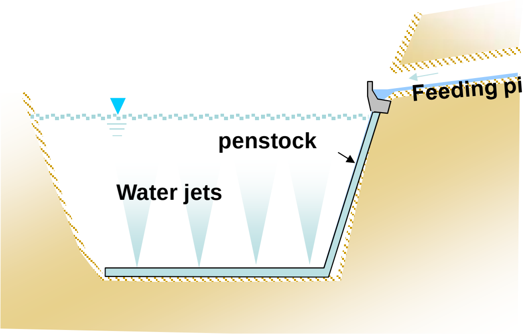

Fig. 9 Schematic view of the water jets supplied by the feeding pipe coming from water transfer tunnels (LCH, EPFL, Switzerland, Jenzer, 2009)

In addition, as countermeasures for long-term turbid water discharge problem, selective withdrawal works are installed at many dams. And, in Katagiri dam at Tenryu River, curtain wall is installed in front of a non-gate outlet conduit to discharge water from the bottom layer of reservoir. Discharge of fine-grained sediment using these facilities can also be classified in density current venting. Furthermore, Flood mitigation dam (FMD) is a gateless outlet dam designed only for the purpose of flood control which provides long-term and efficient protection against floods. Its bottom outlets are installed at the original river bed to facilitate the sediment transport during flood and flush out the deposited sediment at the end of flood.

In USA flood mitigation dams are called “Dry dam”, in Europe “flood retention basins”, (“Hochwasserrückhaltebecken” in German), in Japan “in stream flood control dam” (Ryusuigata dam, Japanese), others “flood mitigation dam”. Therefore, FMD have less influence on reservoir sedimentation than a storage dam. FMD is one of good solutions in dam engineering for sustainable management of reservoirs, downstream river environment, and sediment transport. FMD is expected as environmentally friendly, since almost all incoming sediment during flood periods can pass through dam bottom outlets that designed at the original river bed level and there will be fewer impacts to downstream river environment.

Kantoush and Sumi (2010) have classified FMD based on outlet arrangement: 1) installing regulating gates in bottom outlets or not and 2) securing continuity of the river through these outlets or not. Photos 6 and 7 present two examples of FMD from Europe, Ligistbach dam in Austria and Orden dam in Switzerland, respectively. Because of geographical conditions, there is large difference between both dams.

Photo 6 Flood mitigation dam of Ligistbach, Styria, Austria

Photo 7 Flood retention basin of Orden dam, Switzerland

Another example of from Japan is Masudagawa dam, is shown in Photo 8. Silts are installed for flushing sediment from the stilling basin and achieve fish passage functions. The stilling basin of Masudagawa dam dissipates the energy by hydraulic jump type equipped with an endsill to obtain appropriate tailwater depth. This type of energy dissipater is the most widely used in Japan where downstream water depth is usually small. The width of the stilling basin was designed according to the width of the downstream river.

Photo 8 Masudagawa flood mitigation dam, Shimane Prefecture, Japan

In response, a future research project is established to study updated planning, designing and operating of flood retention dams. In the frame work of a research project, the FMD individualized and characterized for three parts, inlet upstream of the dam, outlets, and stilling basin with downstream reach of the dam. The approach appeared efficient to help flow and sediment practitioners, and ecologists work together, and find technical solutions complying with both flood mitigation and biodiversity preservation requirements. The effects of the geometry will be investigated with systematic physical experiments, numerical simulation, and field data. This will allow identifying the optimal stilling basin shape of the flood mitigation dam that dissipate more energy, minimizes the deposition and reduces the number of horizontal recirculation cells. The results will help to understand the influence of geometry on the flow stability, sediment deposition and flushing process in order to design the stilling basin geometry. The prediction of sediment profile lies in the prediction of flow pattern and, in turn, sediment deposits were able to change the flow structure.

