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Sediment management strategies for sustainable reservoir

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ABSTRACT: The worldwide sediment management techniques consist of three basic strategies: sediment yield reduction, sediment routing, and sediment removal. The paper focuses on reservoir sustainability by considering the following points. One is how we should choose suitable sediment management options under the consideration of each sedimentation conditions. In that case, annual water and sediment inflow volumes comparing to reservoir storage volumes are the key factors for the selection. The other is how we can design suitable volumes to be discharged from reservoirs. Combination of excavation and sediment replenishment option is now becoming common in Japan. Recently these projects are still in trial stage with limited percentages of sediment replenishment ranging between 0.1 to 10% of annual reservoir sedimentation. Case study at Nunome dam is a good example of comprehensive sediment management and it contributes positively to rebuilt sand bars, mitigate the armouring of river bed, and management of reservoir sedimentation.

1 INTRODUCTION

Sustainability of reservoirs and downstream reaches below dams are threatened by reservoir sedimentations. The objective of water and sediment incorporation is to manipulate the river-reservoir system to achieve sediment balance while maximizing the beneficial reservoir storage and minimizing downstream environmental impacts. Several methods for sediment management are available and have been implemented in practice. At the same time, an attempt to return the excavated and dredged sediment to the downstream river (hereafter we all 'sediment replenishment') has been undertaken aiming at balancing sediment inflow and outflow sediment budget. An understanding of channel geomorphic responses to various sediment replenishment technique and natural disturbances is important for effective management, conservation, and rehabilitation of rivers and streams to accommodate multiple, often conflicting, needs. For example, channel changes may have implications for various needs including water supply, infrastructure, navigation, and habitat.

1.1 *Sedimentation 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 Figure 1a. These reservoirs are now facing a critical question of sedimentation. To maintain the existing dams and their facilities over the long term becomes an essential policy issue. 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.

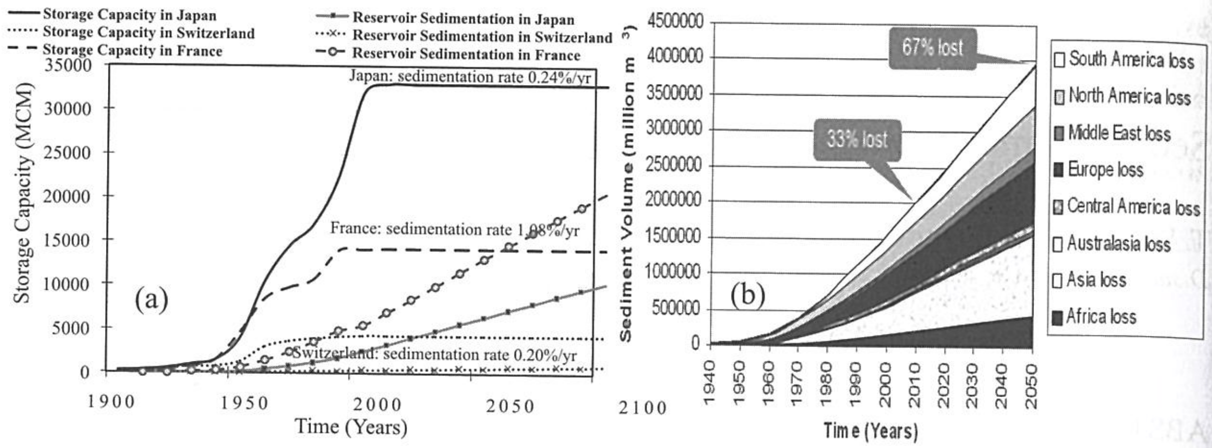

Figure 1. (a) Development and estimated evolution of installed water storage capacity and volumes lost due to reservoir sedimentation; (b) Global reservoir sedimentation rates (Basson, G. 2009).

Figure 1a 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%.

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 Figure 1b. 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 Figure 1b. The graph shows the evolution over the last century, and the predicted future development.

