Proceedings of the Ninth International Symposium on River Sedimentation
October 18 – 21, 2004, Yichang, China

RESERVOIR SEDIMENTATION MANAGEMENT BY COARSE SEDIMENT REPLENISHMENT BELOW DAMS

Masahisa OKANO
Japan Water Resources Environment Technology Center
Mikio KIKUI
Hamamatsu River and Road Office, Ministry of Land, Infrastructure and Transport, Chubu Regional Bureau
Hiroya ISHIDA
Dam Engineering Section, CTI Engineering Co., Ltd.
Tetsuya SUMI
Department of Civil Engineering, Kyoto University

Abstract: There is a growing need for comprehensive reservoir sediment management in order to cope with problems such as riverbed aggradation in the reaches upstream of reservoirs and reduction in reservoir capacity, to maintain intake facilities, and to conserve the environmental conditions of rivers downstream and coastal waters. An effective means of such comprehensive reservoir sediment management is to excavate and transport part of the coarse sediment that has entered and accumulated in reservoirs to the river channels downstream so that the sediment is transported by flood water in the channels to the sea. Efforts are currently underway to develop technologies for making that method possible. In this paper, characteristics of reservoir sedimentation in Japan are explained, and the check-dam-based sedimentation control methods currently practiced in Japan are described briefly. Present practices in coarse sediment replacement, which can be expected to improve the river environment, are also described, and the future direction of coarse sediment replenishment is also discussed.

Keywords: Reservoir sedimentation, Management of coarse sediment, Sediment replenishment, River restoration, Monitoring

1 INTRODUCTION

Many dam reservoirs designed for hydroelectric power generation in Japan have been used to generate electricity from the potential energy of water flowing into reservoirs. Consequently, the influence of sediment accumulation in those reservoirs is relatively small. For multi-purpose dam reservoirs designed for flood control and water supply, however, the influence of reservoir sedimentation is much more important because it is directly related to maintaining the functions of those dams. Therefore, the development of appropriate technologies for sustainable reservoir sedimentation management that can be used at multi-purpose dams is hoped for.

In recent years, check dams have been constructed in the upper reaches of many multi-purpose dam reservoirs to trap coarse sediment and reduce sediment loads into the reservoirs. Trapped sand and gravel are mechanically removed periodically and used as construction materials. In order to achieve the newly defined goal of balancing the sediment transport budget over the entire river system and maintaining a nature-rich river environment, trapped sediment should be returned to the river channel so that it is eventually transported to the coastal areas.

With the aim of letting such a system work on a sustainable basis, attempts are being made at a number of dam reservoirs to supply trapped coarse sediment to the river channels downstream. Here, we call such sediment suppy works as 'sediment replenishment'.

2 OVERVIEW OF RESERVOIR SEDIMENTATION MANAGEMENT IN JAPAN

2.1 Reservoir Sedimentation in Progress

As of 2000, a total of about 2,800 dams with a height of 15 m or more have been constructed (JDF 2003), and the total storage capacity of these dams reaches about 23 billion m^3. Of these dams, sedimentation conditions at the dams with a total capacity of more than one million cubic meters are reported every year to the Japanese government.

Fig. 1 (Sumi 2003) shows the relationship between the age of dam (years after completion) and the sedimentation ratio for about 900 dams.

According to these data, an average of 0.24% of dam reservoir capacity is lost to sedimentation every year (Sumi 2003).

On the other hand, a substantial increase in reservoir capacity due to new dam construction cannot be expected in the coming years.

In the Chubu and Hokuriku regions where sediment transport rates are high, the rates of reservoir capacity loss due to sedimentation are roughly twice as high, so the situation is quite serious (Sumi 2003).