(3) Sediment removal accumulated in reservoirs

Basically, there are two types of systems for accumulated sediment removal from reservoirs:

[1] *Hydraulically*: This comprises sediment flushing, siphoning (HSRS) and redistribution of the sediment inside the reservoir. Hydraulic flushing involves the opening of bottom outlet to completely empty the reservoir and allow stream flow to scour a flushing channel. Basically, there are two types of flushing operations with, and without drawdown, and optional techniques can be used with the complete drawn flushing as shown in Fig.10 (Kantoush et al., 2010).

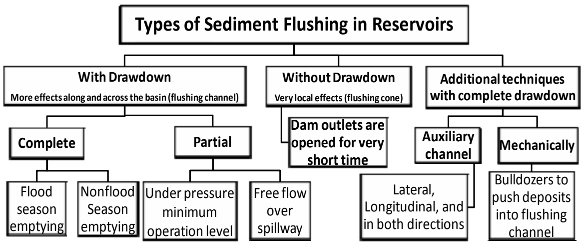

Fig. 10 Classification of sediment flushing techniques

[2] *Mechanically*: This approach is regarded as a last resort in case sediment is accumulated in reservoirs in spite of various efforts being done: 1) mechanically excavating sediment accumulated in the upstream region of reservoirs, and 2) dredging sediment accumulated at the middle and downstream regions. As for excavation and dredging techniques, it is important that the removed sediment should be treated properly and reused.

On the other hand, sediment flushing is a technique to restore tractive force in a reservoir beyond its critical force by means of drawdown of reservoir level, and flush the deposits though bottom outlets in the dam body with inflow water, mainly in an open channel flow condition, to the downstream of dam.

When the amount of sediment inflow is significantly large, man-powered techniques such as excavation and dredging are hard to be adopted because of problems involving transportation and dump site. In such a case, however, sediment flushing can be a permanent measure if conditions are met. Traditionally in Japan, sediment flushing facilities such as flushing sluices and outlets were installed at small-scale hydroelectric dams or weirs for the purpose of discharging sediment deposited in the vicinity of intake. In contrast, at Dashidaira-Unazuki dams in the Kurobe River, where a large amount of sediment is discharged, and sediment flushing is implemented in coordination of upstream and downstream dams (coordinated sediment flushing). The effects of sediment flushing in the Kurobe River should be evaluated. The suitable condition to perform the flushing operation is the taking place of a natural flood more than a constant scale.

Table 2 Comparison of sediment flushing dams in the Japan and Europe

Name of Dam	Country	Dam Height (m)	Initial Storage Capacity (CAP) (Mm^3)	Mean Annual Sediment Inflow (MAS) (Mm^3)	1/(Mean Annual Runoff) (=CAP /MAR)	Reservoir Life (= CAP/ MAS)	Average Flushing Discharge (m^3/s)	Flushing Duration (hrs)	Flushing Frequency (1/ yr)
Dashidaira	Japan	76.7	9.01	0.62	0.00674	14.5	200	36	1
Unazuki	Japan	97	24.7	0.96	0.014	25.7	300	48	1
Gebidem	Switzerland	113	9	0.5	0.021	18.0	10	45	1
Verbois	Switzerland	32	15	0.33	0.00144	45.5	600	36	3
Barenburg	Switzerland	64	1.7	0.02	0.000473	85.0	90	20	5
Ferrera	Switzerland	28	0.23	0.008	0.00018	28.8	80	12	5
Genissiat	France	104	53	0.73	0.00467	72.6	600	36	3
Gmund	Austria	37	0.93	0.07	0.00465	13.3	6	168	N.A.

