Sediment Flushing Efficiency and Selection of Environmentally Compatible Reservoir Sediment Management Measures

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Abstract

The Japanese rivers are characterized by high sediment yield in comparison with other countries due to the topographical, geological and hydrological conditions. This has consequently caused sedimentation problems to many reservoirs constructed for water resource development or flood control purposes. Among them, a significant amount of sediment storage capacity, which was usually designed to accommodate in 100-years, has already been lost because of sedimentation proceeding faster than expected. Since 1980s, when the need for a reservoir safety check on sedimentation was recognized, Japanese dams above a certain size were obliged to regularly conduct sediment investigation. A lot of valuable data collected by these investigations have provided so much knowledge on reservoir sedimentation management.

The necessity for the reservoir sediment management in Japan can be summarized in the following three points: 1) to prevent the siltation of intake facilities and aggradations of upstream river bed in order to secure the safety of dam and river channel, 2) to maintain the storage function of reservoirs, and realize sustainable water resources management for the next generation, and 3) to release sediment from dams with an aim to conduct comprehensive sediment management in a sediment routing system. Which point gains importance depends on each dam and each river; however, it is necessary for every dam to recheck the need for sediment management.

Sediment management approaches are largely classified into the following techniques: 1) to reduce sediment transported into reservoirs, 2) to bypass inflowing sediment and 3) to remove sediment accumulated in reservoirs. In Japan, in addition to conventional techniques such as excavation or dredging, sediment flushing and sediment bypass techniques are adopted at some dams: e.g. at Unazuki dam and Dashidaira dam on the Kurobe river, and at Miwa dam on the Tenryu river and Asahi dam on the Shingu river, respectively. These dams practically using such techniques are focused on as advanced cases aiming for long life of dams.

The problems to promote such reservoir sedimentation management in future are 1)Priority evaluation of reservoirs where sediment management should be introduced, 2)Appropriate selection of reservoir sediment management strategies and 3)Development of efficient and environmental compliance sediment management technique. Especially, when the sediment management measures are selected, it is necessary to consider those environmental effects in the river in the advanced country including Japan. In that case, development of the technique that minimizes the minus influences such as the water quality change caused by the sediment discharge and maximizes the plus influences such as the recovery of the sediment routing system is demanded.

In this paper, the promotion strategy of future reservoir sediment management including such an environmental issue is discussed.

Keywords: *Reservoir sedimentation, reservoir sedimentation management, sustainable water resources management, comprehensive sediment management in the sediment routing system, sediment flushing, sediment bypass, environmental assessment, flushing efficiency*

1. Introduction

The sediment yields of the Japanese rivers are high in comparison with other countries due to the topographical, geological and hydrological conditions. This has consequently caused sedimentation problems to many reservoirs constructed for water resource development or flood control purposes. Under such circumstances, studies on estimation of sediment volume and countermeasures for sedimentation have been conducted since long time ago.

Currently, the reservoir sedimentation management in Japan is embarking on new stages from two points of view. One is, in contrast to the emergent and local conventional countermeasures such as dredging and excavation, the active promotion of introduction of sediment flushing using sediment flushing outlets and sediment bypass systems, which aim at radically reducing the sediment inflowing and deposition. Unazuki dam and Dashidaira dam on the Kurobe River, and Miwa dam on the Tenryu River and Asahi dam on the Shingu River are, respectively, advanced examples of using sediment flushing and sediment bypass techniques, which are placed as permanent measures for sedimentation at dams. The other is, considering a sediment movement zone from mountains through coastal areas, the initiation of a comprehensive approach to recover a sound sediment circulation in the sediment transport system.

However, these advanced techniques for sediment management aiming for long life of dams have only been applied to a limited number all over the world, and therefore continuous study is required. It is also important to solve the social issues, such as consensus building on the need for sediment management throughout the basin people, establishment both of legal system and cost allocation system.

In addition, when the sediment management measures are selected, it is necessary to consider those environmental influences in the river in the advanced country including Japan. In that case, development of the technique that minimizes the minus influences such as the water quality change caused by the sediment discharge and maximizes the plus influences such as the recovery of the sediment routing system is demanded.

In this paper, the promotion strategy of future reservoir sediment management including such an environmental issue is discussed.

2. Necessity of Reservoir Sedimentation Management in Japan

(1) Present State of Sedimentation Problems

Modern development of dams in Japan goes back to approximately 100 years ago. The original targets were mainly the utilization of water for water supply and agriculture purposes. With subsequent economical development, however, several other targets were added to dam development, such as hydropower generation, industrial water use and flood control for mitigating flood damage in the developed cities on the downstream flood plain. At present, the multi-purpose dams make up the majority of the Japanese dams. Approximately 2,730 dams over 15 meters in height have been constructed so far in Japan, but the total reservoir storage capacity is only 23 billion m^3.

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. And, from a geological point of view, there are two large faults, the Median Tectonic Line and the Itoigawa - Shizuoka Tectonic Line, where weathering is proceeding in particular (See Figure 1). Weathering is also seen

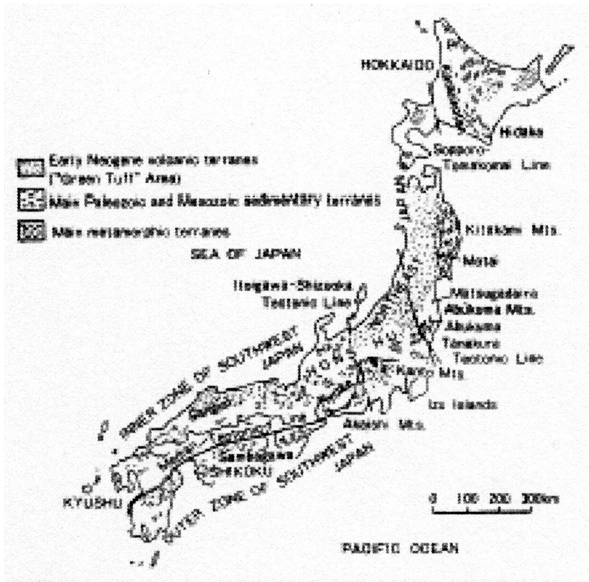

Figure 1 Geology in Japan

in many other regions. 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.

Reservoir sedimentation problems in Japan originated with siltation at power plant intakes of the small-scale hydro projects on the mainstream, and then scoring gates used to be set up as a countermeasure. Later, with sedimentation proceeding at middle-scale dams, the increased flood risk caused by sedimentation at the upstream channel of reservoirs became an object of public concern, and the importance of sedimentation management was recognized on a nationwide scale. In the case of the intake facilities of the run-of-river hydropower projects, necessary storage capacity can be secured without difficulty. However, in case of dams for power generation or those for water utilization and flood control, maintaining storage capacity becomes a major issue.