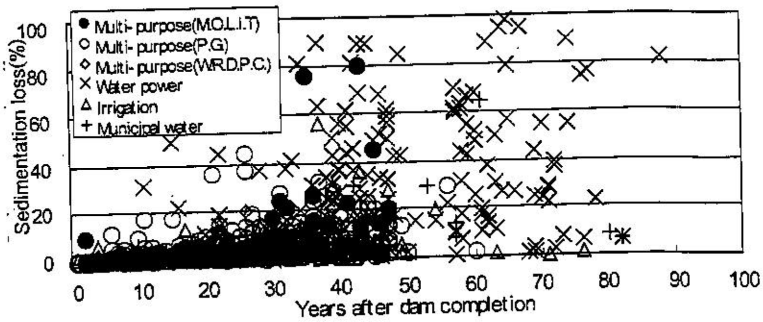


Fig.1 The Ages of Dams in Japan and Reservoir Capacity Losses due to Sedimentation (Sumi 2003)

2.2 Reservoir Sedimentation Patterns and the State of the Riverbed Downstream of the Dam

2.2.1 Sedimentation Patterns and Particle Size Distribution

It is generally said that the ratios of gravel, sand, and silt/clay contained in the sediment transported by rivers in Japan are(0-10%):(35%-40%):(50%-60%) (Fujita *et al.*, 1995). After flowing into a reservoir, sediment forms a delta composed of deposits graded as shown in Fig. 2 according to the deposition characteristics of the reservoir (JDF 2003). As shown, the longitudinal profile of sediment deposits is not necessarily horizontal: areas at higher elevations are more prone to such phenomena as a reduction in effective capacity and backwater formation. Coarse sediment composed mainly of gravel and sand deposited in the upstream zone of the topset bed is not easy to move by lowering the reservoir water level or dredging the shoulder region of the midstream zone.

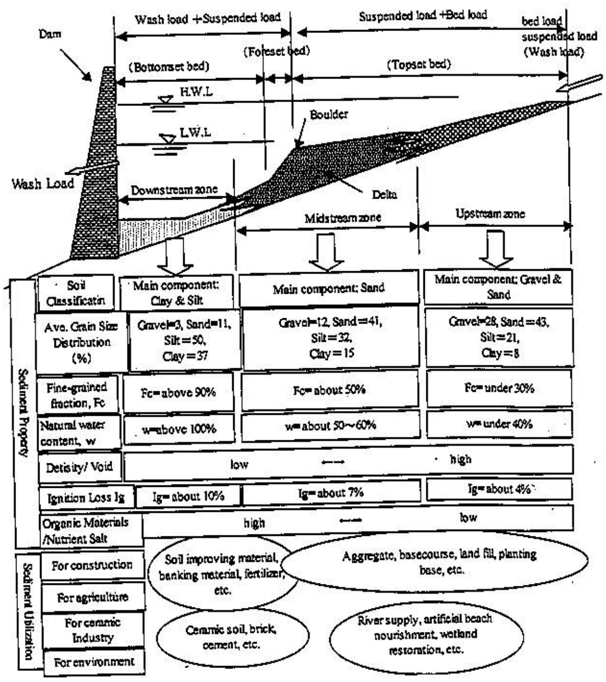
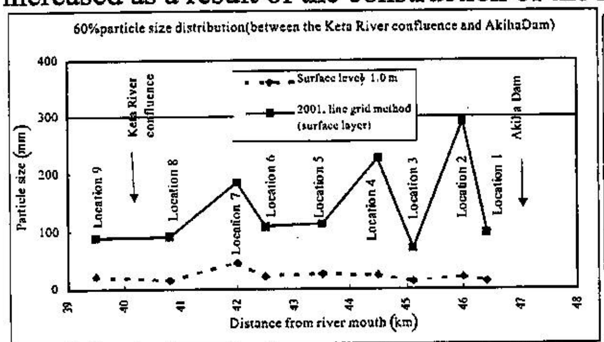


Fig.2 The Properties of Sediments Accumulated in Dam Reservoirs and Applications of Different Types of Sediments (Oya *et al.*,

2.2.2 The State of the Riverbed downstream of the Dam

Actual riverbed changees below dams are generally not well recorded since those dams are located in upper high mountain areas. Even in the case of Akiha Dam located 45 km upstream from the mouth of the Tenryu River, one of the most sediment productive rivers in Japan, continuous observation records of riverbed change are not available, so actual riverbed aggradation/degradation processes are still unknown.