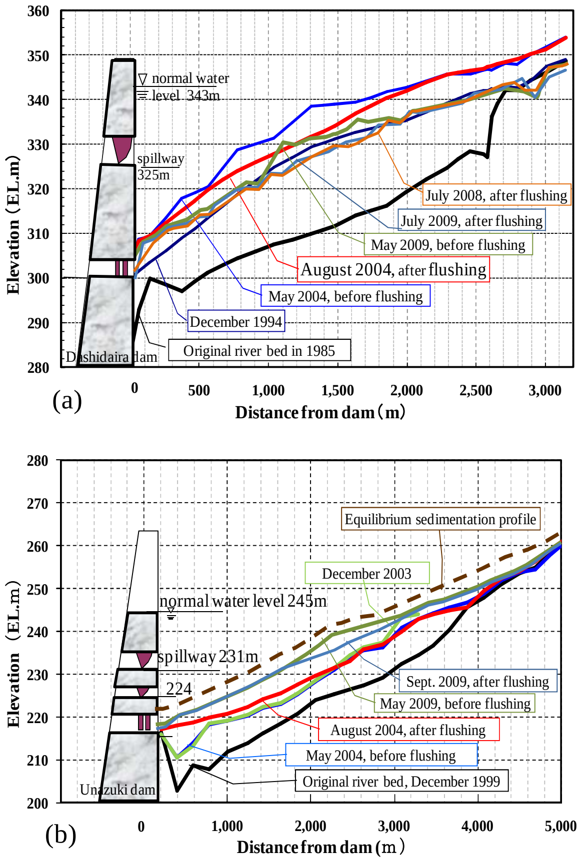

Fig. 11 Actual field longitudinal bed profiles variations in time along (a) Dashidaira reservoir; (b) Unazuki reservoir (Sumi and Iguchi, 2005)

The previous and present longitudinal sediment profiles of Dashidaira and Unazuki dams are shown in Figs.11(a) and 11(b), respectively. Dashidaira dam was constructed fourteen years before Unazuki dam. Therefore, the Dashidaira Dam is currently at an equilibrium state in terms of its sediment, and the quantity of passing through is approximately one million cubic meters yearly.

However, sediment is still being accumulated at the Unazuki Dam. While the majority of sediments of grain size larger than 2 mm are trapped at the reservoir, about 70% of the sediment that has grain size smaller than 2 mm, is sluiced. High sediment deposition is formed in May 2004 within Dashidaira reservoir as shown in Fig. 11(a). Afterward in August 2004, by continuous sediment flushing another bed profile is formed. Longitudinal profiles before and after flushing in 2009 are shown in Figure 11(a). On the other hand in Figure 11(b), the sedimentation in Unazuki dam progresses mainly by the coarse sediment inflow from both sediment flushing of Dashidaira dam and a tributary river. The flushing efficiency calculated from the water consumption including the discharge during drawdown and the sediment volume flushed out is about 2%. For this reason, it can be estimated that sediment flushing by using a natural flood discharge in the rainy season is executed regardless of the previous year's amount of sedimentation to prevent the sediment from changing in quality in the reservoir every year, and in that case while doing an enough dilution.

5. Case studies of sediment replenishment technique at Nunome Dam Japan and Sylvenstein Germany

In Japan, it is common practice to remove accumulated coarse sediment by excavation and dredging, and to make effective use of the removed sediment. Sediment replenishment method is one of new measures of sediment management. In this method, trapped sediment is periodically excavated and then transported to be placed temporarily downstream of the dam. In a manner decided according to the sediment transport capacity of the channel and the environmental conditions. Therefore, the sediment is returned to the channel downstream in the natural flooding processes. The procedure of the experiments consists of four steps: (1) extracting mechanically the accumulated sediment at check dam; (2) transporting it by truck to downstream river; (3) placing the sediment with specific geometry (Fig.12), and (4) monitoring flow, sediment, and environmental parameters.

