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Evaluation of Efficiency of Reservoir Sediment Flushing in Kurobe River

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From viewpoint of the comprehensive sediment management in a sediment routing system, it is important to select appropriate sediment management strategy in each storage reservoirs. In the Kurobe River, coordinated sediment flushing operations of Dashidaira and Unazuki dams have been executed since 2001. These flushing operations have advantages on effective use of river water to discharge sediment using sediment erosion and transport phenomena by temporal reservoir drawdown operation.

If examining reservoirs satisfy suitable conditions, this sediment flushing operation is one of the most attractive methods from the point of view of necessary costs and contribution for sediment supply to downstream. Possibility to apply this sediment flushing operation to reservoirs is largely dependent on the sediment flushing efficiency (F_e =S/W) that is defined by the sediment volume (S) and the water consumption (W). The sediment flushing efficiency changes widely by various factors such as configuration of reservoir, elevation of sediment scouring gates, volume and grain size of deposited sediment, discharge rate during sediment flushing, duration time from the start of draw down flushing and so on. In order to forecast the sediment flushing efficiency, it is important to analyze erosion process of sediment in reservoirs.

In this paper, the coordinated sediment flushing of Dashidaira and Unazuki dams in the Kurobe river that is the representative case of sediment flushing in Japan is discussed, and the effective operation and the sediment flushing efficiency are studied through by monitoring of erosion process of deposited sediment in Dashidaira and Unazuki reservoir.

Key Words : *Reservoir sediment management, sediment flushing, flushing efficiency, Kurobe river*

1. APPROPRIATE SELECTION OF RESERVOIR SEDIMENT MANAGEMENT

Sediment management in reservoirs is largely classified into 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. **Fig.1** shows Japanese large dams, higher than 15m and larger than one million m^3 storage volume, that are 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).

In **Fig.1**, existing practice of sediment management in reservoirs can be specified referring to these parameters. It is understood that selected measures 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 the sediment management measures are greatly dependent on the volume of water that can be used for the sediment transport. Here, the quality of sediment (size etc.) and the river environmental conditions which may restrict the sediment discharge are not considered.

It is important to clarify the range that the sediment flushing or 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 impacts on the downstream river.

2. THE COORDINATED SEDIMENT FLUSHING IN KUROBE RIVER

(1) Project outline

Unazuki dam, completed in 2001 by the Ministry of Land, Infrastructure and Transport, and Dashidaira dam, completed in 1985 by the Kansai

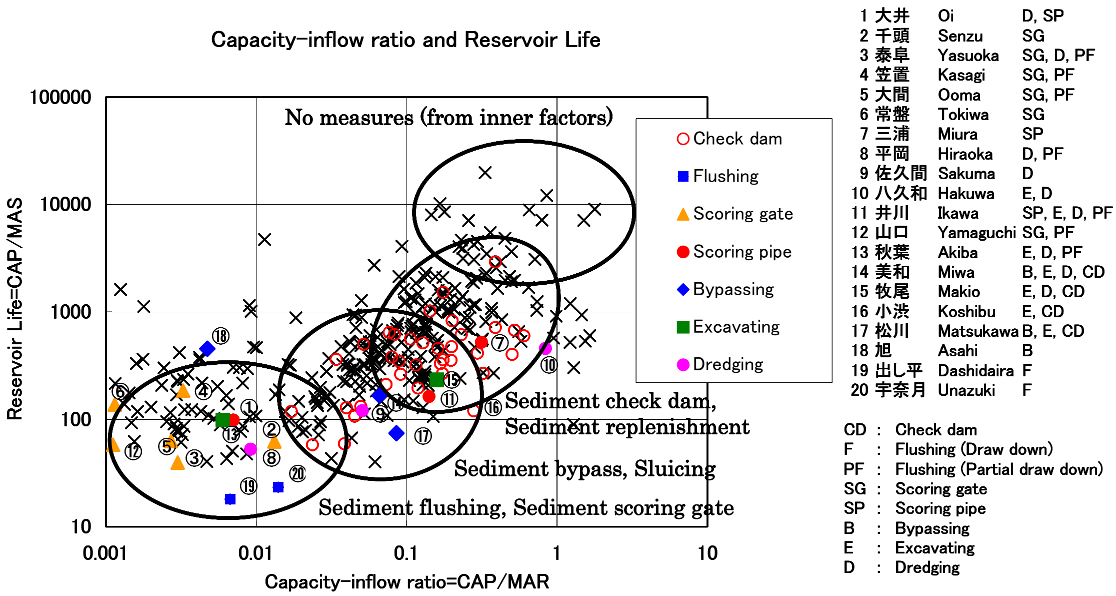

Fig. 1 Representative sediment control examples in Japan (Relationship between capacity-inflow ratio and reservoir life)