1.2 *Influences of sediment deficit on downstream reaches below dams*

Reservoir construction and operation can have a substantial effect on the stability of the river channel downstream from the dam (Sumi and Kantoush, 2010). Reservoirs can trap and permanently store virtually the entire sediment load delivered from the upstream basin (Petts, 1979; Williams and Wolman, 1984). Thus, immediately downstream from a dam, a river's sediment load is greatly reduced. In addition, typical downstream changes in the flow regime include a reduction in the magnitude of peak flows and a possible increase in the magnitude of low flows (Williams and Wolman, 1984). In response, the downstream river may adjust in an attempt to re-establish an approximate equilibrium between the channel and the discharge and sediment load being transported. Possible adjustments include channel-bed erosion or deposition, channel widening or narrowing, and changes in channel pattern or shape. 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. 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.

1.3 *Objectives*

The main purpose is to explain, how to select appropriate sediment management strategy in each reservoir according to sedimentation conditions within reservoir and in downstream reaches. The other is how we can design suitable volumes to be discharged from dam reservoirs. In this paper, the results of study in Japan that used sediment replenishment strategy to investigate the geomorphic responses of channels to disturbances are presented. The examples provided demonstrate the use of sediment excavation and replenishing to downstream reaches to reduce sedimentation in reservoir and improve downstream reaches. Given that currently about 20 reservoirs in Japan are excavated and sediments were supplied, the techniques described here may have utility for sediment replenishment and geomorphic response investigations nationally.

2 SUSTAINABILITY OF RESERVOIRS

2.1 *Concept and economical feasibility*

The concept of sustainability applied to agriculture developed, ground water development, and road engineering. The essential concept of sustainable development is that the welfare of future generation should logically figure into the project decision-making. Reservoirs arguably represent today's class of non-sustainable infrastructure. The objective of reservoir sedimentation management is to minimize the adverse effect that sediment deposition in a reservoir has on its usability. The sustainability of reservoir should seek to balance sediment

Figure 2. Concept of a sustainable reservoir.

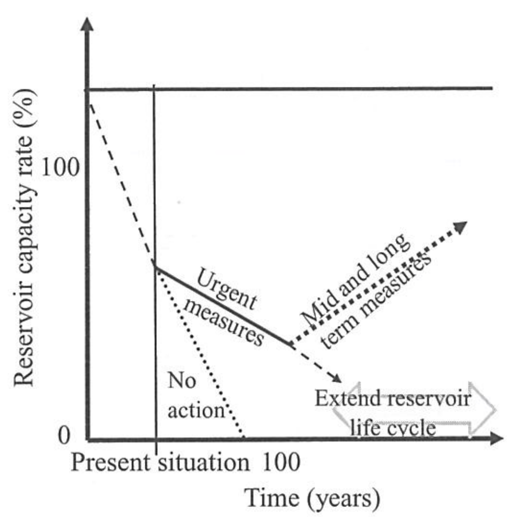

Figure 3. Illustration of prolongation of reservoir lifetime.

inflow and outflow across the reservoir while maximize the long-term benefits, the concept of sustainability is shown in Figure 2. The optimization of sediment removal methods as a dam group is inexpensive if a dam group was linked with each other for sediment management. 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 Figure 2.

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. 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 Figure 3, should allow the research to obtain some significant advances in the understanding of dam impacts.

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.

