Comprehensive Sediment Management Strategies in Japan: Sediment bypass tunnels

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Abstract: *This paper presents different sediment management techniques of Japanese dams with focusing on sediment bypass tunnels. In Japan, Miwa dam on the Tenryu River and Asahi dam on the Shingu River are good examples for sediment bypass tunnels where routing incoming sediment directly to downstream reaches. These dams are practically using sediment bypass tunnel successfully to realize a sustainable reservoir management. The paper aims at how to select this technique among several other solutions and introducing monitoring techniques to improve sediment bypass operation. The results show that sediment bypass is suitable for medium size reservoirs with steep original river bed slope and effectively functioned for successful reservoir sediment management. The facility proved its effectiveness in mitigating reservoir sedimentation in Miwa dam and turbidity of river water contributing towards restoration of downstream environment.*

Keywords: *Sediment management techniques, sediment bypass tunnels, reservoir sedimentation.*

1. INTRODUCTION

Reservoir sedimentation is proceeding at dams in the world. Current gross storage capacity in the world is 6,000 km^3 with 45,000 large dams and total storage loss and annual sedimentation rate are about 570km^3 (12%) and 31km^3-year (0.52%-year) respectively. If additional new development projects are not considered, total capacity will be decreased even to less than half by 2100. In many countries, various countermeasures have been implemented to decrease sediment accumulation and loss of storage capacity. They are (i) reduce sediment inflow by erosion control and upstream sediment trapping, (ii) route sediments by sediment sluicing, off stream reservoirs, sediment bypass, and venting of turbid density currents, and (iii) sediment removal by hydraulic flushing, hydraulic dredging or dry excavation. Sediment bypassing and flushing are considered to be as permanent remedial measures.

Worldwide, limited numbers of sediment bypass tunnels have been constructed because of topographical, hydrological or economical conditions. Bypass tunnels, however, have many advantages such that they can be constructed even at existing dams and prevents a loss of stored reservoir water caused by the lowering of the reservoir water level. They are also considered to have a relatively small impact on the environment downstream because inflow discharge can be passed through tunnels naturally during flood time. In Switzerland, five bypass tunnels have been constructed and proved an effective means to counter reservoir sedimentation (Visher et al., 1997). It is found that problems may arise with tunnel abrasion, particularly if the sediment has a considerable quartzite component.

In Japan, sediment bypass tunnels at Nunobiki Dam, completed in 1908, and at Asahi Dam, completed in 1995, have been successfully introduced to realize sustainable reservoir management (Sumi et al., 2005, Kataoka, 2003). Sediment bypasses at Miwa Dam have been completed in 2004 (Suzuki, 2009) and ones at Matsukawa Dam and Koshibu Dam are under construction. For the purpose of designing these bypass systems, hydraulic characteristics of tunnel and diversion weir have been studied (Ando et al., 1994, Kashiwai et al., 1997, Harada et al., 1997).

In this paper, we discuss design criteria and lessons learned from existing facilities, and future challenges of planning projects. We focus on tunnel geometries such as diameter, slope, bottom shape etc., and monitoring techniques to improve sediment bypass operation.

2. SEDIMENT CONTROL STRATEGIES

2.1. Classifications of sediment management techniques

Controlling reservoir sedimentations means in fact the control of sediment deposition in reservoir. It consists of three basic strategies:
[1] Sediment yield reduction: to reduce sediment inflow to reservoirs. Apply erosion control techniques to reduce sediment yield from tributary catchments.
[2] Sediment routing: to pass sediment inflow around or through the reservoir so as not to accumulate in reservoirs, by employing techniques such as partial drawdown sluicing and turbidity re-lease.
[3] Sediment removal: to remove accumulated sediment by drawdown flushing, dredging and excavation by mechanically or hydraulically techniques. Figure 1 shows how sediment management is undertaken and classified. And some representative dams and examples from Europe and Japan, which exercise sediment management, are listed up.