In Japan, sedimentation was taken into account by design sedimentation depth to calculate the silt pressure on dam body in the early years. Later, the idea of sediment storage capacity was specified, for the first time, in the Manual for River Works in Japan made by the Ministry of Construction in 1957. According to the specifications, multi-purpose dams were so planned and constructed as to secure commonly 100 years' design sediment storage capacity in addition to active storage capacity. In case of estimating design sediment storage capacity, various proposed equations (such as on the basis of topography, geology or reservoir capacity) and the actual sedimentation records of neighboring dams or erosion control dams have been referred. However, in some cases, because the amount of inflowing sediment was assumed to be significantly large, sediment storage capacity of less than 100 years (e.g. 30 or 50 years, etc.) was compelled to be used. And in other cases, where 100 years' design sediment storage capacity was able to be secured, the actual sediment yield largely surpassed the originally estimated sediment yield. Consequently, more sediment has already accumulated than the design sediment yield and active storage capacity is decreasing year by year.

(2) Analysis of Sedimentation Data

In Japan, following the widespread recognition of sedimentation problems, all dams having a storage capacity over 1 million m^3 were obliged to report sediment condition to the authority every year since 1980s. As of 2003, from 922 dams accounting for approximately 1/3 of all dams in Japan, annual changes in sedimentation volume and the shape of accumulated sediment were reported. It is probably only Japan that established such a nationwide survey system, and such accumulated data is regarded as considerably valuable records on a global basis.

Figure 2 is the "Sediment yield potential map of Japan" that is made by GIS (Geographical Information System) by using the reservoir sedimentation records and existing geographical features and geological data. The topographic data used here is the "Relief (altitude difference of the highest point and the lowest point in the mesh)" and the "Average altitude" calculated by the "digital national land information" of secondary mesh (about 100km²) and, in addition, "Relief degree" that considers the distribution of the "Relief".

Regarding geological data, the geologic division decided by hardness of the rock and crack development frequency in consideration of the kind and formation ages of the rock of the basin and the difference of the resistance to the erosion and the collapse etc. Figure is presumption of the specific sediment yield volume obtained thus. Quite a lot of sediment yield volumes were recorded up to several hundreds to thousands m^3/km^2/year in Japan and it is understood that a high rate area is coincided with the Median Tectonic Line and Itoigawa-Shizuoka Tectonic Line by comparing Figure 1.

Figure 3 shows the relationship between reservoir sedimentation rate and years after dam completion. Here, the sedimentation rate is calculated using sedimentation volume to gross storage capacity. Concerning the dams constructed before World War II (ended in 1945) and used for more than 50 years, sedimentation proceeded in the range from 60 to beyond 80 % in some hydroelectric reservoirs. Likewise, for the dams constructed approximately between 1950 and 1960, or from the postwar years of recovery through the high economic growth period, and used for more than 30 years, sedimentation rates beyond 40 % were found in many cases. The influence of sedimentation in those hydroelectric reservoirs depends on the type of power generation. Following this period, meanwhile, large numbers of multi-purpose dams gradually came to be constructed. This type of dams does not have high sedimentation rates compared to the hydroelectric type, though, the rates of 20 to beyond 40 % were found in some dams. Since maintaining storage capacity is directly linked to maintaining the function of dams such as flood control, the influence of sedimentation in the multi-purpose reservoir becomes large.

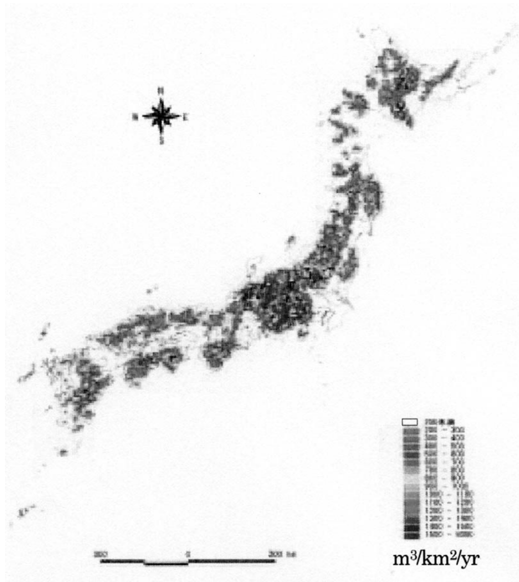

Figure 2 Sediment yield potential map of Japan

Figure 4 shows the relationship between the annual storage capacity loss and the gross storage capacity. The annual storage capacity loss generally decreases with increase in the gross storage capacity and the reservoir life is extended. Figure 5 shows the relationship between the annual storage capacity losses and specific storage capacity (mm), which is defined as ratio of gross storage capacity to catchment area. Many multipurpose dams have specific storage capacities of 50 to 1000 mm and annual storage capacity losses of approximately 1.0 to 0.1 %. In other words, it is noted that the reservoir lives to the gross storage capacities are approximately 100 to 1000 years. On the other hand, in some cases of the hydroelectric dams constructed on the main streams, the catchment areas to the storage capacities are usually very large and the annual storage capacity losses are extremely high.

(3) The Need for Reservoir Sedimentation Management

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 routing system, to release sediment from dams.

The point in 1), as stated above, became major con-

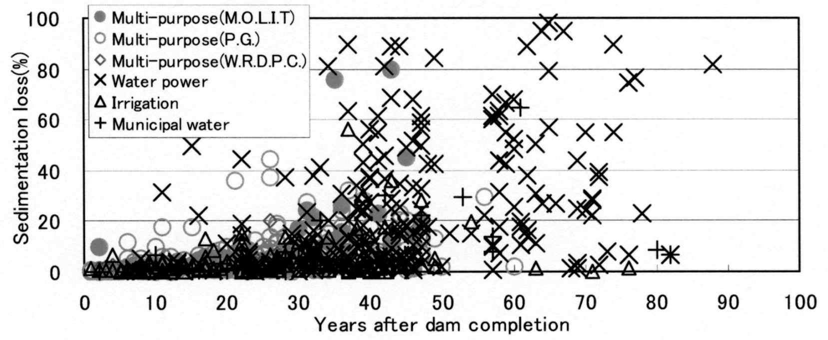

Figure 3 Relationship between reservoir sedimentation rate and years after dam completion

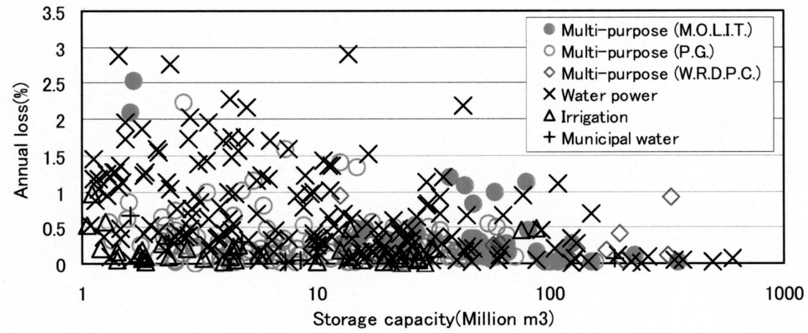

Figure 4 Relationship between annual storage capacity loss and gross storage capacity