3 SEDIMENT CONTROL STRATEGIES

3.1 *Classifications of sediment management techniques*

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

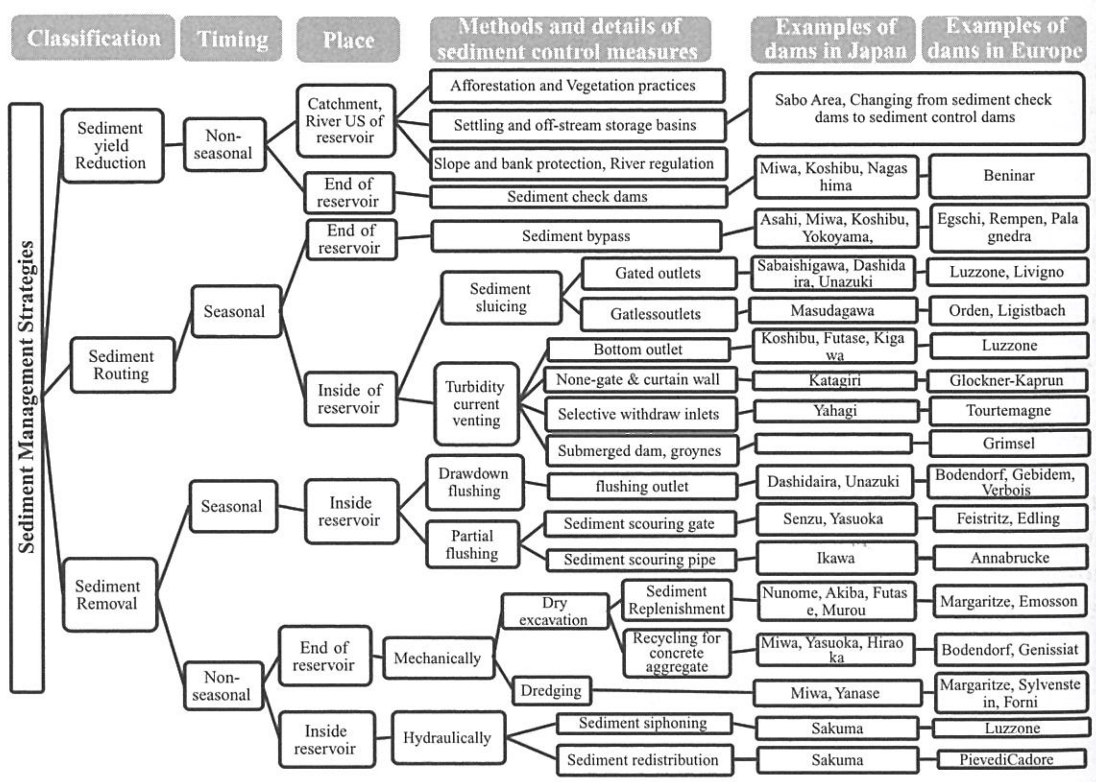

Figure 4. Classification of strategies of sediment control in Japanese and European reservoirs.

1. Sediment yield reduction: to reduce sediment inflow to reservoirs. Apply erosion control techniques to reduce sediment yield from tributary catchments.
2. Sediment routing: to pass sediment inflow around or through the reservoir by techniques such as sediment bypass, partial drawdown sluicing and turbidity release.
3. Sediment removal: to remove accumulated sediment by drawdown flushing, dredging and excavation by mechanically or hydraulically techniques.

Figure 4 shows how sediment management is undertaken and classified. And some representative dams and examples from Europe and Japan, which exercise sediment management, are listed up.

4 SEDIMENT REPLENISHMENT TECHNIQUE

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. In the technique with sediment trap, a low dam is constructed at the end of reservoir as to deposit transported sediment, mainly bed load of relatively coarse grain size. The accumulated sediment can be excavated on land except for flood time, and the removed sediments have been utilized effectively as concrete aggregate. As of 2000, the check dams have been constructed at 57 out of the dams under jurisdiction of Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

4.1 *Sediment replenishment projects in Japan: Volume and grain size*

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, and (4) monitoring flow, sediment, and environmental parameters.

Recently, sediment replenishment tests have been carried out in 20 dams in Japan. Okano et al. (2004) summarized sediment replenishment projects in Japanese Rivers. 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. Seto et al. (2009) analyzed sediment replenishment effects on the downstream river of Yahagi dam.