The particle size distribution of the surface and lower (1 m below surface) bed layers in the 17-km-long section from just downstream of the Akiha Dam to the confluence with the Keta River, a tributary without a large reservoir, was measured in 2001. Fig. 3 shows the changes in 60% particle size distribution in the longitudinal direction. This indicates that the 60% particle size tends to become smaller as the distance from the Akiha Dam increases in the downstream direction. Fig. 4 shows particle size distribution of the surface and lower bed layers at 46.0km and 39.5km points. This shows that particle size of surface layer at just downstream of the Akiha Dam(46.0km) is coarser than the one at the confluence of the Keta river(39.5km). These results are thought to indicate that the particle sizes of bed material (surface layer)have increased as a result of the construction of the Akiha Dam.



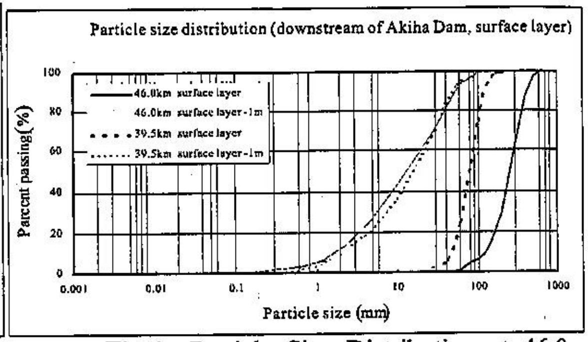


Fig.3 Changes in Representative Particle Size (60%) 39.5kmDistribution at Different Distances from the Akiha Dam

Fig.4 Particle Size Distribution at 46.0 and

2.3 Problems Caused by Sedimentation, and Corrective Measures

At some dams in Japan, particularly in the mountainous areas in the Chubu region, reservoir sedimentation might impair the functions of dams by causing the upstream riverbed to rise or the reservoir capacity to decrease. Combined with large amount of gravel extraction from riverbeds in the 1960's, reservoir sedimentation contributes to riverbed degradation in the channels downstream and coastal erosion in estuary zones. It has also been pointed out that supplying an appropriate amount of sediment from dams is also important from the standpoint of preserving the sound sediment environment and then the habitats for various forms of flora and fauna at the lower reaches of rivers and coastal areas. These aspects have been drawing attention in recent years.

In Japan, it is common practice, as a means of reservoir maintenance, to remove accumulated coarse sediment by excavation and dredging, and to make effective use of the removed sediment. More or less stopgap measures and localized remedies, therefore, have been taken to cope with problems such as sediment clogging in intake areas or riverbed aggradation at the upstream end of a reservoir.

Currently, serious efforts are underway to drastically reduce sediment inflow and accumulation by using, for example, flushing gates in the Kurobe River or bypass tunnels at the Asahi Dam and the Miwa Dam (Sumi 2003). These measures, however, involve important considerations: cost and environmental impacts. From experience with past sediment removal projects, Okano *et al.* (2003) recommended a sediment replenishment method, consisting primarily of trapping coarse sediment with a check dam, as a widely applicable corrective measure. In this method, trapped coarse sediment is periodically excavated (or dredged depending on the site conditions) and then transported and placed temporarily on the channel immediately downstream of the dam, in a manner decided according to the sediment transport capacity of the channel and the environmental conditions, so that the sediment is returned to the channel downstream in natural flooding processes.