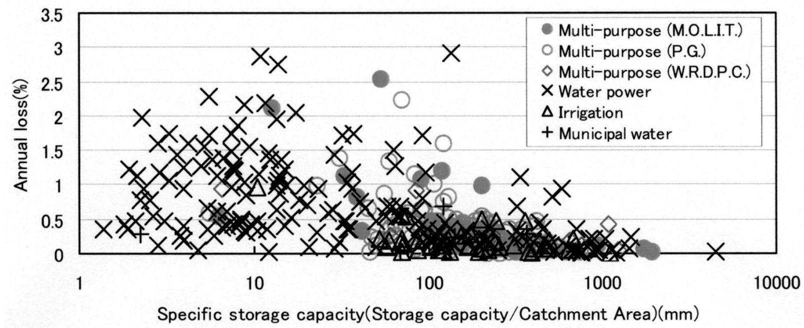

Figure 5 Relationship between annual storage capacity loss and specific storage capacity

cerns 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 Figure 3, the reservoirs in Japan 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 recent social changes in environment-conscious trend and an era of low-growth economy, it seems to be difficult to promote new development at the same pace as before.

Here, an average annual capacity loss rate that is obtained by the annual sedimentation survey described in Figure 3 is 0.24 %/year and it is very high up to 0.42 %/year in Chubu region along the Tectonic Lines where a large amount of sediment is produced in the catchment.

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 channel, oversimplification of river channel, and retreat of shoreline due to the decrease in sediment supply to the coast.

In Japan, Sabo (Erosion and Sediment Control) Plan has been developed from the viewpoint of prevention of sediment disasters such as debris flow. According to this plan, a reference point was set at the exit of the area where sediment was produced in the upstream basin of a river, and the construction of erosion control dam was carried out to control the dischargeable amount of sediment to the downstream region; however, the amount of sediment transported to the downstream region including reservoir area was beyond the scope of the plan.

On the other hand, under the comprehensive sediment management in which the water system is considered consistent, reference points are set at each point, including storage dam and alluvial fan area, in addition to the area of sediment production. Sediment budget at each point is figured out and then a proper amount of sediment to be transported in future is determined on both normal time basis and flood time basis. The important thing here is to focus on the quality of sediment (grain size) as well as the amount, and to recognize the need for the linkage between water management and sediment management considering the indispensability of water for sediment transport.

Following a recommendation by River Council of Japan in 1997, this comprehensive sediment management is now being advanced earnestly. 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. For storage dams, sediment bypass or sediment flushing outlets are also progressively added in order to reduce sedimentation and accelerate sediment discharge to the downstream and, at the same time, an attempt to return the excavated and dredged sediment to the downstream river has been undertaken. The influence of storage dams on the sediment routing system is extremely huge, and therefore it is highly meaningful to reduce sediment trap there by means of appropriate sediment management.

As stated above, reservoir sediment management is an unavoidable issue in Japan. The level of importance depends on each dam and water system, and the establishment of techniques to trap less transported sediment and discharge as much as possible to the downstream is required. The next section describes the present situation and future issues on reservoir sedimentation management in Japan.

3. Reservoir Sedimentation Management in Japan

Sediment management in reservoirs is largely classified into the three approaches: 1) to reduce sediment inflow to reservoirs. 2) to route sediment inflow so as not to accumulate in reservoirs, and 3) to remove sediment accumulated in reservoirs. Figure 6 shows how sediment management is undertaken and classified in Japan. In Figure 7, dams in the Japanese whole country were plotted by the parameter of the turnover rate of water (CAP/MAR=Total capacity/Mean annual runoff) and sediment (CAP/MAS=Total capacity/Mean annual inflow sediment). It is thought that the selected sediment management measures are changed by these two parameters. This is described later.