Sediment replenishment volume and grain size are recognized as key factors for a successful management in the river basin to create and maintain physical habitats, aquatic and riparian ecosystems. Figure 5 shows the relationship between the annual excavated sediment volumes from reservoirs and annual reservoir sedimentation volumes within reservoir (Sumi and Fujita, 2009). Percentages of sediment replenishment are very limited ranging between 0.1 to 10% of annual reservoir sedimentation since these projects are still in trial stage. Figure 6 shows the grain size distributions of replenished sediment which are very much different in each dam because of the location to take sediment out from reservoirs. In Miharu and Nunome dams, relatively fine sediments are dredged in upstream secondary reservoirs for trapping nutrient rich sediments. Others are mainly excavating coarse sediments from conventional check dams.

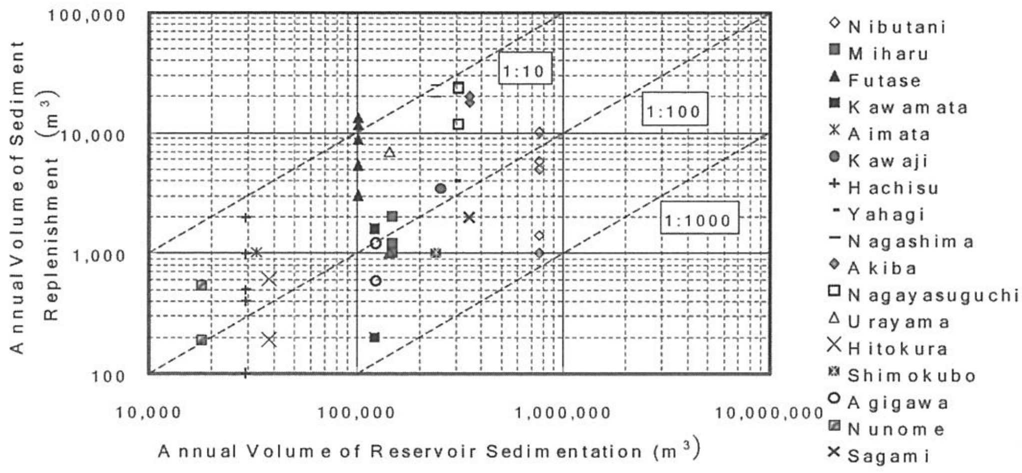

Figure 5. Relationship between annual reservoir sedimentation and replenishment volumes in Japan.

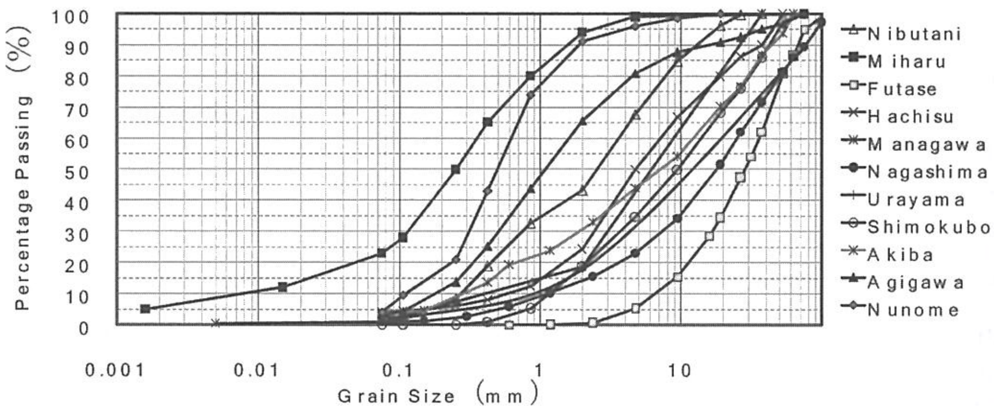

Figure 6. Grain size distributions of sediment replenishment.