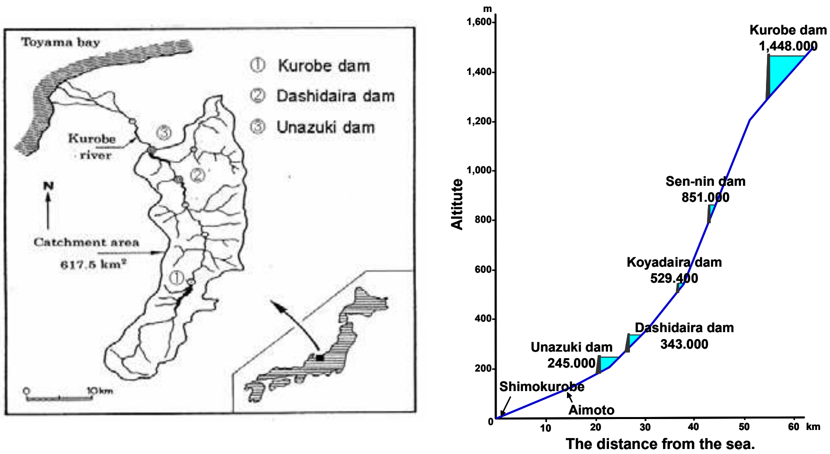

Fig.2 Kurobe river basin

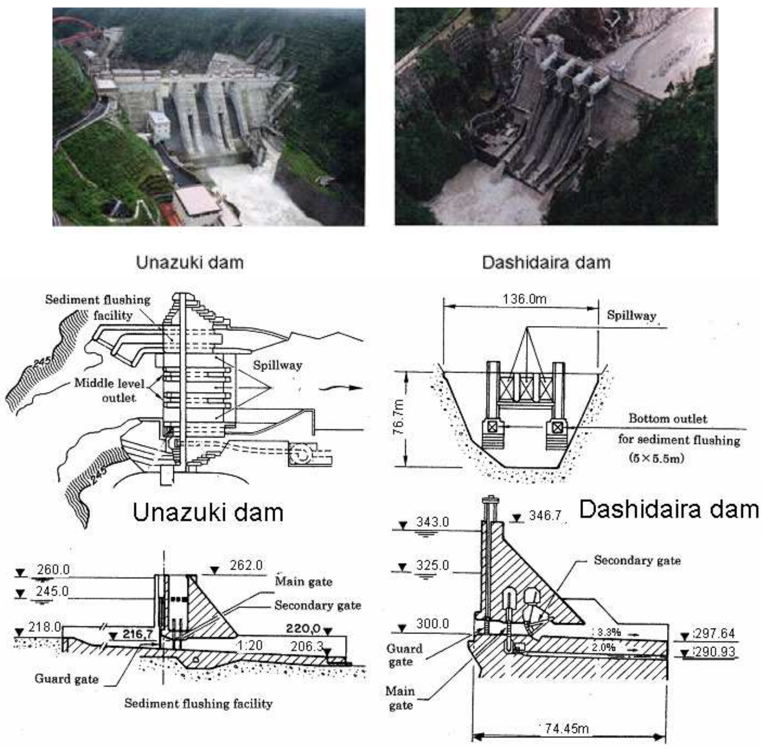

Fig.3 Unazuki dam and Dashidaira dam

Table 1 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

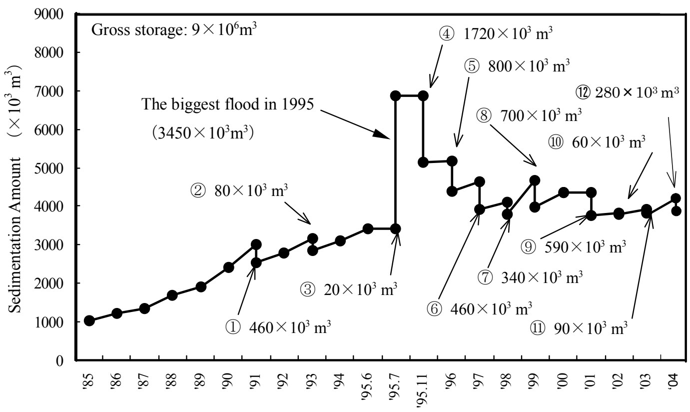

Fig.4 Sedimentation volume change in Dashidaira dam

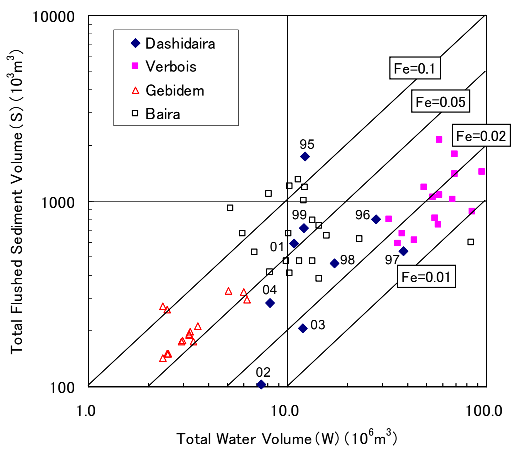

Fig.5 Water volume and flushed sediment volume in sediment flushing dams

electric power co. are both located in the downstream of Kurobe river basin (**Fig.2**). They have been constructed as the first dam with full-scale sediment flushing gates in Japan in place of securing 100 years' sedimentation volume since extremely a lot of sediment volume compare to these possible reservoir capacities was expected (**Fig.3**). Sediment flushing also has the following purposes; 1) sustaining these original functions such as flood control and hydro power, 2) maintaining sediment routing system in the basin. Actually, beach erosion progresses in the downstream coastal areas and the necessity of the sediment supply is extremely high.

In Dashidaira dam, the sediment flushing of 18 times in total have been carried out by July, 2007, and the sediment of 6 million m^3 or more that equaled to 2/3 or more of the total reservoir capacities in total was discharged as in **Fig.4**. In addition, after completion of Unazuki dam, a coordinated sediment flushing of these dams have started and the sediment flushing of 7 times and sediment sluicing of 7 times have been carried out up to July, 2007. 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 same reservoir operation to prevent additional sediment deposit in the reservoir.

At present, sediment flushing operation in the Kurobe river is aiming at maintaining a constant bed form without storing sediment in the reservoir as much as possible by executing at the natural flood events between June and August. As a result, the water quality deterioration such as at the sediment flushing in 1991 doesn't occur recently and it contributes to maintain the reservoir capacity greatly. The present rule that executes the sediment flushing according to the natural flood in a constant frequency so that the interval should not become longer agrees well with the findings in Switzerland and France that have longtime results for the sediment flushing. It becomes a good reference to promote the reservoir sedimentation management in the future very much.