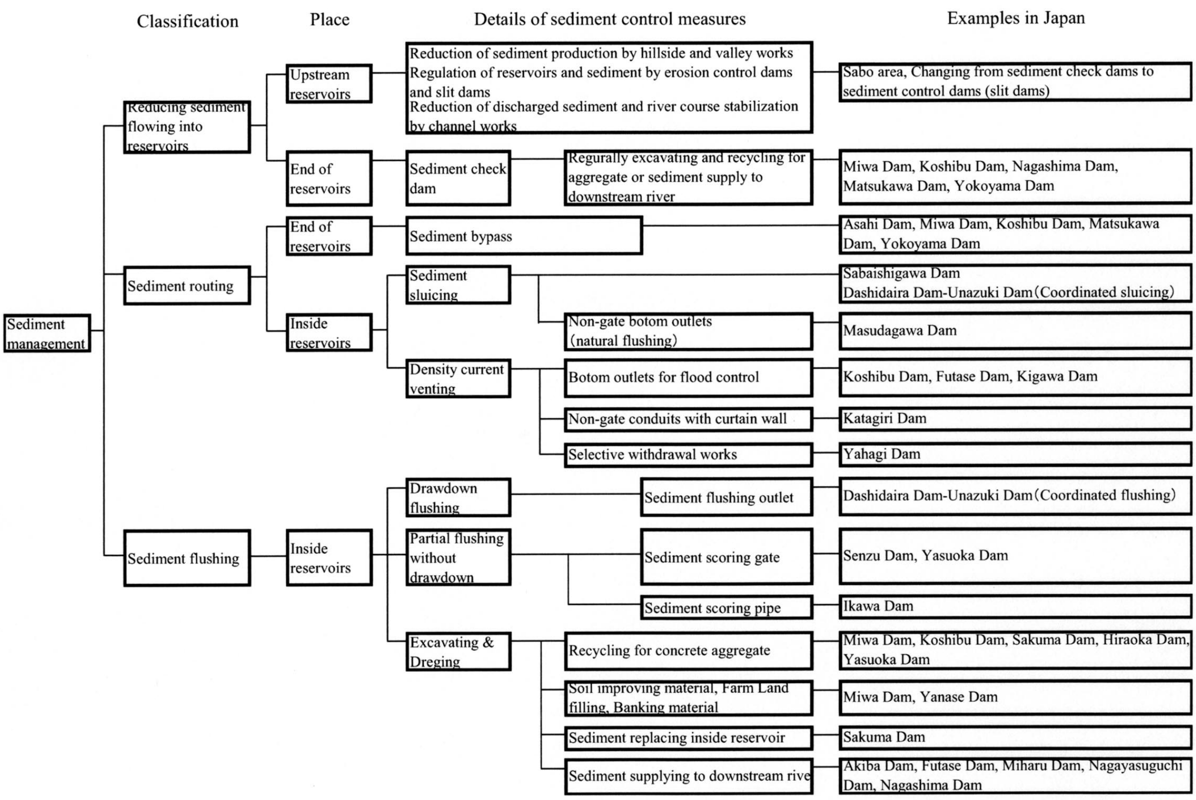

Figure 6 Classification of Reservoir Sedimentation management

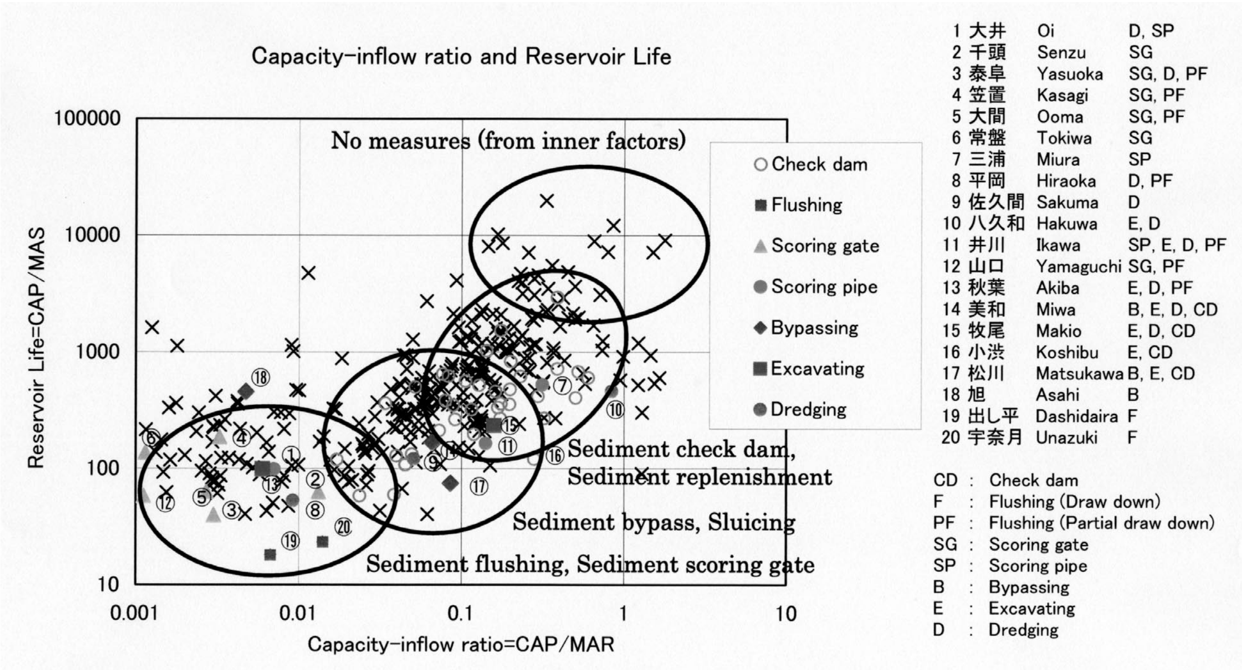

Figure 7 Representative sediment control examples in Japan
(Relationship between capacity-inflow ratio and reservoir life)

(1) Reduction of Sediment Inflow into Reservoirs

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. Some other factors are also contributing to an increase in sediment yield: Management system is complicated because the boundaries between national forest land and private property are intricate; natural hardwoods have been intentionally converted to softwoods of commercial value; and forest road construction has been implemented for forest management work. Especially some mountain streams, where landslides frequently occur and a large amount of sediment is produced, are designated as the areas for erosion and sediment control, and countermeasures are taken to control sediment discharge, such as the construction of erosion control dams. 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, an attempt to trap sediment using check dams is found effective for the reservoirs where bed load of relatively coarse grain size accounts for a large percentage of sediment inflow, so recently many dams have proceeded in constructing them. In this technique, a low dam is so constructed at the end of reservoir as to deposit transported sediment, and then the deposited sediment is regularly removed. The accumulated sediment can be excavated on land except for flood time, and the removed sediment is 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 and Transport.

Figure 8 shows the longitudinal profile of Koshibu reservoir. The upstream check dam (overflow section: 65 m wide x 10 m high) which was constructed in 1978, is shown in Photo 1, and a private plant for taking aggregate in Photo 2.

Recently, sediment replenishment tests have been carried out in some dams. Trapped sediments in the sediment check dam upstream of the reservoir are excavated and transported to the downstream of the dam. These sediments are put on the downstream river channel temporarily and washed out by the natural flood flows. Nagashima dam, Miharu dam, Akiba dam, Futase dam, Shimokubo dam, Urayama dam, Hachisu dam, and a Nunome dam etc. are typical cases. Moreover, there is an example of combining with the environmental flushing flow such as in the Managawa dam and the integrated improvement of the river environment is expected by the flood disturbance and the sediment supply.

(2) Routing of Sediment Inflow into 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, the following techniques are adopted: 1) sediment bypass by directly diverting sediment transport flow, and 2) density current venting by using a nature of high-concentration sediment transport flow.

In Japan, it is sediment bypass tunnels that have

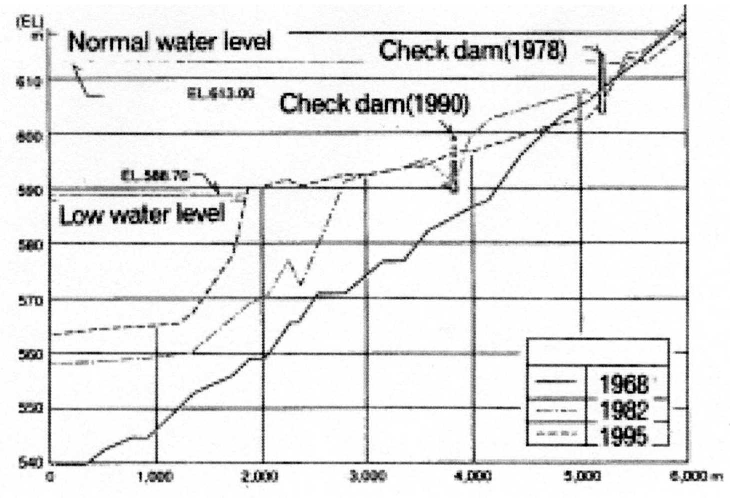

Figure 8 Longitudinal profile of Koshibu reservoir

Photo 1 Upstream sediment check dam of Koshibu dam (Constructed in1978)

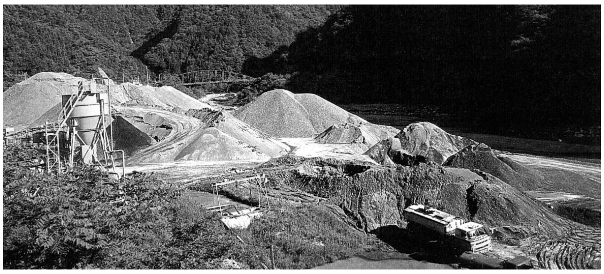

Photo 2 Private plant for taking aggregate

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. Nunobiki dam is an initial example of the bypass tunnel in Japan. The reservoir to which longevity is estimated to be only 25 years without bypass is prolonged to over 1000 years. Recently, the effect is clarified since the bypass completion of the Asahi dam, and the planning and construction of the bypass have been advanced also in the Miwa, Matsukawa and Koshibu dam.