4.2 *Case study of Nunome dam actual sediment replenishment tests*

Since 2004, six experiments of sediment replenishment projects with different sediment volumes are undertaken below Nunome dam. Tracking the history and performance of these projects is helping to understand the evolution of sandbars. Table 1 summarizes the replenishment history, flushing flow and sediments characteristics. The volume of placed sediment is limited to several hundreds of cubic meters each time. To implement this method, consideration has to be given to environmental problems in the lower river basins, to the occurrence of turbid water, and to safety risks due to sediment deposition in the channel. The data in Table 1 indicates that there is a need to increase the amount of the supplied sediments in Nunome River every year. The replenished sediment is placed at such an elevation; in order to reduce the turbidity during normal flow period. The top of the sediment is adjusted so that the sediment is completely submerged during flood at several times a year and all sediment is eventually transported downstream (Figure 7).

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. Figure 8 shows the remained sediment of 2008 and during the heavy rain with peak discharge of 81 m^3/s. When the discharge exceeds 8 m^3/s, the erosion starts and about 40 m^3 of sediments are transported. Figure 8 shows the photos of field tests phases. All of the remained sediments are removed, and then new dredge sediments are placed.

Table 1. History of the sediment replenishment tests downstream of Nunome dam.

Year	Setting sediment period	Flood period	Volume of remained sediment (m^3)	Volume of placed sediment (m^3)	Volume of eroded sediment (m^3)
2004	28-9-2004	29-9-2004	0	190	190
2005	9-8-2005	4, 5-10-2005	0	540	80
2006	NA	19, 21-7-2006	460	0	370
2007	9-8-2007	23, 29-8-2007	90	720	810
2008	27-6-2008	8-7-2008	0	100	35
	7-8-2008	5, 19-9-2008	0*	100	100
	12-11-2008	NA	0	500	0
2009	NA	2-8-2009	500	0	500
	2-10-2009	7, 8-10-2009	0	500	500

* The remained 65 m3 sediment is removed.
NA: No placed sediment or No flood occurred.

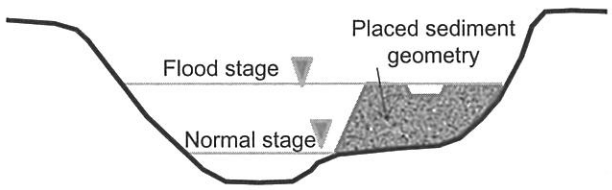

Figure 7. Concept of sediment replenishment.

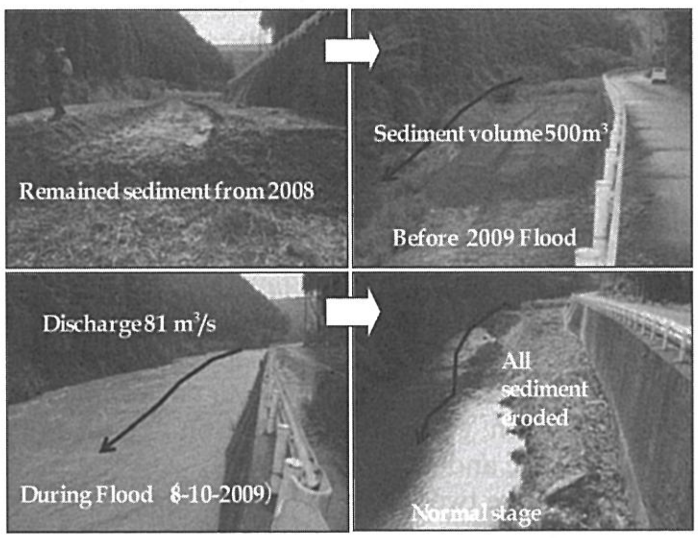

Figure 8. Evolution of replenishment experiments.

By using satellite images 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 as shown in Figure 9. The downstream reach of the dam, first 150 m from dam, experienced the greatest change in channel structure and loss of bars and islands. The replenishment processes are efficient to restore the bed load transport and the associated habited by coupling reintroduction with floodplain habitat restoration. In Figure 9 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 Figure 9.