5.1 Sediment Replenishment Projects in Japan

Large Japanese rivers are often trained to a large extent, to maintain services such as navigation, hydropower generation and flood defense. Okano et al., (2004) summarized sediment replenishment projects in Japanese Rivers, such as Tenryu, Ota-kine, Abukuma, Ara, Oi, Naka, Kuzuryu, Yodo, Kanna, and Tone, have been conducted by Minis-try of Land, Infrastructure and Transport (MLIT). Kantoush et al. (2010) investigated the morphological evolution and corresponding flow field during replenishment experiments in Uda River, Japan. Sediment treatment system is applied by Sumi et al. (2009), to produce appropriate grain sized material with less turbidity.

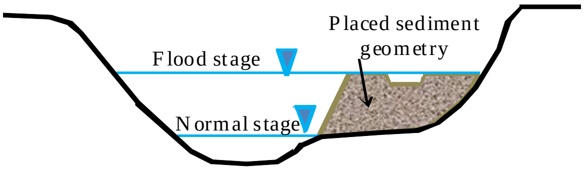

Fig. 12 Concept of sediment replenishment and placed sediment geometry on the bank of Nunome River.

Sediment transport and associated channel bed mobility are recognized as key processes for creating and maintaining physical habitats, aquatic and riparian ecosystems. In Japan, sediment replenishment projects are undertaking with different configurations and characteristics of sediment and discharges. Fig.13 summarizes factors that influence the sediment replenishment research. These factors are classified in six groups as shown in Fig.13.

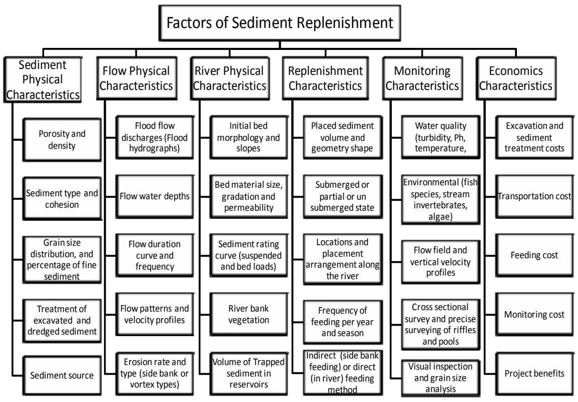

Fig. 13 Main groups of sediment replenishment characteristics and managing factors.

Several significant gaps in the scientific understanding of these processes remain, particularly concerning how riverbed deposition and geometry are influenced by variability in water and sediment release. Sediment replenishment scenarios may, induce undesirable morphological and ecological consequences as well as significant channel adjustments that can result in failure of the restoration project itself. That is, it is necessary to better understand reversibility, direction and time scale of changes, and the sustainability of replenishment intervention before is implemented.

5.2 Field experiment for sediment replenishment in Nunome River

Yodo River (Yodo-gawa) system is 75 km in length, located in the central part of Japan. There are five completed dams in the Kizu River System, Nunome, Shourenji, Hinachi, Takayama, and Murou dams. Nunome dam is a gravity dam for flood control and water supply, completed on 1994, 16 years ago. The test site is placed by the Japan Water Agency (JWA) on the left side bank of Nunome River (Fig.14). The sediment is located in the down-stream reach at 300 m from the Nunome dam. Planning, design, implementation and longterm monitoring of tests are guided by JWA. Fig.14 shows the location map of the placed sediment and reservoir shape.

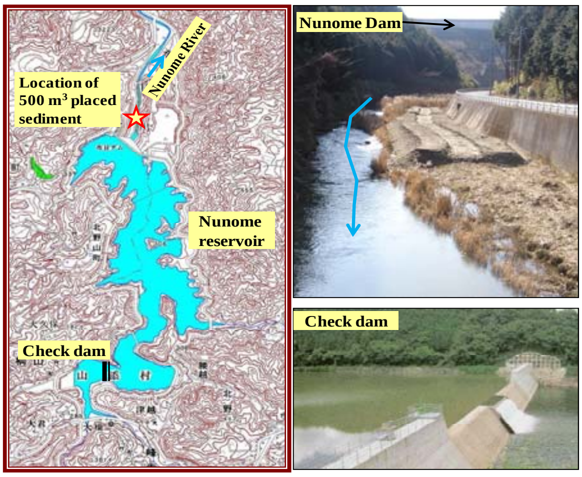

Fig 14 Map of Nunome reservoir, dam, and placed sediment. Photo of geometry and check dam.