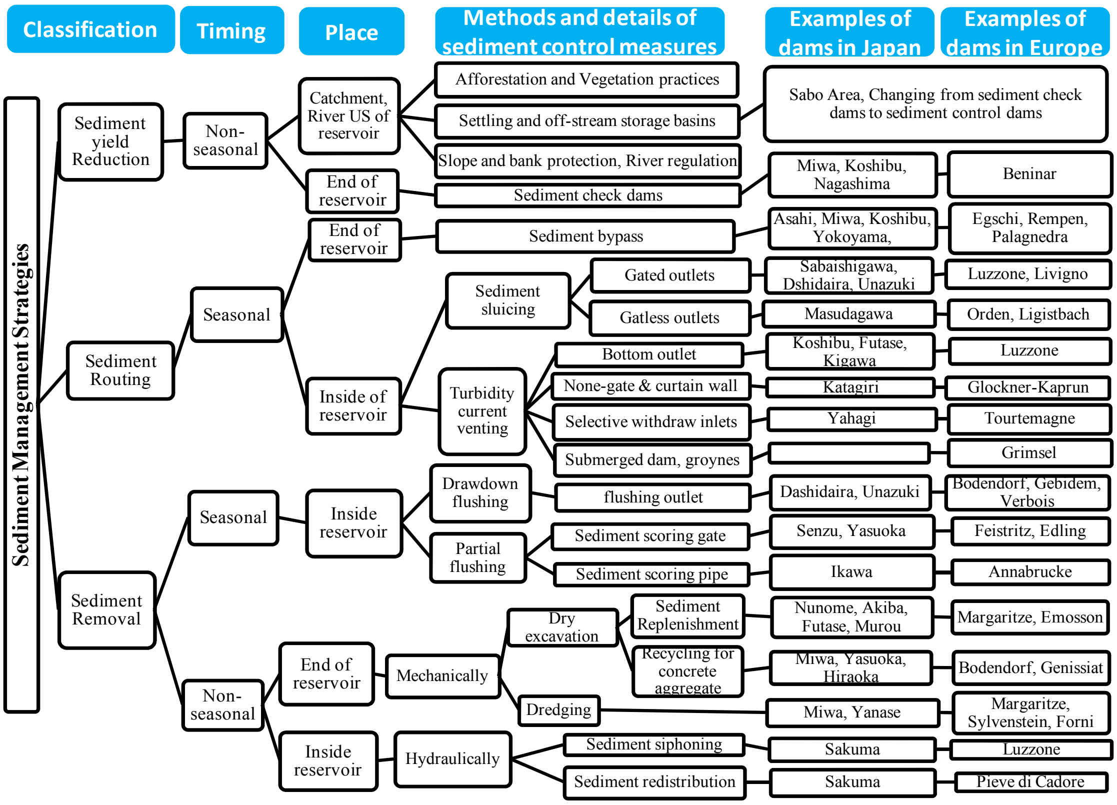


Figure 1 Classification of strategies of sediment control in Japanese and European reservoirs

2.2. Sediment bypass tunnels in Japan

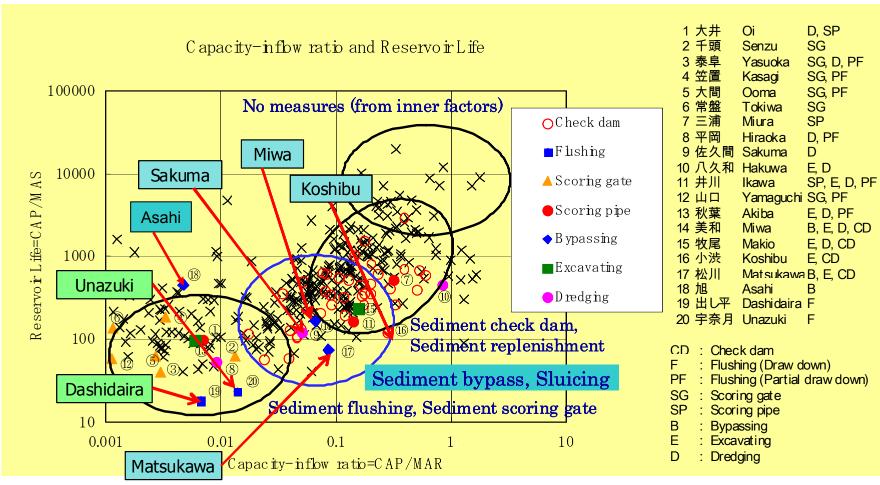
In Japan, sediment bypass tunnels have been studied most exhaustively. Although this technique involves high cost caused by tunnel construction, there are many advantages such that it is applicable to existing dams; it does not involve drawdown of reservoir level and therefore no storage capacity loss; and it has relatively small impact on environment because sediment is discharged during natural flood events compared to sediment flushing which discharge accumulated sediment in a short period.