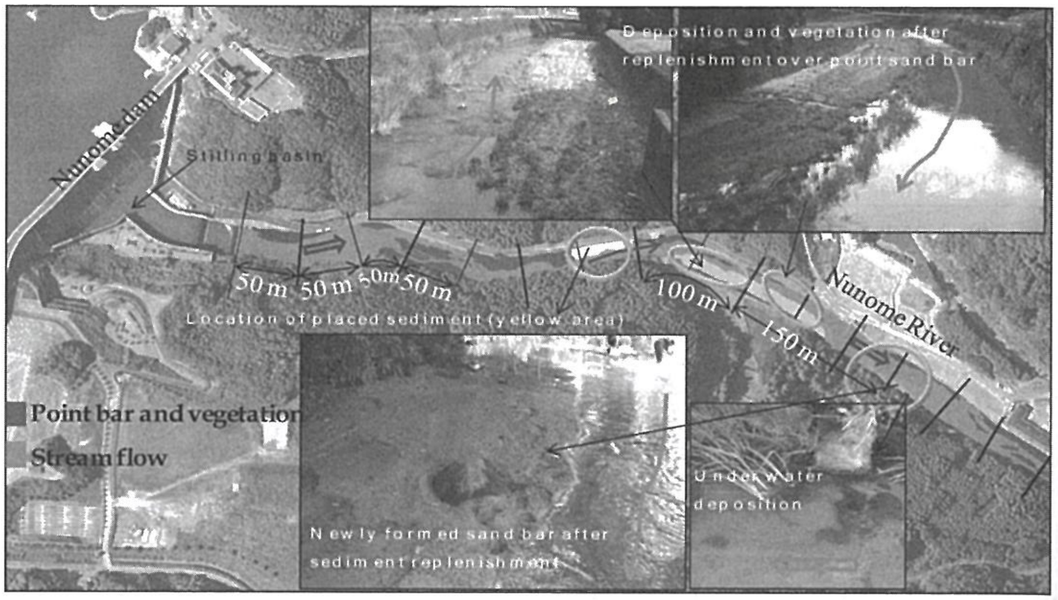

Figure 9. Aerial photographs of Nunome dam with the downstream reach of Nunome River. Morphological changes and the self forming sand bar due to sediment replenishment below the dam (14-10-2009).

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.

5 SUITABLE SELECTION OF SEDIMENT MANAGEMENT TECHNIQUE

Figure 10 shows flow chart for setting up sediment management strategy. Firstly, we have to pick up dams for sediment management (1) and select high priority dams (2). We should consider design life cycle for redevelopment project for these dams to calculate investment cost and benefit (3). Based on past record of reservoir sedimentation, we can estimate future expected sediment inflow to the reservoir (4). Here, stochastic approach considering extreme flood events is recommended to assess long term sediment yield and transport process (Sumi and Kantoush, 2010).

After that, we should consider parallel studies; one is to design necessary reservoir capacity volume for maintaining original functions of dams (5) and design necessary sediment supply volume to realize it (6). The other is to design sound river environment described representatively such as by river bed elevation, grain seize and morphological dynamics (7) and design necessary sediment supply volume and grain size (8).

Finally, we should combine these two needs and decide appropriate scenario to discharge sediment from dams (9). If there do not exist suitable scenarios, we should go back to (3). Based on the proposed scenarios, we can select optimal sediment management measures from several possible options such as reservoir flushing, sediment replenishment, bypass tunnel etc. (10). If technical significant problems may arise, we should modify the scenario.

Selected sediment management measure should be evaluated by benefit/cost analysis (11) and, if the project is not economically feasible, we should revise the project from the master planning stage. Sediment management of reservoirs is very much complicated project which will affect reservoir sustainability and also maintaining downstream river health. So we should start to implement step by step basis (12) by conducting filed monitoring under the adaptive management concept (13). Sediment replenishing case study at Nunome dam is a part of comprehensive sediment management in upper Kizu river basin containing five multi-purpose dams (Sumi et al., 2009). We are now starting to clarify how to sustaining reservoir functions and how to improve river environment at the same time by coordinating operation.