3 PRACTICES OF EXCAVATION AND DREDGING OF COARSE SEDIMENT IN RESERVOIRS

3.1 Excavation and Dredging, and Utilization of Excavated/dredged Sediment

In 1998, the Ministry of Construction (now restructured into the Ministry of Land, Infrastructure and Transport (MLIT)) conducted a questionnaire survey of dam managers in Japan (MOC 1999). According to the questionnaire results of 580 dams, accumulated sediment is removed by excavation at 147(25%) dams. Fig. 5 shows changes over time in the volume of sediment removed from reservoirs. The challenge in sediment removal by excavation is to find a place to which to transport the excavated sediment.

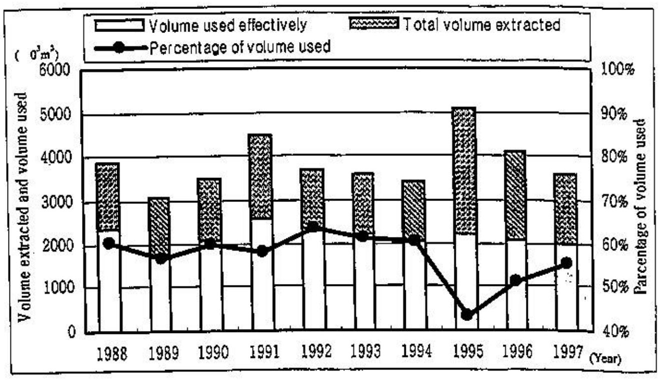


Fig.5 Changes in the Volume of Sediment Removed

According to the results of the questionnaire mentioned earlier, 2.2×10^6 m^3 (about 60%) of the excavated sediment is used as concrete aggregate or embankment material. In order to make more effective use of excavated sediment, it is necessary to address a number of problems such as the cost for sorting out, disposing of and transporting excavated sediment and traffic environment problems, but it is not easy to solve these problems.

In view of the natural continuity of sediment transport processes in river cources, it is also necessary to supply the volume of sediment needed by the river channels downstream.

3.2 Functions and Configuration of Check Dams

Use of check dams to trap sediment is effective in Japanese reservoirs because the percentage of bed load to the total sediment load tends to be high. The check dam method, therefore, has been used for many dams in recent years as shown in Fig. 6. In this method, a low dam is constructed at the upstream end of the reservoir to settle relatively large sediment particles so that accumulated sediment can be removed periodically. The check dam method has the following advantages: (1) accumulated sediment can be easily removed by land-based excavation during non-flood periods; and (2) excavated sediment can be used as, for example, concrete aggregate because excavated sediment is composed mostly of relatively large particles. The check dam method, therefore, is usually used in cases where trapped sediment is to be removed at low cost, so the method may be thought of as a supplementary means of sediment removal. By 2001, check dams have been constructed at 57 dams out of 440 dams managed directly by MLIT and most of them are gravity concrete ones.

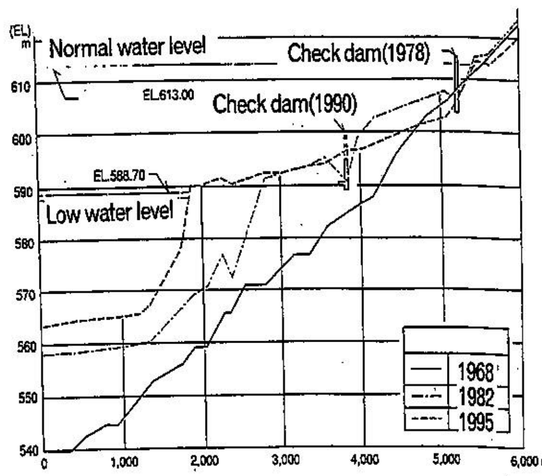


Fig.6 Longitudinal Profile of Koshibu Reservoir

4 OUTLINE OF DOWNSTREAM CHANNEL SEDIMENT REPLENISHMENT TESTS

4.1 Overview

If excavated or dredged sediment can be returned to the river channel immediately downstream of the dam, the hauling distance can be made very short and the cost of disposal of excavated or dredged sediment can be eliminated. Moreover, the need to conserve the river environment by supplying necessary sediments is now getting noticeable. Because of these reasons, the sediment replenishment tests have been planned and executed at many places.