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 examples of existing sediment bypass tunnels in Japan and Switzerland.

Table 1 Sediment Bypass Tunnels in Japan and Switzerland

No	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
1	Nunobiki	Japan	1908	Hood	2.9×2.9	258	1.3	39	-	-
2	Asahi	Japan	1998	Hood	3.8×3.8	2,350	2.9	140	11.4	13 times/yr
3	Miwa	Japan	2004	Horseshoe	2r = 7.8	4,300	1	300	10.8	2 times/yr
4	Matsukawa	Japan	Under constr.	Hood	5.2×5.2	1,417	4	200	15	-
5	Koshibu	Japan	Under constr.	Horseshoe	2r = 7.9	3.982	2	370	9	-
6	Egshi	Switzerland	1976	Circular	r = 2.8	360	2.6	74	9	10days/yr
7	Palagnedra	Switzerland	1974	Horseshoe	2r = 6.2	1,800	2	110	9	2~5days/yr
8	Pfaffensprung	Switzerland	1922	Horseshoe	A= 21.0m2	280	3	220	10~15	~200days/yr
9	Rempen	Switzerland	1983	Horseshoe	3.5×3.3	450	4	80	~14	1~5 days/yr
10	Runcahez	Switzerland	1961	Horseshoe	3.8×4.5	572	1.4	110	9	4 days/yr

It is an important question how to select suitable solutions for reservoir sedimentation on each reservoir. Capacity-Inflow ratio, 'CAP/MAR' and Capacity-Inflow sediment ratio, or Reservoir Life, 'CAP/MAS' are helpful guiding parameters. Figure 2 shows all Japanese dams based on these parameters and typical sediment bypassing dams are located around CAP/MAR = 0.02 - 0.2 and CAP/MAS = 50 – 500. These ratios indicate that sediment bypass is suitable for medium size reservoirs. The medium size meant not only that of reservoir, but also a hydrological size related to the catchment as well. For instance, smaller reservoirs are easier to drawdown and refill comparing with the medium size. Therefore, sediment flushing may be more suitable such as Unazuki and Dashidaira dams in Kurobe River since temporal draw-down operation is much easier and more cost effective to discharge sediment from all reservoir area (Sumi et al, 2009, Kantoush et al, 2010). On the other hand, sediment bypass tunnels are more efficient and saving water resources for medium size reservoirs as the new bypass tunnels in Matsukawa, Koshibu and Sakuma dams (Figure 2).



CAP: Original total storage capacity volume, MAR: Mean annual runoff, MAS: Mean annual sediment inflow

Figure 2 Classification of reservoir sediment management measures in Japan

2.3. Asahi dam

The lower regulating reservoir Asahi dam completed in 1978, located in the Shingu river, belongs to the Okuyoshino pumped-storage type power plant,1,206 MW, operated by the Kansai Electric Power Co. Inc. The lower regulating scheme is composed of a 86.1m high arch dam and 15.47million m^3 gross storage volume reservoir with 39.2km^2 catchment area.

Since completion of the dam, the prolonged turbidity problem has been getting noticeable due to the upstream condition changes by the collapse of mountain slopes and the devastation of forests caused by large-scale runoffs (Kataoka 2003). Moreover, because of the frequent typhoons in 1989 and 1990, the mean annual accumulated sediment volume from 1989 to 1995 also increased sharply to 85,000m^3/yr which is more than four times of that from 1978 and 1988.