5.3 Results of Replenishment DS of Nunome Dam

The evolving of bed topography and grain size distribution is monitored, along with water surface, velocities and rate of sediment transport at the downstream end of the Nunome River. Fig.15 shows the remained sediment of 2008 and during the heavy rain with peak discharge of 81 m^3/s. When the discharge exceeds 8m^3/s, the erosion starts and about 40 m^3 of sediments are trans-ported. Figure 8 shows the photos of field tests phases. All of the remained sediments are removed, and then new dredge sediments are placed. To understand the process of erosion and deposition of the placed sediment during flood, series of pictures are taken at different time and discharges are shown in Fig.16.

The erosion at the base of the placed sediment causes the sand mass of placed sediment bank to slide downward and deposit. Deposited sand mass is then eroded due to water flow. Deposition occurs when the bottom shear stress is less than the critical shear stress. Only sediment with sufficient shear strengths to withstand the highly disruptive shear stresses in the near bed region is deposited and adheres to the bed. The erosion region developed from a straight bank line into the alcove shaped as seen in Fig.16 (b). At the peak discharge the water level increased at 11h50 produces a greater erosion area and the water submerges the placed sediment as shown in Fig.16(c).

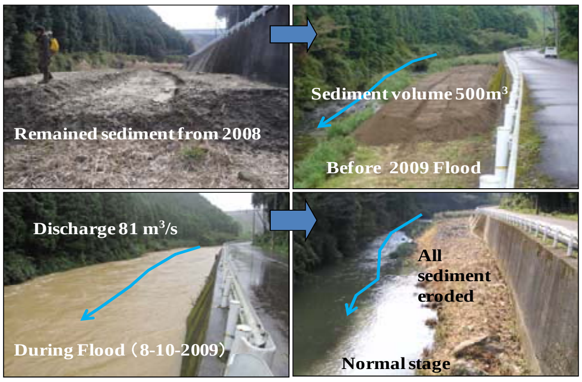

Fig. 15 Evolution of sediment replenishment experiment

The peak discharge is lasted for two hours and permits a deeper cut in the inner side bank. With peak flow, the eroded volumes increased in the range of 45 percent. Reduction of flood discharge reduces the erosion rate, therefore 50 m^3 of the placed sediment remains as shown in Fig.16(d). By using satellite imagery and aerial photos a map of Nunome River in 2009 is constructed for 1 km below the dam. The river channel, island, point bars, and vegetation area are identified and distinguished by color as shown in Figure 10. The downstream reach of the dam, first 150 m from dam, experienced the greatest change in channel structure and loss of bars and islands.

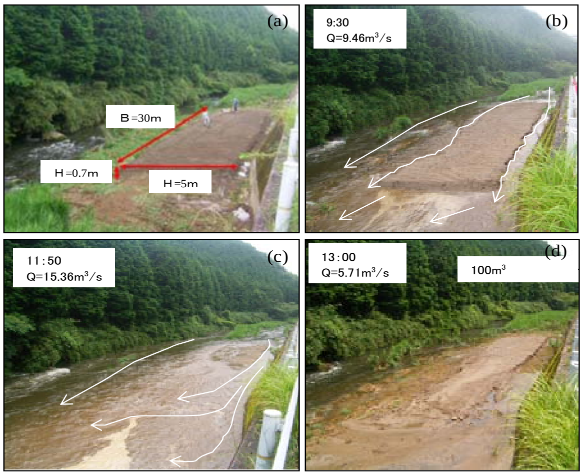

Fig. 16 Processes of erosion and deposition of the placed sediment during flood

The surface flow area in the first reach is greater than the bars and vegetation areas. Between fourth and seventh cross sections, 300 m from dam, reach exhibits variable patterns of channel change and intermediate in loss of island and vegetation. The reach after cross section 7, has a small sand bars, islands, and riparian vegetations.