Table 1 Examples of Tests for the Downstream Replenishment Method

Name of dam	Name of river	Drain-age area (km^2)	Location	Year	Purpose	Sediment used for replenishment (Particle size)	Transportation distance (km)	Volume used for replenishment (10^3m^3·cycle)	Average annual rate of reservoir sedimentation ($10^3m^3·Y^{-1}$)
Akiha	Tenryu River, Tenryu River System	4,490	Shizuoka Pref	'99 -'01	Prevention of riverbed Degradation and coastal erosion	Sediment accumulated in reservoir (Gravel 67%、Sand 29%	Akiha 3 Funagira 23	18-20	430
Miharu	Otakine River, Abukuma River System	226	Fukushima Pref.	'99 -'03	(1) Prevention of downstream riverbed degradation (2) Prevention of increase in coarse grain content	Sediment accumulated in front reservoir (Sand 60%、Silt 28%)	4	1-2	149
Futase	Ara River, Ara River System	260	Saitama Pref.	'99, '01 -'02	(1) Improvement of habitat of fish (sculpin)	Sediment accumulated at check dam (Gravel ,boulder)	15	3-8.8	101
Nagashima[*1]	Oi River, Oi River System	958[*2]	Shizuoka Pref	'00 ~'01	(1) Acquisition of basic data for annual sediment replenishment planning for Nagashima Dam (2) Determination of influence on downstream river environment	Sediment accumulated just upstream of an embankment dam downstream of the dam (Average particle diameter 31mm)	1[*3]	20-25	400
Urayama	Urayama River, Ara River System	51	Saitama Pref.	'00,'02, '03	(1) Improvement of habitat of fish (2)Prevention of increase in coarse grain content	Sediment accumulated in reservoir (-)	4	1-14	144
Hachisu	Hachisu River, Kushida River System	80	Mie Pref.	'02	(1) Improvement of habitat of *ayu* (sweet fish) (2) Prevention of riverbed degradation	Sediment accumulated in reservoir (-)	5	0.3	29
Nibutani	Saru River, Saru River System	1,215	Hokkaido	'02	(1) Disposal of sediment accumulated at check dam (2) Improvement of downstream river environment	Sediment accumulated at check dam (-)	11 20	1	764
Shimokubo	Kanna River, Tone River System	322	Gunma Pref.	'03	(1) Conservation of landscapes of Sanbaseki Ravine downstream of the dam (prevention of armoring)	Sediment accumulated in reservoir (Gravel)	5	1	240

*1: Sediment accumulated at *Shiogo Weir* downstream of Nagashima Dam is used.
*2:The size of a catchment area at *Shiogo Weir* *3:Distance from *Shiogo Weir* to a temporary place

Table 1 summarizes sediment replenishment tests that have been conducted at multi-purpose dams managed by MLIT. Since the Akiha Dam, designed specifically for power generation, is managed by the Electric Power Development Co. Ltd., a branch office of MLIT which is responsible for river management have organized the Committee on Tenryu River Sediment Replenishment Test consisting of academic experts (river engineering, bioecology), river administrators, dam managers, and representatives from local autonomous bodies, fishery workers' associations, and sand and gravel miners cooperatives (Suzuki 1998).

4.2 Extraction and Transportation of Sediment to be Returned to the River

Sediment accumulated behind a check dam is excavated mainly by land-based backhoes. Dump trucks are usually used to haul the excavated sediment from the upstream end of the reservoir where the check dam is located to the area just downstream of the dam where the sediment is to be returned to the river. At the Akiha Dam, sediment is extracted from the reservoir by using a grab dredger and is hauled to the area just downstream of the dam body (about 5 km) in 11-ton dump trucks.