Following the above view points, a sediment bypass system (comprised of a 13.5m high diversion weir and a 2,350m long bypass tunnel with a maximum discharging capacity of 140m^3/s) was constructed in April 1998 to reduce the prolonged turbidity and reservoir sedimentation. Figure 3 shows the schematic diagram of the bypass system.The bypass system was designed to flow both suspended load and bed load, and the design discharge, 140 m^3/s, was determined considering a scale of one-year return period flood with a peak discharge of ca. 200 m^3/s. Hood type cross section of the tunnel was selected from the viewpoint of economy and easy maintenance.

During the four years from 1998 to 2002, sediment bypassing was performed about 16 times a year and about 40 percentage of the annual run-off was diverted through the tunnel. It is found that bypass could have reduced both turbidity period and sediment inflow. It is estimated that only 10% to 20% of the annual inflowing sediment is deposited in the reservoir, while the remaining 80% to 90% is bypassed downstream through the bypass system. Figure 4 shows the effect on the reduction of reservoir sedimentation by the bypass tunnel up to 2006 (Mitsuzumi et al, 2009).

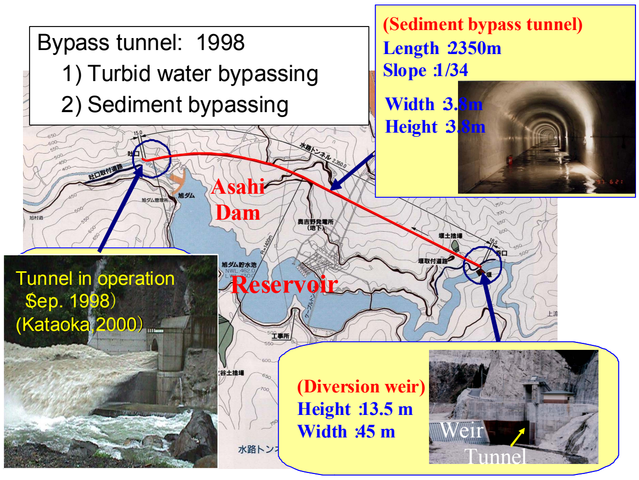


Figure 3 Sediment bypass scheme of Asahi Dam

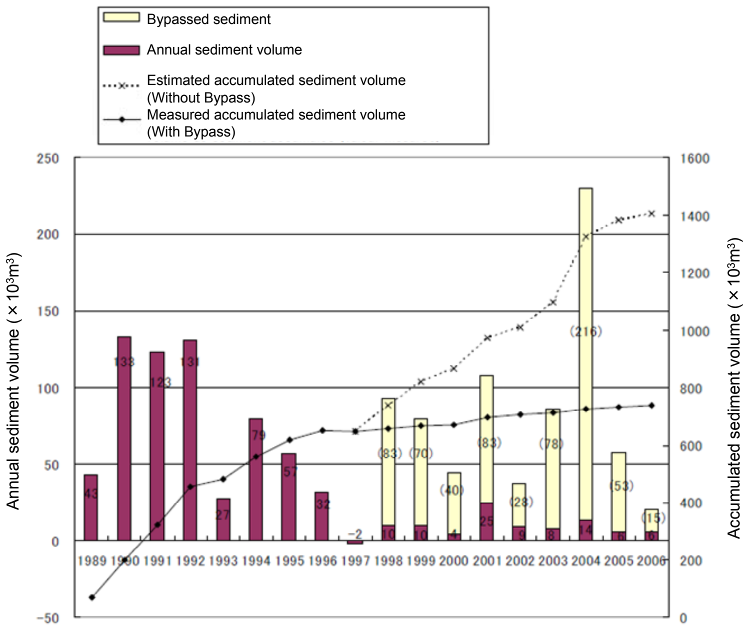


Figure 4 Sediment bypass effect of Asahi dam (Mitsuzumi et al, 2009)

From just after the tunnel operation, local abrasion damages were found on the tunnel invert. A total of 400m^3 of abrasion on all tunnel invert (area 9,000 m^2) and an average abrasion depth of 45 mm, locally up to maximum 200mm, was found in 1998. From a study on the relationship between the mean abrasion depth and the estimated bypassed sediment from 1998 to 2001, it can be found that the abrasion quantity is almost proportional to the bypassed sediment volume.