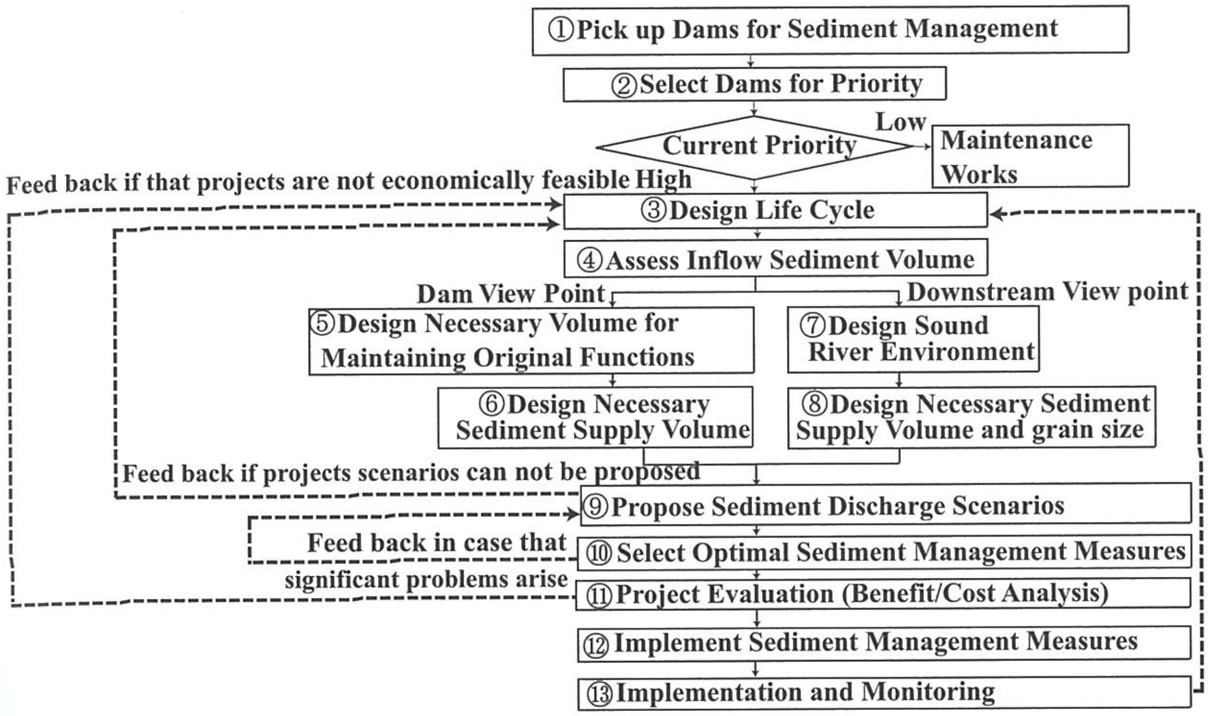

Figure 10. Flowchart for setting up sediment management strategy.

6 CONCLUSIONS AND DISCUSSIONS

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. It is necessary to find out appropriate combination of flow and sediment release which can meet demands of various functions based on data of hydrology, water quality, river morphology and ecosystem, etc. Furthermore, the integrated sediment management approach should be considered in sediment routing system which covers not only river basin but also connecting coastal area. Since suitable sediment replenishment volumes and grain sizes are key parameters to design effective management strategy, these values should be decided from two points of view of reservoir sustainability and downstream environmental improvements. Regarding to the case study of Nunome by replenishing sand at different locations of the Nunome River within the downstream reaches, the replenishment directs future supplements for a more widespread dispersal of suitable sand for fish habitat including spawning beds.

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