4.3 Sediment Placed for Replenishment and Its Transport Downstream

4.3.1 Sediment Placement Method

Sediment haulted to the river channel is placed so that it does not get waterborne in times of normal flow and it is gradually transported downstream after flooding river water begins to become turbid. Thus, replenishment sediment is placed at such an elevation that it does not become a source of turbidity in times of normal flow and bank erosion occurs as streamflow increases. The top of the sediment placed for replenishment is adjusted so that the sediment is completely submerged in flood water several times a year and all sediment is eventually transported downstream (see Fig. 7).

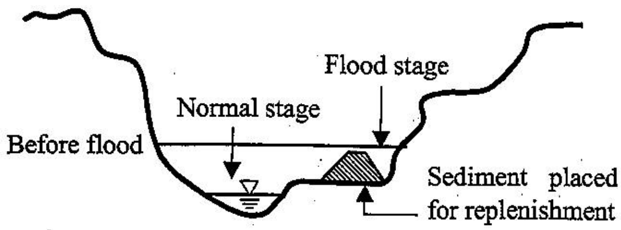


Fig.7 Concept of Sediment Replenishment

In the case of the Akiha Dam, replenishment sediment was placed on top of the bed protection works (reinforced concrete structure) constructed in connection with left-bank tailrace construction downstream of the dam. The sediment was placed so that it would begin to be submerged at a flow rate of ca.400 $m^3 \cdot s^{-1}$. The elevation of the embankment made of replenishment sediment was set so that the sediment would be fully submerged up to the top about three times a year (at a discharge of ca.1,500 $m^3 \cdot s^{-1}$). The width of the sediment embankment was ca.28 m, which was determined according to the structure of the bed protection works mentioned above. The length of the bank erosion zone (length in the streamwise direction) was ca.130 m, which was determined by referring between bank erosion length (length in the streamwise direction) and bank erosion width in case of ordinary natural rivers defined by Yamamoto (1994). An embankment slope was finished in 1:1.5.

Sediment replenishment works including excavating at the check dam, haulting and placing on the river channel was carried out during the same period that is selected in usual cases, eg. from March to June which is toward the end of a non-flood period.

Table 2 Rates of Transport of Replenishment Sediment Placed Downstream of Akiha

Year	Flood	Maximum discharge rate ($m^3 \cdot s^{-1}$)	Volume of sediment transported downstream (m^3)
1998	6.19 - 7.4	2,261	2,500
Ca. 10,000 m^3 of sediment placed downstream of Funagira Dam	8.26 - 9.4	515	7,500
	9.16 - 9.20	1,045	
	9.21 - 10.30	3,078	
Subtotal			10,000
1999	5.27 - 5.29	929	3,800
Ca. 20,000 m^3 placed downstream of Akiha Dam	6.24 - 7.19	4,455	7,700
	9.15 - 9.17	1,466	10,000
	9.21 - 9.30	1,484	1,200
2000	6.9 - 6.12	577	2,200
Ca. 20,000 m^3 placed downstream of Akiha Dam	6.25 - 7.2	1,152	8,400
	9.11 - 9.25	3,366	12,000
2001	6.19 -	1,303	1,800
Ca. 20,000 m^3 placed downstream of Akiha Dam	8.21 - 8.22	1,411	10,000
	9.10 - 9.11	1,511	3,200
	10.1 - 10.2	996	3,000
Subtotal			63,300
Total			73,300

4.3.2 The Volume and Particle Size Distribution of Replenishment Sediment

The volume of sediment moved from a check dam to the river channel was 300 $m^3$to 25,000 m^3 per year which is usually equal to 0.1% to 10% of the total annual reservoir sedimentation volume.