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.

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.

On the other hand, it is possible to reduce the impounded water volume of the reservoir by greatly draw downing and emptying during a certain period of the flood season with a lot of sediment inflow to promote the sediment passing thorough the reservoir. These operations are generally called sediment sluicing and there are a lot of adoption cases in China and Taiwan. The Sabaishigawa dam where reservoir water level is regularly drawn down in the snow-melting season corresponds to this case in Japan.

Table-1 Sediment Bypass Tunnels in Japan and Switzerland (Sumi 2004)

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
Nunobiki	Japan	1908	Hood	2.9×2.9	258	1.3	39		
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 = 21.0m²	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

In addition, the request to the flood control has risen relatively in the river basin. Then, the number of dams only for the flood control that has the gateless conduit which can also sluice inflow sediment during flood events increases. Figure 9 shows an example of the Masudagawa dam. The reservoir is emptied through year and it is paid attention as a dam without reservoir sedimentation.

If such an idea is advanced further, the idea of "Separated dam project for the flood control and the water use" where the dam only for the flood control is constructed in the main stream without sediment management and the water use capacity is secured in the tributary stream separately is worth the examination, too. This is an examination problem in relation to the fact of rearranging capacity mutually so that it may become easy to manage reservoir sediment not only in the new construction project but also in the reorganizing project whole in the river basin in the future.

(3) Removal of Sediment Accumulated in Reservoirs

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, 2) dredging sediment accumulated at the middle and downstream regions, and 3) flushing out sediment with tractive force. 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, manpowered techniques such as excavation and dredging are hard to be adopted because of problems involving transportation and dump site. In such a case, however,

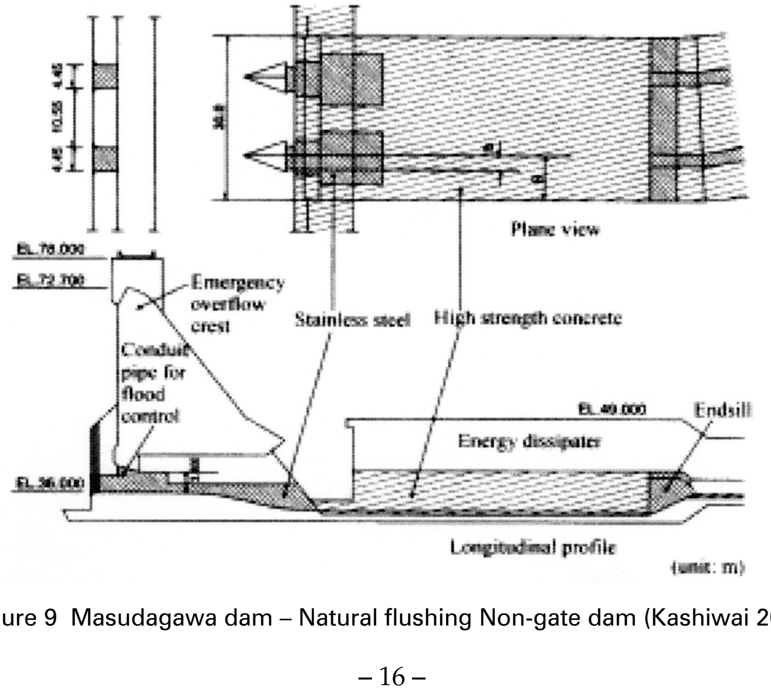

Figure 9 Masudagawa dam – Natural flushing Non-gate dam (Kashiwai 2000)

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, sediment flushing is implemented in coordination of upstream and downstream dams (coordinated sediment flushing).

Sediment flushing is performed at many dams all over the world, as shown in Table-2. The necessary conditions for dams' adopting sediment flushing are; they are equipped with bottom outlets (sediment flushing outlets) through which reservoir level is drawn down and flowing water can be discharged in an open channel during sediment flushing; sufficient amount of water is secured for a series of operations of reservoir level drawdown, open channel discharge and reservoir refill. Sediment flushing is considered as an extremely effective technique for discharging sediment in terms of harnessing tractive force in natural river channel. However, when this technique is introduced, an extensive study is required in the planning stages, considering such conditions as inflow, sediment inflow, storage capacity, grain size distribution and reservoir operation. At the same time, it is also required to consider measures concerning environmental problems under sediment flushing process.

Moreover, HSRS (Hydro-suction Sediment Removal System) where can intake and discharge sediment using only the water level differences without the mechanical force is developed in some types in recent years. There are stationary and movable types in the system. In case of the stationary type, establishment of the measures to move sediment to the system neighborhood in the reservoir and, in case of the movable type, securing enough operation time corresponding to the target sediment volume to be discharged during a year and a safe work environment are problems to be solved.

4. Promotion strategy of reservoir sedimentation management

The problems to promote such reservoir sedimentation management in future are 1) Priority evaluation of reservoirs where sediment management should be introduced, 2) Appropriate selection of reservoir sediment management strategies and 3) Development of efficient and environmental compliance sediment management technique.

(1) Priority evaluation of reservoirs where sediment management should be introduced

The World Bank is advancing RESCON project (Reservoir Conservation Project) (Palmieri 2003). It will be thought that reservoir sedimentation problem becomes a key issue while putting the target on the redevelopment project in the future though the World Bank has financed the developing country only to the new construction projects. For instance, when there are several dams in the same water system, estimated each reservoir life when measures are not taken is concretely presented. And, if it is understood that remain-