(2) Sediment flushing efficiency

Furthermore, it is a very much interest how much efficiencies have been obtained by these sediment flushing operations. **Table 1** shows sediment flushing dams in the world. Among them, the relation between the water consumption and the amount of the sediment flushing was shown in **Fig.5** 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 fine sediment discharge actually starts from 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 (S) and the water consumption (W). Among them, 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 Rhône River and the sediment flushing is executed with a large amount of water from Lac Léman, the sediment flushing efficiency is not large. In Dashidaira dam, though there are great fluctuations in the amount of the flushing sediment and the water consumption, the flushing efficiency is not so high similarly to Verbois dam except one after the big flood in 1997.

In these four dams, the sediment flushing is strictly managed in Dashidaira and Verbois dams so as not to cause a remarkable water quality change to the downstream river by maintaining considerably a lot of water discharge compare to the amount of sediment. As a result, in consideration of the downstream river environment, enough volume of water is required so that the flushing efficiency may be decreased. In the sediment flushing of 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 out the fine sediment silted in the downstream river channel and thus the sediment flushing needs more volume of water.

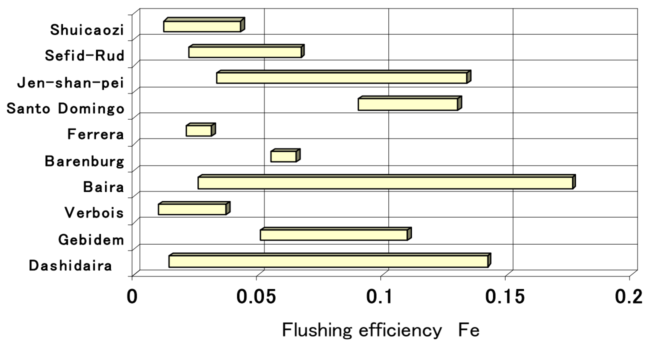

Fig. 6 Sediment flushing dams and flushing efficiency

The sediment flushing efficiency of other dams is shown in **Fig.6**. The sediment flushing efficiency is about F_e =0.01-0.15, and it thought to be decreased to about F_e =0.05 or less when consideration to the river environment is especially necessary.