The particle size distribution of sediment used for replenishment has not been studied sufficiently, but sediment used for replenishment is usually composed mainly of sand and gravel. At some dams, excavated sediment includes small quantities of silt or clay, or even boulders several tens of centimeters in diameter.

4.3.3 Sediment Transport Results

Table 2 shows sediment transport results obtained at the Akiha Dam, determined by photographs and simple survey results. As shown, all sediments introduced as a source of replacement were transported downstream by flood flows of ca.1,500 $m^3 \cdot s^{-1}$ occurring at a frequency of several times a year.

4.4 Downstrean Impact Study

4.4.1 Overview of Monitoring

In general, a study on the influence of sediment removal on the river downstream can be classified into a monitoring study conducted mainly to determine whether or not sediment removal has adverse effects on the physical and biological environments, and a study conducted to determine whether or not sediment removal improves the environment of the river downstream. Both types of study require long-term monitoring.

In the replenishment method of sediment removal, the quantity and quality of sediment to be used can be chosen in advance. To some degree, adverse effects can be avoided or controlled even at the planning stage. In a test conducted to find a way to improve the environment of the river downstream, priority can be given to evaluating the environment-improving effect. Table 3 shows the monitoring items for different dams

Table 3 Monitoring Items for Downstream Replenishment Tests for Different Dams

Name of dam		Akiha	Miharu	Futase	Naga-shima	Ura-yama	Hachi-su	Nibu-tani	Shimo-kubo
Observation of sediment transport process			○		○				
Bedform	Cross-sectional survey	○	○	○	○	○		○	○
	Riffles/pools		○	○		○			
	Natural bare land distribution					○			
Bed Material	Particle size distribution	○	○					○	○
	Tracer survey	○	○		○	○			
	Bed material composition		○			○			
Water quality	Turbidity	○	○				○		
	SS	○	○		○		○		
	DO		○				○		
	COD		○				○		
	BOD		○				○		
	Water temperature		○				○		
	pH		○				○		
	Others	○							
Flora and fauna	Fish	○	○	○	○	○			
	Attached algae	○	○	○	○		○		○
	Benthic organisms	○	○	○	○		○		
	Plants		○	○	○				○
	Others			○	○				
Landscape			○						○

4.4.2 Riverbed Changes Resulting from Sediment Replenishment

No significant riverbed changes in the channel downstream of the dam deemed attributable to the sediments used for replenishment can be identified from the results of annual cross-sectional and profile surveys, and visual inspections. Riverbed changes are strongly related to the maximum discharge rate from the dam. In the case of the Akiha Dam, there was a tendency toward degradation in 1998 when the discharge rate tended to be high, and a tendency toward aggradation in 2000 when the discharge rate tended to be low (Okano *et al.*,2004).

At Miharu Dam, the particle size of the bed material showed a tendency to become smaller. At Shimokubo Dam, sediment raden flows have polished the famous "Forty-eight Stones," which constitute the Scenic Site and Natural Monument "Sanbaseki Ravine" designated by the national government in the 3.8-km-long section downstream of the dam, thereby contributing to the restoration of the scenic landscapes of this tourist destination (Shimokubo Dam Website 2004).

4.4.3 Water Quality Surveys

Turbidity and suspended solids (SS) concentration rose as flood discharge increased. Conversely, turbidity and SS concentration fell as discharge decreased. At Nagashima Dam, SS concentration was measured at locations upstream and downstream of the sediment placement area, but the measurement results did not indicate noticeable differences (Okano *et al.*, 2002).

4.4.4 Biological Surveys

Fishery workers' associations pointed out the possibility of adverse effects of sediment replenishment at the Akiha Dam on fish species, but at that stage, concrete information, such as where adverse effects could occur and to what extent fish species could be affected, was not available (Okano *et al.*, 2003). The number of species and population sizes of attached algae and benthic organisms showed a tendency to decrease temporarily after floods, but they also tended to return to former levels subsequently. The relationship between this tendency and sediment replenishment tests, however, is not clearly understood (Okano *et al.*, 2004).