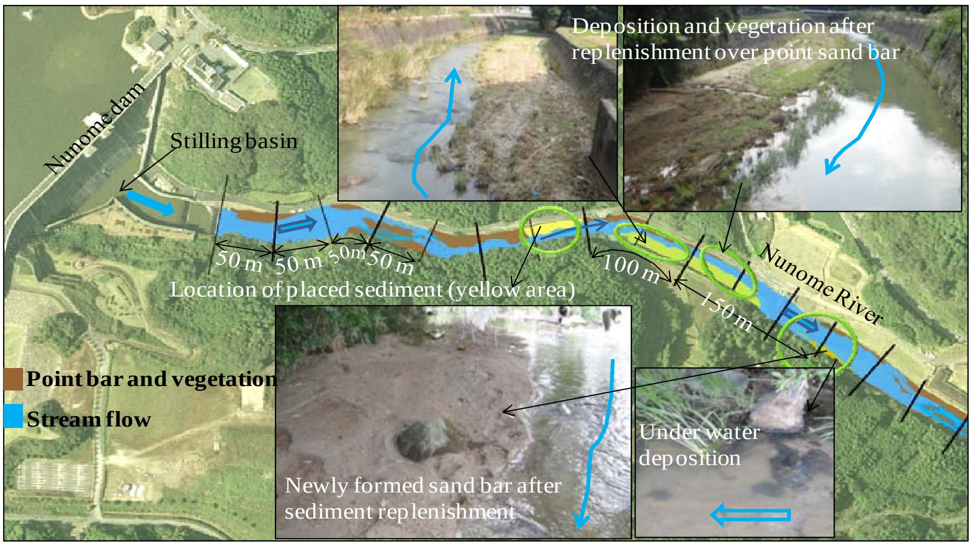

Fig. 17 Processes of erosion and deposition of the placed sediment during flood

The replenishment processes are efficient to restore the bed load transport and the associated habited by coupling reintroduction with floodplain habitat restoration. In Fig.17 along the Nunome River, several cross sections are identified to survey after replenishment. Newly depositions over sand bars and in the river channel are shown in Fig.17. Moreover, a completely new sand bar is formed after 600 m from dam. With the field experiments the processes are directly visible, and will be used for validation of numerical models.

The effects of sediment replenishment are investigated for cross section bed deposition, flow velocity, grain size distribution, water quality and organisms. Eleven monitoring points are shown in Fig.18. The distribution of river bed materials are analyzed by visually determining the sizes of river bed material in quadrate of 1 to 2 m in dimensions and preparing a two dimensional map, which enabled changes in distribution before and after sediment replenishment to be compared.

Fig.18 shows bed material size in three different monitoring times and 10 observation points along the river. By comparing Fig.18(a) and 18(b), a significant riverbed changes can be identified from cross sectional surveys, and visual inspections such as at section No. 1 and No. 11.

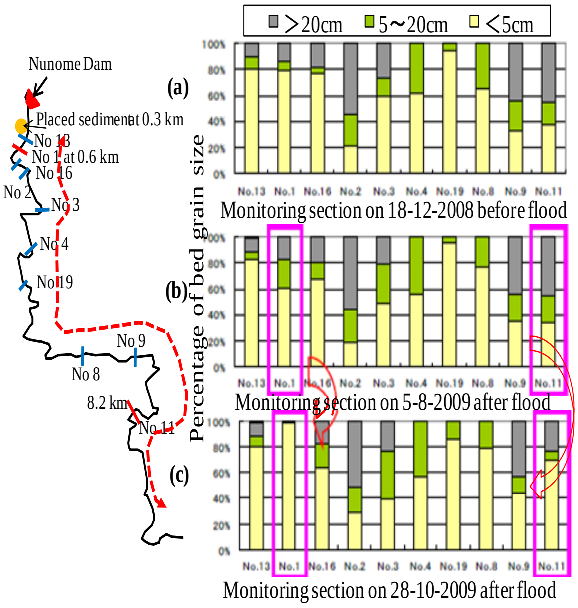

Fig. 18 Variations of river bed material size at 10 cross sections along the Nunome River