(3)Feasibility evaluation of the sediment flushing

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 the parameters shown in **Fig.1**. 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.

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

In **Fig.7 (a)** and **(b)**, possible range of the sediment flushing in the case where F_e changes to 0.01, 0.02 and 0.05 under the fixed β=0.1, and in the case where β changes to 0.05, 0.1, 0.2 under the fixed F_e =0.2 are shown respectively. Sediment flushing is feasible in the left side of each line. According to them, 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 increase of F_e under constant β. If the river environmental is considered, possible range of the sediment flushing becomes narrower because F_e should be estimated low. On the other hand, if β can be increased, the sediment flushing possibility will be increased under the same F_e since the water volume ratio for the sediment flushing increases. However, β and the original storage purposes of the reservoir are in the relation of the trade-off and too large β can not be assumed. Even in Dashidaira dam, β are ranging between 0.01 and 0.07 from 2001 to 2007 actually.

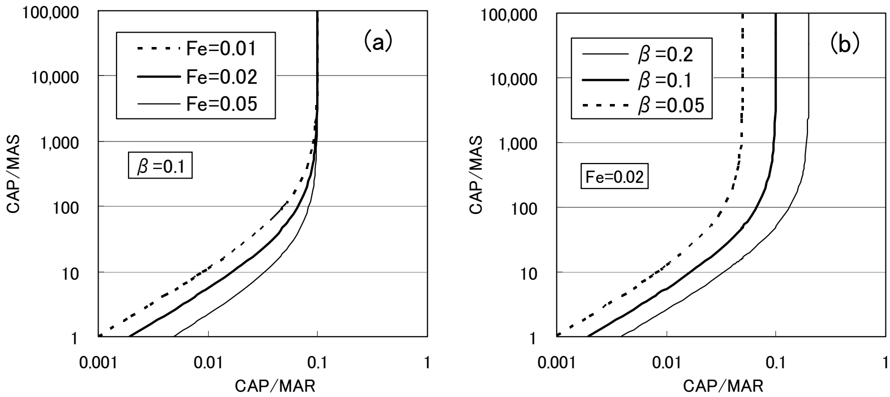

Fig. 7 Possible range of the sediment flushing
((a) Proportion of the water consumption to the mean annual runoff volume β is fixed; (b) Sediment flushing efficiency F_e is fixed)

3. EVALUATION OF THE SEDIMENT FLUSHING EFFICIENCY BY MONITORING OF SEDIMENT FLUSHING PROCESS

As we can find in **Figs.5** and **6**, the sediment flushing efficiency changes widely by various factors such as configuration of reservoir, elevation of sediment flushing gates, volume and grain size of deposited sediment, discharge rate during sediment flushing, duration time from the start of draw down flushing and so on. In order to forecast the sediment flushing efficiency, it is important to understand the erosion process of sediment in reservoirs. **Photo 1** shows erosion process of deposited sediment in Dashidaira reservoir in 2003. We can find that longitudinal and lateral erosions created by river bed degradation and side bank erosion.

Photo 1 Sediment Flushing in Dashidaira Reservoir

Recently, we have conducted field measurements of sediment erosion process with 3D laser scanning technology in Unazuki reservoir (Sumi, Murasaki, Fujinaga, Nagura and Tamaki, 2004, Sumi, Murasaki, Nagura, Tamaki and Imaki, 2005). The 3D laser scanner used for the measurement is shown in **Photo 2**. Side bank erosion process of sand bars formed in the Unazuki reservoir and water surface profiles near by banks have been measured as shown in **Fig.8**. By these data, we could estimate that side bank of the height of 1.0-1.2m was eroded with the speed of 7.5m/hr. Slope of water surface is also estimated as 1/75 and water waves generated by the anti-dune are also observed. Since the bed morphological change where water and sandbars exist together complicatedly can be also measured even in a night time, this technique can be used to understand sediment transport in a reservoir and to estimate the sediment volume flushed out by the operation.