5 CONCLUDING REMARKS: CHALLENGES FOR THE DOWNSTREAM REPLENISHMENT METHOD

5.1 Replenishment and River Management

If fine sediment is placed in a sediment placement area for the purpose of replenishment, the sediment is expected to be transported downstream upto somewhere near the river mouth without any changes in the bed elevation and the bed slope. Coarse sediment, however, would not be transported downstream because the present bed slope is not steep enough. It is thought that coarse sediment can only be transported downstream by stronger flood flows from an upper reach of the river at a higher bed elevation with a steeper bed slope. In contrast, fine sediment could be smoothly transported downstream, but in many cases fine sediment is not used for replenishment because of the need to prevent the occurrence of high turbidity.

In order to carry out the sediment replenishment on a larger scale dealing with both coarse and fine materials, it is necessary to establish an institutional cooperative framework between reservoir sedimentation management and downstream river management and discuss quantity and quality of sediments to be used for replenishment.

5.2 Reduction of Transportation Cost

Sediment replenishment for the purpose of keeping a dam functional needs to be performed semipermanently. If the downstream replenishment method is to be used as a means of reservoir sedimentation control, cost reduction is an important consideration. It is necessary to develop new technologies to enhance transportation efficiency. In Japan, for example, transporting on a reservoir water surface or capsule pipeline systems are under planning.

5.3 Downstream Environment Monitoring and Social Acceptance

The downstream sediment replenishment method is currently being field-tested at a number of dams, but so far not enough knowledge has been accumulated about its influence on lives in rivers and coastal areas. The authors think that the only way to gain necessary knowledge is to conduct a monitoring study on changes in the physical environment of the river downstream and their influence on various forms of lives.

In order to put the downstream sediment replenishment method to practical use, it is also important to share information in an open forum with the people concerned in the same river basin, such as fishery workers' associations and environmental groups, and endeavor to make the method socially acceptable.

ACKNOWLEDGMENT

This paper is based on data provided by the management offices of the dams mentioned herein besides the works cited in the References section. The authors would like to express their appreciation for that generous assistance.

REFERENCES

Fujita, K., Uda, T. and Hattori, A., 1995, Concept of "effective particle group" for analysis of sediment budget in a river system (in Japanese), *Civil Engineering Journal,* 37-12, pp.33-39

Japan Dam Association, 2003, *Dam Yearbook* (in Japanese)

Japan Water Agency, 2004, *Shimokubo Dam Website*

Ministry of Construction (Development Division, River Bureau) and Public Works Research Institute (Hydraulic Engineering and Water Resources Division), 1999, Study on dam reservoir sedimentation management (in Japanese), *Study report on a theme designated under the* 1999 (53rd) *MOC research program, Ministry of Construction,* pp.13-1-23

Okano, M., Umeda, M., Tanaka, N. and Yokomori, G., 2003, Determination of the behavior of fine sediment transported into a dam reservoir during flood and its application to reservoir sedimentation management (in Japanese), *Proceedings of River Engineering*, JSCE, Vol. 9, pp. 73-78

Oya, M., Sumi, T. and Kamon, M., 2002, Characteristics of dam reservoir sedimentation: determination and applications (in Japanese), *Journal of Japan Society of Dam Engineers*, 12(3), pp.174-187

Sumi, T., 2003, Reservoir sedimentation management in Japan, *Proceedings of the session "Challenges to the Sedimentation Management for Reservoir Sustainability," The* 3rd *World Water Forum*, pp. 123-142

Suzuki, T., 1998, Need for early sedimentation control and sediment replenishment test on the Tenryu River (in Japanese), *Kasen*, pp. 18-23

Yamamoto, K., 1994, Chuseki Kasen Gaku (Alluvial River Engineering) (in Japanese), *Sankaido*, pp. 173-182