Table-2 Sediment flushing dams in the World

Name of Dam	Country	Dam completed	Dam Height (m)	Initial Storage Capacity (CAP) (million m^3)	Mean Annual Sediment Inflow (MAS) (million m^3)[1)]	1/(Mean Annual Runoff) (=CAP/MAR)	Reservoir Life (=CAP/MAS)	Average Flushing Discharge (m3/s)	Flushing Duration (hrs)	Flushing Frequency (1/ yr)
Dashidaira	Japan	1985	76.7	9.01	0.62	0.00674	14.5	200	12	1
Unazuki	Japan	2001	97	24.7	0.96	0.014	25.7	300	12	1
Gebidem	Switzerland	1968	113	9	0.5	0.021	18.0	15	70	1
Verbois	Switzerland	1943	32	15	0.33	0.00144	45.5	600	30	3
Barenburg	Switzerland	1960	64	1.7	0.02	0.000473	85.0	90	20	5
Innerferrera	Switzerland	1961	28	0.23	0.008	0.00018	28.8	80	12	5
Genissiat	France	1948	104	53	0.73	0.00467	72.6	600	36	3
Baira	India	1981	51	9.6	0.3	0.00489	32.0	90	40	1
Gmund	Austria	1945	37	0.93	0.07	0.00465	13.3	6	168	N.A.
Hengshan[2)]	China	1966	65	13.3	1.18	0.842	11.3	2	672	2～3
Santo Domingo	Venezuela	1974	47	3	0.08	0.00667	37.5	5	72	N.A.
Jen-shan-pei[2)]	Taiwan	1938	30	7	0.23	N.A.	30.4	12.2	1272	1
Guanting	China	1953	43	2270	60	1.5	37.8	80	120	N.A.
Guernsey	USA	1927	28.6	91	1.7	0.0433	53.5	125	120	N.A.
Heisonglin	China	1959	30	8.6	0.7	0.6	12.3	0.8	72	N.A.
Ichari	India	1975	36.8	11.6	5.7	0.00218	2.0	2.16	24	N.A.
Ouchi-Kurgan[2)]	Former USSR	1961	35	56	13	0.00376	4.3	1000	2400	N.A.
Sanmenxia[2)]	China	1960	45	9640	1600	0.224	6.0	2000	2900	N.A.
Sefid-Rud[2)]	Iran	1962	82	1760	50	0.352	35.2	100	2900	N.A.
Shuicaozi	China	1958	28	9.6	0.63	0.0186	15.2	50	36	N.A.

1) Average after dam completion, 2) Sluicing dams

der of the life is very short, the feasible sediment management measures considering economy etc. is concretely proposed.

It will be thought that such an approach is important also in Japan. Especially, when several dams exist in the water system, it is realistically difficult to introduce the sediment management all together from the limit of the budget under the present situation. Then, it is necessary to evaluate priority according to some indices. Then, I want to propose the following three points as an index that evaluates the priority of the sediment management.

The first point is an inner factor concerning the sustainability of the dam, and has two indices. In one, the excess extent (sedimentation speed magnification) at the actual sedimentation speed to the planning speed for a hundred years, and another one is the reservoir life (CAP/MAS) of ahead. Among these, as for the sedimentation speed magnification, about 1/4 in the entire dam where sedimentation volumes are annually investigated is twice or more, and the priority of such a dam is high. On the other hand, if reservoir lives of multipurpose dams in Japan are evaluated, 1000 years or more is 34%, and 500-1000 years is 25%, and 100-500 years is 34%, and 100 years or less is 7%, and 400-500 years is the average. From this, for dams which have below the half of the average reservoir life such as CAP/MAS<200, it is necessary to materialize some sediment management strategies immediately in the future. In this case, if the reservoir life of 1000 years or more which is realized at the Nunobiki dam is made as a target, selection of the applicable measures and evaluation after the project execution become clearer.

The second point is an external factor concerning the continuity of sediment routing system such as the impact degree to the downstream river and an actual environmental deterioration degree there. As for the impact to the downstream river, height of a dam, a turnover rate of the reservoir (1/(CAP/MAR)) and the river extension until the major river is joined become indices. On the other hand, armoring of the river bed, the immobilization of the sand bar, degradation and immobilization of the channel, decreasing the gravel bed surface area and increasing the grove area in the actual downstream river channels become indices as an environmental deterioration degree of the downstream river.

The third point is a technical difficulty viewpoint when the sediment management of each dam is introduced. Height of dam, the turnover rate of the reservoir, the reservoir extension, and the average annual sedimentation volume generally become indices though technical difficulty is different depending on the sediment management measures.

Priority can be evaluated comprehensively by combining the above-mentioned three points and putting the appropriate weight for each index. As the trial, the priority was evaluated for the seven existing dams of the Yodogawa river system and the dam where the sediment management strategy should be studied previously became clear.

(2) Appropriate selection of reservoir sediment management strategy

If the dam where priority is high is selected, it is necessary to select a concrete sediment management strategy. In Figure 7, existing sediment management practice dams were specified referring to the parameter of the turnover rate of water and sediment. It is understood that measures actually selected have changed in order of the sediment flushing, the sediment bypass, sediment check dam and excavating, and dredging as CAP/MAR increases (decrease in the turnover rate) roughly. This is because of greatly depending on the volume of water to be able to use the sediment management measure that can be selected for the sediment transport. Here, the quality of sediment (size etc.) and the river environment conditions which may restrict the sediment discharge are not considered.

Here, it is important to clarify the range that the sediment flushing and the sediment bypass that uses the tractive force for the sediment discharge can be applied for selecting the sediment management strategy. Especially, it is a trade-off in the sediment flushing between maximizing sediment discharge and minimizing environmental impact on the downstream river. In a Kurobe river, Dashidaira dam in Japan that is a typical sediment flushing case, the sediment was discharged for the first time in 1991. The sediment flushing of 13 times in total was carried out by June, 2005, and the sediment of six million m3 or more that equaled 2/3 or more of the total reservoir capacities in total was discharged as in Figure 10.

In addition, after completion of Unazuki dam downstream of Dashidaira dam in 2001, a coordinated sediment flushing of these dams have started and the sediment flushing of five times in total and sediment sluicing of four times are executed up to July, 2005. The sediment flushing is executed at the first major flood event every year and the sediment sluicing is done at the successive bigger ones by the similar sediment flushing operation preventing additional sediment deposit in the reservoir.

A present sediment flushing operation in the Kurobe river assumes 'Execute it to maintain a constant bed form without storing sediment in the reservoir as much as possible at the natural flood events between June and August' to be a principle. As a result, the phenomenon of the water quality deterioration because of the sediment flushing at first in 1991 is not seen, and it contributes to the maintenance of the capacity of the reservoir greatly. The rule that executes the sediment flushing at constant frequency so that the interval should not become long according to this natural flood agrees with the finding in Switzerland and France that has longtime results for the sediment flushing, and becomes a good reference to promote the reservoir sedimentation management in the future very much.