Though these abrasion damages are within the range forecast at the design stage, locations where invert concrete of the tunnel with design strength of 36 N/mm^2 is seriously damaged are repaired during non-flood season.

2.4. Miwa dam

The multi-purpose reservoir Miwa Dam completed in 1959, located in the Tenryu river system in Nagano prefecture, is operated for the purpose of flood control, irrigation water supply and hydroelectric power generation by the Ministry of Land, Infrastructure and Transport. The scheme is composed of a 69m high gravity concrete dam and 29.95 million m^3 gross storage volume of reservoir with 311 km^2 catchment area.

Since the dam was completed, extreme runoff events occurred in 1959, 1961, 1982 and 1983 causing serious disasters and sediment yield in the catchment river basin that resulted in quick increasing of reservoir sedimentation. Since 1966, gravel have been constantly removed by a maintenance plan and then approximately 5.32 million m3 sediment have been dredged in 33 years up to 1998. If those gravel is not removed, the total sedimentation is approximately 19.47 million m^3, and estimated the mean annual sedimentation is 0.47 million m^3/yr.
From the view point of the eternal reservoir sedimentation management, a sediment bypass system (comprised of a 20.5m high diversion weir and a 4,300m long bypass tunnel with a maximum discharging capacity of 300m^3/s) is completed in March 2004 to reduce sedimentation of the reservoir. Figure 5 shows the schematic diagram of the bypass system.

This bypass system was designed to flow mainly wash load since about 3/4 of the sediment deposited in the reservoir is wash load smaller than 74 μm. According to the master plan of the redevelopment project, 685,000 m^3 of sediment including 525,000 m^3 of wash load, and 160,000 m^3 of bed load and suspended load will flow into the reservoir. The bypass tunnel will divert 399,000 m^3 of wash load and the remaining 126,000 m^3 will flow into the main reservoir. The bed load and the suspended load that flow in at an annual average of 160,000 m^3 are captured by the 15.0m sediment trap weir that has sedimentation capacity of 200,000 m^3, then it is removed mechanically and transported for construction materials.

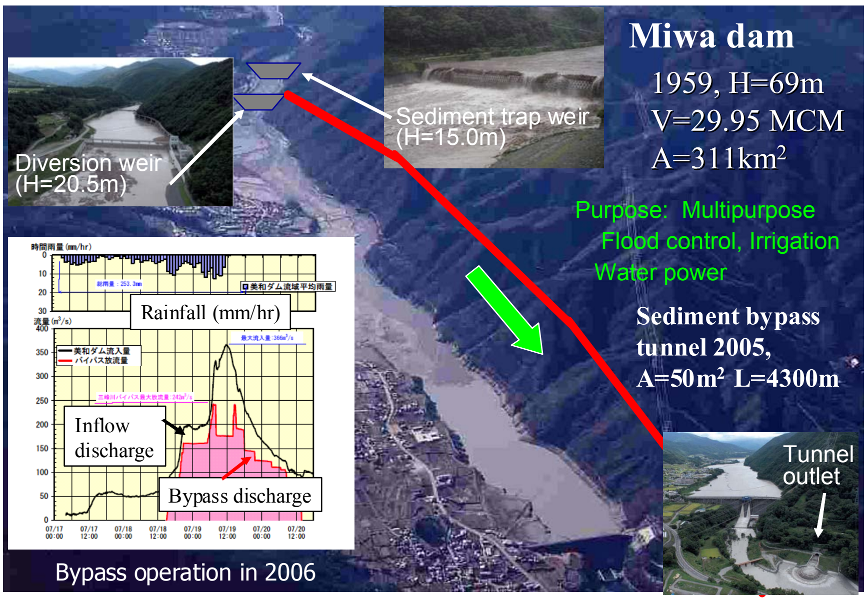


Figure 5 Sediment bypass scheme of Miwa dam

3. SEDIMENT MONITORING FOR OPERATION IMPROVEMENT IN MIWA DAM BYPASS SYSTEM

In order to improve the bypass operation, we should predict sediment inflow to the reservoir during flood events and real time monitoring both of flow and sediment concentration distribution in the reservoir area is needed. In Miwa dam, several parameters have been monitored namely, rainfall precipitation in the upstream, turbidity and suspended sediment concentration in the upstream, the reservoir and the downstream areas. These data can be used for switching operation modes as shown in Figure 6.