After 600 m from the dam the survey at point No. 1 shows that the rate of gravel of less than 50 cm in-creased after natural flood, grace to the replenishment. Similar sediment grain sizes are found at point No 11 after 8200 m from dam point. Before sediment replenishment in point No 1 and No 11, the material is coarser gravel than in the middle points No 4 and No 19 (Fig.18(a)). After flood, the fine material content of the channel deposits strongly increased. The sediment deposition in point No 1 and No 11 after replenishment consist of a nearly continuous layer of fine sand, but no change occurs from No 2 to No 9 (Fig.18(b)). But after second flood where another placed sediment conducted, the bed material is transported and much of the coarsest sediment is supplied to point No 1, and No 11 (Fig.18 (c)).

5.4 Sediment Replenishment in Isare River Germany

(1) ALPRESERV project

In the frame of an international established project called Sustainable Sediment Management of Alpine Reservoirs considering ecological and economical aspects ALPRESERV. Within the EU Interreg IIIB project, ALPRESERV 17 project partners from 5 alpine countries worked together to develop and evaluate a sustainable sediment management and economic issues, and de-sedimentation options. The project aims on a wise management of sediments on basis of experiences gained on national level to establish trans-national guidelines taking into account the EU Water Framework Directive and spatial development needs to preserve existing reservoirs and to avoid uncontrolled exploitation by constructing new storage capacity.

As flood protection is a major task and of high public interest trans-national strategies are needed to implement a sustainable management aiming on a dynamic balance to avoid reservoir sedimentation as well as degradation processes of rivers in the peri-alpine belt to reduce the risk of floods and to avoid severe damages to infrastructure and private property. Accumulation in reservoirs reduces valuable morphological processes of rivers downstream affecting biologic diversity and ecologic dynamics.

As achievement a comprehensive guidelines on sedimentation processes in the Alpine region for enhanced training of water authorities, local administrations and private businesses.

Seven typical Alpine reservoirs were selected for pilot projects ranging from a high region facility directly influenced by glacier activity down to peri-alpine belt river reservoirs to cover most sedimentation problems in the Alpine region. The activities are focused on different strategies to transfer or remove sediments in a larger scale taking into consideration the fragile environment of the Alps. Immediate information of local authorities and all relevant interest groups (inhabitants, fishermen, land owners) can reduce disputes significantly. Experiences of how to encourage locals to join the planning process will be shared within the partnership and published as recommendations to administrations and reservoir owners.

(2) Reuse and deposition of sediments

Technical measures are mostly using different dredging techniques (Photo 9) to either relocate the material into the downstream section or deposit it outside of the water body. All options, especially technical measures, encounter additional problems in the alpine environment compared to lowland applications. The specific conditions described in ALPRESERV project affect time, duration and costs of sediment removal.

For example, Lake Margaritze, a small artificial reservoir in the Austrian Grossglockner region at an altitude of 2.000 m (6.560 ft), is accessible by a paved road. It needs more than 15 truck loads to carry a small water injection dredger, disassembled in parts, to the site. 6 – 8 weeks are necessary to assemble the equipment at the lake before it is operational.

Photo 9 Excavation activities in reservoirs: Suction dredger and floating pipeline at the pilot action Margaritze (left) and conventional hydraulic excavator at Sylvenstein (right) (ALPRESERV project).