Next, it is a very much interest how much efficiencies were obtained by these sediment flushing operations. There are not a lot of dams surveyed in detail

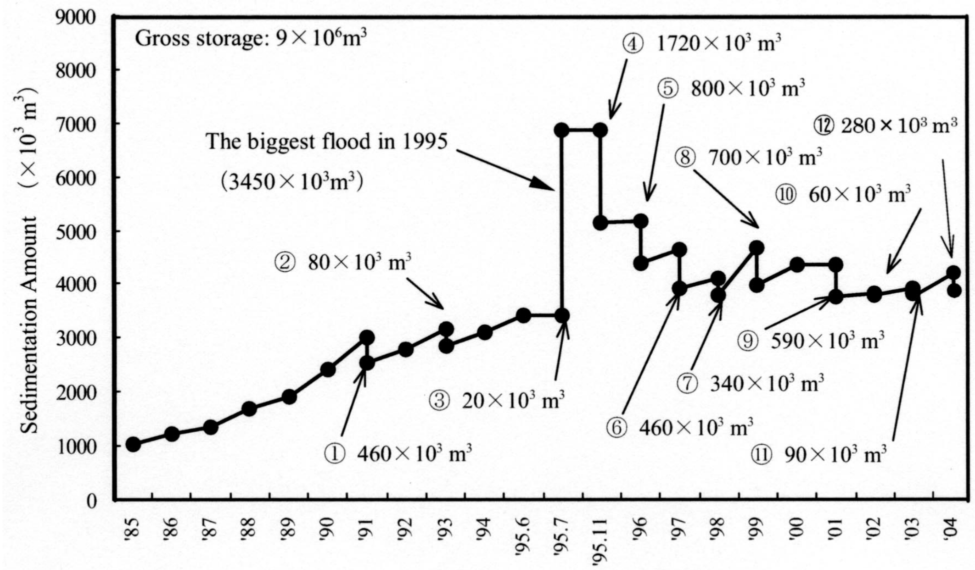

Figure 10 Sedimentation volume change in Dashidaira dam

about usual results among sediment flushing dams listed in Table 2. Then, the relation between the water consumption and the amount of the sediment flushing was shown in Figure 11 about four dams, Dashidaira dam in Japan, Gebidem and Verbois dams in Switzerland and the Baira dam in India, where each flushing result was recorded. Here, the water consumption for the sediment flushing is only calculated during the fully draw down period though the sediment discharge actually starts from fine materials during the reservoir drawdown period and this water volume should be included in the water consumption.

Figure shows sediment flushing efficiency ($F_e = S/W$) calculated by the sediment volume and the water consumption. Among these, the sediment flushing efficiency in Gebidem dam is comparatively high since the sediment flushing is executed with a low flow discharge for a long time. Moreover, in Baira dam flushing efficiency is also comparatively high though there are some fluctuations. On the other hand, since Verbois dam is located at the mainstream of the Rhone River and the sediment flushing is executed with a large amount of water from Lac Leman, the sediment flushing efficiency is not large. In Dashidaira dam, the sediment flushing efficiency is not so high but close to Verbois dam except the sediment flushing after the Big flood in 1997 though there are great fluctuations in the amount of the sediment flushing and the water consumption.

In these four dams, the sediment flushing is strictly

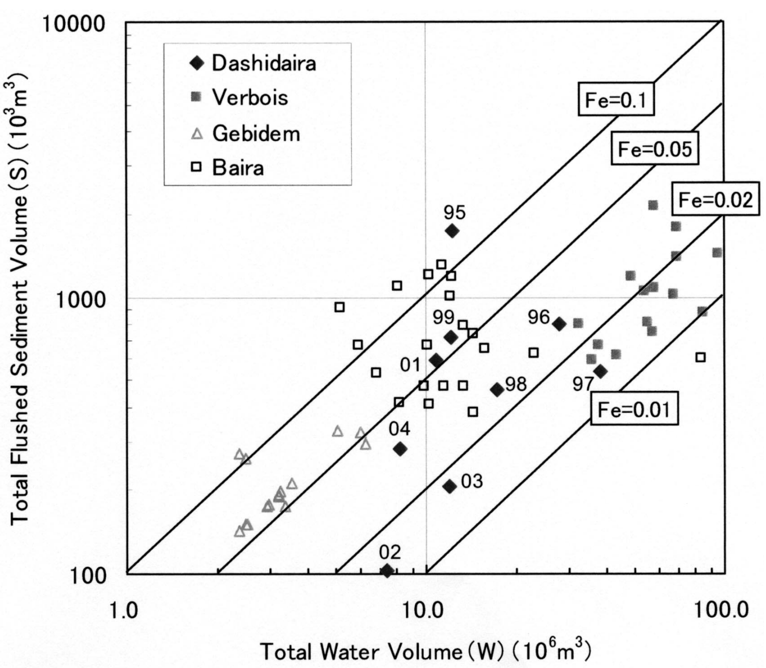

Figure 11 Total water volume and flushed sediment volume in sediment flushing dams

TO DISCHARGE RIVER MAINTENANCE FLOW�

managed in Dashidaira dam and Verbois dam so as not to cause a remarkable water quality changing to the downstream river by maintaining considerably a lot of water compare to the amount of sediment. As a result, in consideration of the downstream river environment, an enough volume of water is required to be used so that the sediment flushing efficiency may come to be suppressed. In the sediment flushing of the Kurobe River, the sediment flushing is executed by securing enough river discharge just after the natural floods and also the additional discharge is recently examined to wash the fine sediment silted in the downstream river channel after the sediment flushing, and thus the sediment flushing is using more volume of water.

Next, the sediment flushing efficiency of other dams is shown in Figure 12. The sediment flushing efficiency is about roughly F_e=0.01-0.15, and it is thought that it is necessary to suppress it to about F_e =0.05 or less when consideration to the river environment is especially necessary. According to the research on the feasibility evaluation of the sediment flushing, a possible range of the sediment flushing can be obtained by the following equation by using the parameter shown in Figure 7 (Sumi 2000). Here, the sediment flushing efficiency and the proportion of the water consumption by the sediment flushing to the mean annual runoff volume (MAR) are defined F_e and β respectively.

$$\frac{CAP}{MAS} > \frac{\frac{CAP}{MAR}}{F_e\left(\beta - \frac{CAP}{MAR}\right)} \qquad (1)$$

In Figure 13(a) and (b), possible range of the sediment flushing in the case where F_e changes to 0.01, 0.02 and 0.05 with the fixed β=0.1, and in the case where β changes to 0.05, 0.1, 0.2 with the fixed F_e =0.2 are shown respectively. Possible ranges are shown in the left side of each line. According to these, the change in F_e mainly influences within the small range of CAP/MAS and even a small turnover rate of the reservoir, e.g. large CAP/MAR, becomes a possible rising of F_e under β constant. If the river environment conservation is considered, possible range of the sediment flushing becomes narrower because it should estimate F_e low. On the other hand, if β can be enlarged, the sediment flushing possibility will extend under the same F_e since the water volume ratio that can be used for the sediment flushing increases. However, β and the original storage purposes of the reservoir is in the relation of the trade-off and it is not possible to adopt a too big value.