The first normal mode is that all incoming flood flow will overflow the diversion weir into main reservoir (Mode 1). While the second mode is some part of incoming flood flow will be diverted to bypass tunnel after opening the bypass main gate (Mode 2). The last mode is refilling mode by closing the bypass main gate (Mode 3). Generally we can use inflow discharge to design and guide the timing for switching these operation modes. But we should pay attention to sediment concentration, because the flow discharge and sediment concentration are not linear relationship including sometime hysteresis. For example, sediment concentration during discharge increasing stage in the hydrograph is usually higher than that during decreasing stage.

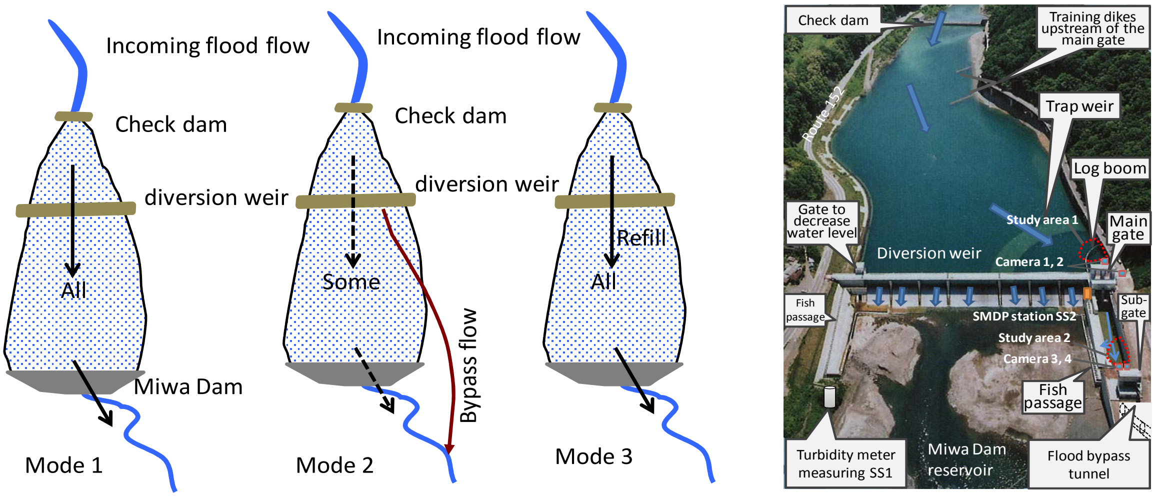


Figure 6 Switching operation modes during flood and field monitoring at Miwa Dam.

Field monitoring measurements was conducted during flood seasons in June and July 2010 by using digital image techniques. Surface flow velocity and suspended sediment concentration were measured to clarify the performance before and after the commencement bypassing operation mode. The results of surface velocity measured by LSPIV are shown in Figure 7. The main flow is directed towards the diversion weir at Mode 1 and a large circulation cell in front of the bypass was formed see Figure 7(a,b). The velocity vectors show a low velocity inside the reservoir around 30 cm/s. Interesting effects of the flow separations in front of the bypass, such as concentration of inflow to the bypass and increase of velocities up, can be detected by the LSPIV measurements Figure 7(c).