Photo 10 Gravel replenishment into Isar at the Oberfohringer Wehr: Transport of excavated material by truck and deposition in the river bed as depots (left) and naturally distributed gravel material after minor flood events after 3 months (right) (ALPRESERV project)

Due to climatic conditions transportation to the lake is limited to spring time, while disassembling and transport downhill has to be finished before the freezing period. Thus operation is limited to the summer months. Beside logistic difficulties (preparation, operation, supply) and resulting costs administrative issues have to be taken into consideration, too. As alpine regions are sensitive environments high elevated areas are often protected as National Parks resulting in restrictions to minimize the impacts of technical measures like noise, exhaust, possible contamination, etc. One good example had been replenishment of more than 100.000 m^3 of gravel material in the river ISar at the Oberfhringer Wehr (Photo 10). A further example of sediment replenishment is documented for pilot action Forni in the ALPRESERV publication.

6. Conclusions

Various integrated management strategies of water and sediment incorporation to preserve river environments downstream of dams in Japan are presented. Water management measures are presented as “Flexible Dam Operation” and instream flow which discharge rate is defined to maintain habitats of river biota, water quality in the each studied section of the rivers depending on each season. For sediment management measures are reservoir flushing, sediment replenishment, bypass tunnel, and flood mitigation dams are discussed.

The present problem for maintaining river health is to determine the adaptive range of the river system to the flow and sediment regimes, which is the basic of all the measure. In detail, it is necessary to find out flow and sediment release which can meet demands of various functions based on data of hydrology, water quality, ecosystem, etc. Furthermore, the integrated management measure for flow and sediment should be researched further, which means how to realize the reasonable and order exploitation and how to regulate and control reasonably by large hydropower project. The sediment flushing of the Kurobe River is extremely important from both sides of the sustainable management of dam reservoir and the securing of the sediment mobility in the sediment routing system. By replenishing sand at different locations of the Nunome and Managwa Rivers within the downstream reaches, the replenishment may direct future supplements for a more widespread dispersal of suitable sand for fish spawning.

Reservoir sedimentation management in Japan is entering a new era. Although there still technical problems to be solved, we believe that the importance of pursuing sediment management will increasingly grow. Assessing issues, depending on each case, of dam security, sustainable management of water resources and sediment management in a sediment transport system, we have to draw up an effective sediment management plan with a limited budget and take specific action. Needless to say, of course, our best endeavors should be exerted to minimize negative environmental impacts involved in sediment management.

Reservoir sedimentation problem has been a challenging issue for many countries all over the world, however only a limited number of countries have been actively playing roles in reservoir sedimentation management. Under the present situation, for those countries which have progressively developed various techniques and possess example cases, key questions are not to put off dealing with this problem but to make continuous effort of further developing techniques and putting them into practice, and to widely share the resulting information and knowledge with every country in need of them.

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日本およびヨーロッパアルプスにおける河川形態および持続可能な貯水池土砂管理計画

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要　旨

ヨーロッパアルプス地域のダム貯水池は，流入河川がもたらす土砂の堆積作用によって，その持続可能性が著しく脅かされている。このような貯水池に対する土砂管理計画を，一般化された基準や方策で記述することはなかなか難しい。本報では，日本とアルプス地域のダムにおける土砂堆積に伴うリスクを定義し，これを適切に計測することを目的としている。特に，総合土砂管理の導入によって，水資源の持続的利用，生物環境の保全，さらには，人間と自然の調和を図るために，健全な河川流域を如何に維持するかが最終的な目的である。土砂管理を成功させるためには，河川マネジメントから根本的に変える必要があり，これには，いくつかの対策の組み合わせにより，ダムを通過する水量と土砂量をバランスさせることが重要である。アルプスの大規模貯水池では，密度流が細粒土砂を高濃度で輸送する現象がしばしば観察され，これを適切に制御することが求められる。

キーワード：アルプス貯水池，ダム堆砂，貯水池土砂管理，土砂管理計画，持続可能な貯水池，ダム影響