It is also necessary to advance the examination of coverage in the sediment bypass as well as the sediment flushing. In this case, it is necessary to estimate the sediment sluicing efficiency that can be achieved in the sediment bypass as well as the sediment flushing efficiency and to study how much water volume can be used for bypassing and how the operation rule can be defined become problems. Though it is necessary to consider the downstream river environment for the sediment bypass, it is thought that it doesn't become a big problem since only it is to pass what flows into the reservoir from upstream basically. The operation results of the sediment bypass are limited, and anyway, it will be necessary to accumulate these data in the future and to advance the examination. Moreover, the verification work is also necessary though sediment sluicing is roughly assumed that its coverage is similar to the sediment bypass.

(3) Development of efficient and environmental compliance sediment management technique

Finally, it is necessary to develop wide sediment management measures other than the sediment flushing and the sediment bypass. Especially, the appropriate sediment management measure to the area where the coverage of sediment bypass and sediment sluicing is exceeded in Figure 7. In this area, the necessity intended for a large amount of sediment can be a little, and the sediment check dam and it's regularly excava-

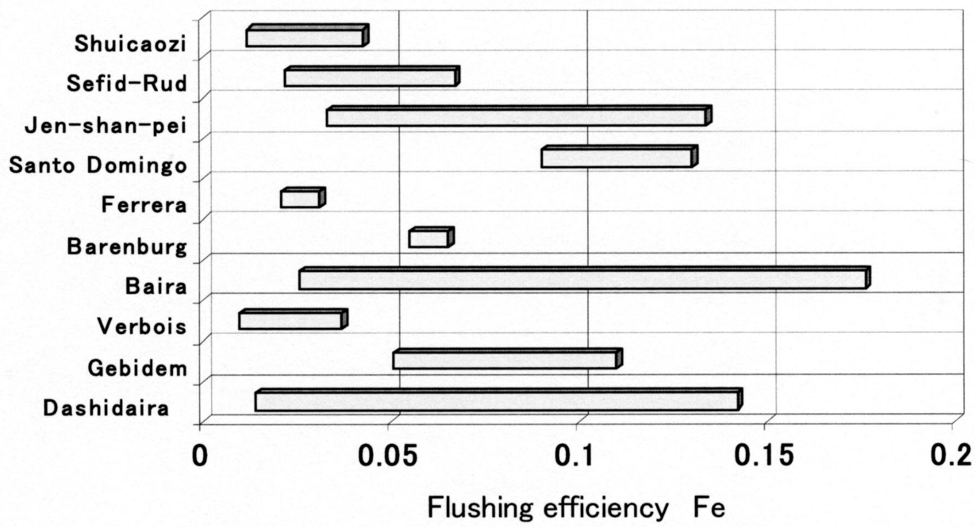

Figure 12 Sediment flushing dams and flushing efficiency

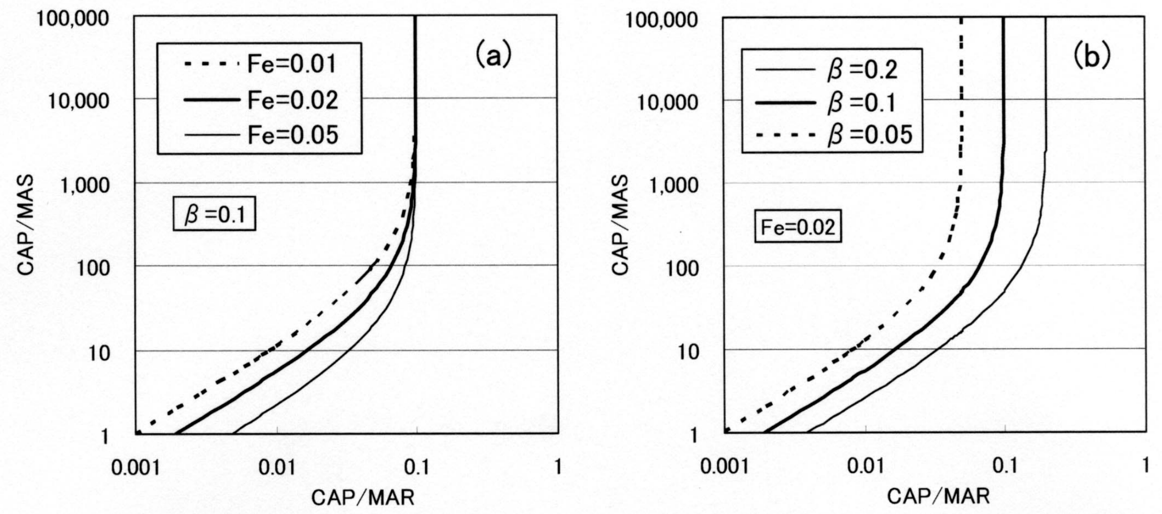

Figure 13 Possible range of the sediment flushing
((a) Proportion of the water consumption to the mean annual runoff volume β is fixed; (b) Sediment flushing efficiency F_e is fixed)

tion can be applicable. However, its effect doesn't continue because of the insufficient maintenance of the check dam in the past and a fundamental solution is hoped for. The sediment replenishment measure is the one of them and the technological development expected in this area is summarized into "Take it", "Transport", and "Discharge" technologies.

Regarding "Take it" technology, more development of the Hydro Suction Sediment Removal System (HSRS) is expected very much. A current problem is thought that the establishment of the way of positively adopting it by promoting such a new technology to the practical level.

Regarding "Transport" technology, it is necessary to examine other transportation methods by the situation as though it is the most natural to use the stream of the river. In that case, the belt conveyer transportation, capsule transport, and hydraulic transportation of slurry, etc. can be applied besides usual trucking if the condition is suitable.

Regarding "Discharge" technology, it is necessary to develop the technology that discharges sediment safely to the river from the view points of a local piling up problem of the coarse sediment in the downstream river channel and the water quality problem of the generation of a high turbid water by the fine sediment and so as not to become the trouble of the sediment management.

5. Conclusions

It has passed for a while being recognized the necessity of the integrated integrated sediment management of the sediment routing system. It is securing of the continuity of the sediment mobility. The reservoir sediment management especially occupies the important position among them. The dam is a property of a society, and it is necessary to aim at sustainable use by appropriate reservoir sediment management without doing to disposable. It is an extremely important point for the idea of "Intergenerational equity" that doesn't turn the load of sediment measures to future generations not to postpone the reservoir sedimentation management. The reservoir sedimentation problem is given to one of the reasons why the new dam construction is criticized. It is likely to come at time when the dam project of the type of the 21st century and the ideal way of the dam management are presented.

Reservoir sedimentation management in Japan is entering a new era. Although there still exist 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 routing 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.

Finally, I'd like to emphasize the technologies for the reservoir sedimentation management is very much paid attention not only in Japan but also in the world. 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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