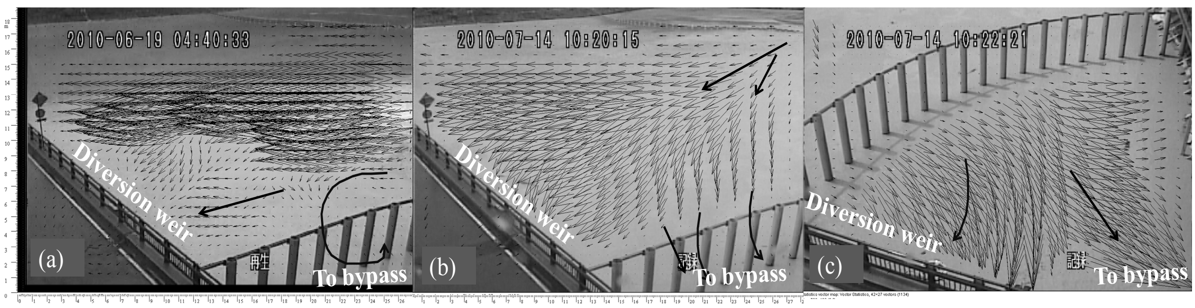


Figure 7 Stationary flow fields for (a) Mode 1, (b and c) Mode 2.

SMDP using differential pressure transmitter by Sumi et al., (2002) and INFINITY-Turbi by JFE-Advantech (Miniature Super-High Turbidity Data Logger with Wiper), were installed for sediment monitoring in the river. Furthermore, river water samples were taken constantly to calibrate these monitoring systems and to obtain grain size distributions of the suspended load. Operation record for flood event in July was well monitored as Figure 8. The maximum bypass discharge was almost equal to the inflow discharge. Suspended sediment concentration was up to 10,000 mg/l at the diversion weir and high turbid flow was effectively diverted through the tunnel. In this case, bypass efficiency was estimated up to about 80 % as shown in Figure 8.

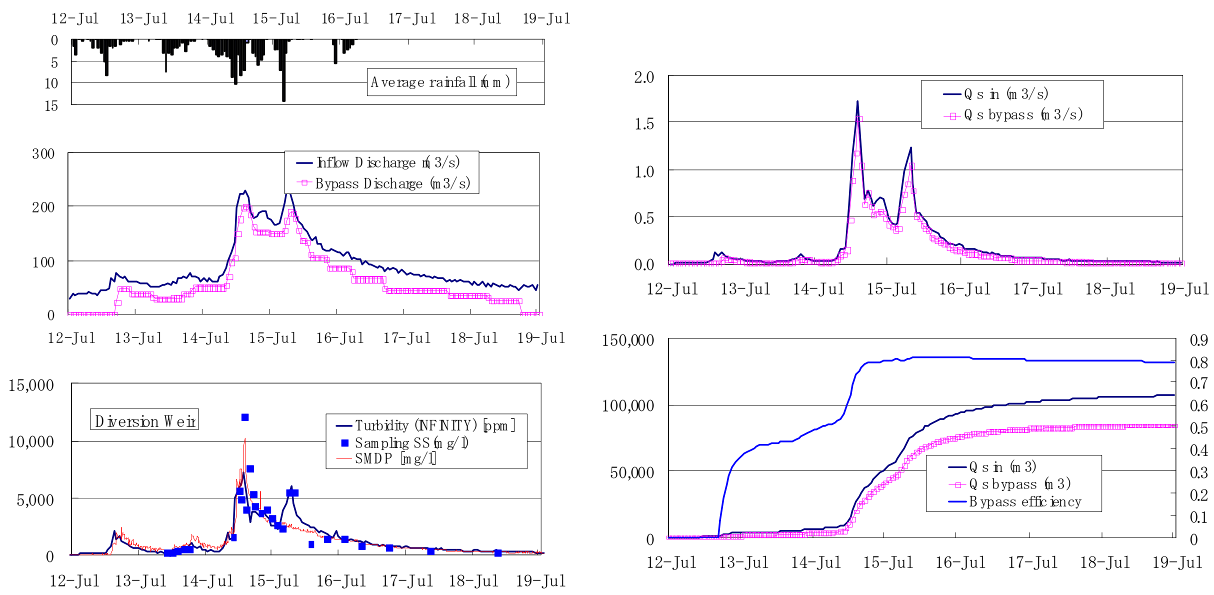


Figure 8 Rainfall, inflow and bypass discharges, suspended sediment measurements, calculated inflow and bypassed sediment, calculated efficiency for Miwa dam bypass scheme.