Time and spatial variations of reservoir surface velocities during drawdown and flushing period were also measured by PIV (Particle Image Velocimetry) using CCTV camera and image data processor (Sumi, Murasaki, Taira, Shinbo, Nagura, and Tamaki, 2007). These data can be converted to actual velocities by the 3D laser scanner data. Both reservoir water level and flow velocity changing during the drawdown and flushing period are very much helpful for us to understand sediment erosion and discharge processes from the reservoir.

From the viewpoint of the comprehensive sediment management in a sediment routing system, monitoring of quantity and quality of sediment transport during these flushing events in rivers and reservoirs is also very important. Field observation was carried out to measure suspended sediment concentration (SS) both by the manual sampling and SMDP (Suspended Sediment Concentration Measuring System with Differential Pressure Transmitter), turbidity by a turbidimeter for high sediment concentrations and grain size distribution (Sumi, Baiyinbaoligao and Morita, 2007). Based on these data, movement of the suspended sediment load discharged from Unazuki dam during flood, flushing and sluicing periods were clarified.

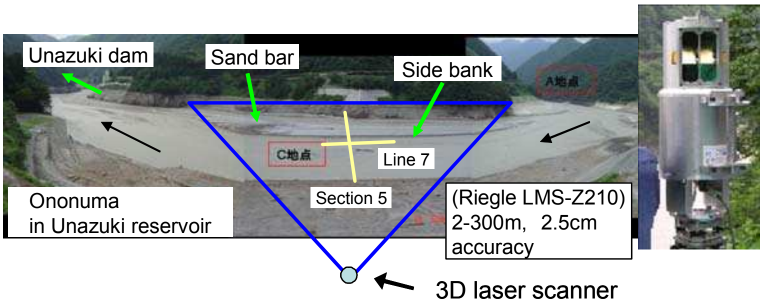

Photo 2 Sediment Flushing in Unazuki Reservoir and 3D laser scanner

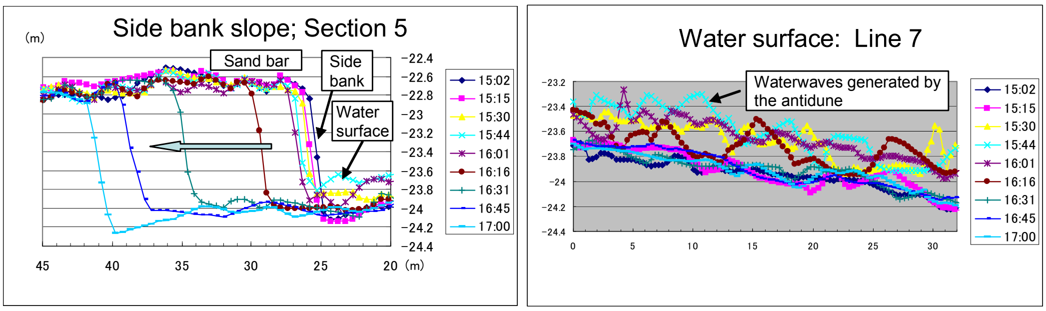

Fig.8 Process of the side bank erosion and water surface changes in the channel

4. CONCLUSION

The conclusions of this paper are as follows.

1) From viewpoint of the comprehensive sediment management in a sediment routing system, it is important to select appropriate sediment management strategy in each reservoir. Existing practices of sediment management in reservoirs can be specified referring to the parameter of the turnover rate of water and sediment.
2) In Kurobe River, coordinated sediment flushing operations of Dashidaira and Unazuki dams have been successfully executed since 2001 and these flushing operations are contributing to sustain these original functions such as flood control and hydro power and to maintain sediment routing system in the basin.
3) Possibility to apply the sediment flushing operation to reservoirs is largely dependent on the sediment flushing efficiency that is defined by the sediment volume and the water consumption. The sediment flushing efficiency changes widely by various factors such as configuration of reservoir, elevation of sediment scouring gates, volume and grain size of deposited sediment, discharge rate during sediment flushing, duration time from the start of draw down flushing and so on.
4) In order to forecast the sediment flushing efficiency, it is important to understand the erosion process of sediment in reservoirs such as longitudinal and lateral erosions created by river bed degradation and side bank erosions.
5) 3D laser scanning technology and PIV are useful to monitor sediment erosion process in a reservoir and to evaluate the sediment flushing efficiency.

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