We also tried an image processing to determine the suspended sediment concentration by which correlates with the light intensity based on every 2 sec SMDP measurements. A simple calibration procedure was conducted for camera and each point pixel on the layer surface, to establish the relation between SS and the values of gray scale in the frames representing light intensities. The estimation of pixels density was made by DigiFlow software. Inflow suspended sediment concentration was recorded in June as shown in Figure 9. Peak concentration was almost equal to inflow discharge peak and turbid flow of from 2500 to 1000 mg/l was bypassed. Turbidity trend is well monitored by several measurement data and very much helpful to switching from Mode 1, Mode 2 and Mode 3.

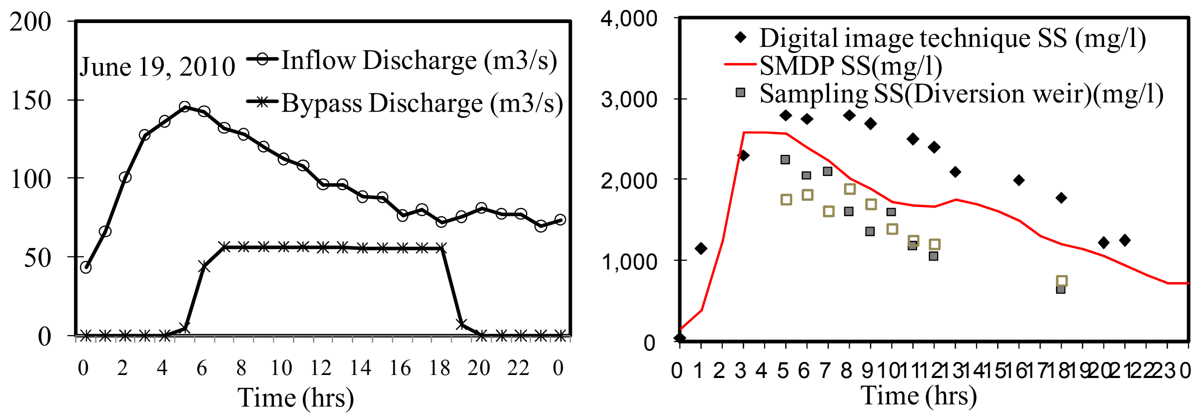


Figure 9 Comparison of monitored suspended sediment concentrations by four different measurement techniques during bypassing on June 19, 2010 flood.

4. CONCLUSIONS AND FUTURE CHALLENGES

Sediment management of reservoirs is very much complicated project which will affect reservoir sustainability and also maintaining downstream river health. The present paper highlighted several lessons learned from existing facilities and the need for further research regarding sediment bypass tunnels. Sediment bypass system in Miwa dam is effectively routing incoming fine sediment directly to reservoir downstream. The measured efficiency of sediment bypassed by optical turbidity meter was up to 80% of the total inflow sediment. This efficiency was also measured at selected events by image processing which is a very useful tool in characterizing the performance of bypass tunnel operation.

There are several issues of sediment bypass technique to be resolved in the future as following:
Hydrological point of view: prediction of upstream rainfall and runoff by distributed hydrological modelling and monitoring techniques. Moreover, optimizations of sediment bypass operation.
Hydraulic point of view: clarification of the hydraulic behaviour of flow and sediment in tunnels for the purpose of designing safe and economical sediment tunnels (i.e., cross section, velocity, curvature, invert, slope and material design), as well as the establishment of countermeasures for abrasion damages on channel bed surface. The main problem of sediment bypass tunnels is abrasion along the invert. To counter abrasion, selecting high strength concrete and preparing enough abrasion depth on top of necessary tunnel invert depth are recommended from the view points of initial construction cost and easy maintenance.
Environmental point of view: In order to improve the bypass operation, we should predict sediment inflow to the reservoir during flood events and real time monitoring both of flow and sediment concentration distribution in the reservoir area is needed in order to switching bypass operation modes effectively. SMDP using differential pressure transmitter by Sumi et al. and INFINITY-Turbi were effectively used for sediment monitoring in the river.

5. ACKNOWLEDGMENTS

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