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Impacts of sediment flushing on channel evolution and morphological processes: Case study of the Kurobe River, Japan

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ABSTRACT: Flushing is vital for the preservation of long-term storage in reservoirs. However, downstream impacts can act as a constraint in the planning and operation of sediment flushing. In order to understand the processes and the impacts of flushing, two examples are given of the Unazuki and Dashidaira reservoirs, located at the Kurobe River eastern region of Toyama prefecture, in Japan. For both reservoirs sediment inflow is extremely high compared to the storage capacity. During minimum pool level the incoming floods erode a flushing channel in the deltaic deposits. The channel is gradually increased in width by bank-erosion processes during this period. The paper investigates the impacts of flushing on the dynamic dimensions of flushing channel, and the varying location. Furthermore, it clarify the development of channel formation in both reservoirs. Quantitatively and qualitatively monitoring measurements during flushing have been conducted for sediment erosion process with 3D laser scanning, surface velocity (LSPIV), and suspended sediment concentrations. The flushing channel within Dashidaira reservoir has a stable profile and extends across the entire impoundment width of 170 m at distance of 640 m from the dam.

Keywords: Drawdown flushing, Flushing channel formation, Coordinated flushing, Kurobe River.

1 INTRODUCTION

1.1 *Background*

Dam construction disrupts the longitudinal continuity of the river system and interrupts the action of the conveyor belt of sediment transport (Kondolf, 1997). Upstream of the dam, all bedload sediment and all or part of the suspended load is deposited in the stagnant water of the reservoir (reducing reservoir capacity) and upstream of the reservoir in reaches influenced by backwater.

Downstream, water released from the dam possesses the energy to erode the channel bed and banks, but has little or no sediment load. The rapid reservoir sedimentation not only decreases the storage capacity, but also increases the probability of flood inundation in the upstream reaches due to heightening of the bed elevations at the upstream end of the reservoir and the confluences of the tributaries (Liu et al., 2004). In order to remove and reduce reservoir sedimentation, many approaches such as flushing, sluicing, dredging and water and soil conservation are developed (ICOLD, 1989). Among these approaches, flushing is considered the only economic approach to swiftly restore the storage capacity of the reservoir with severe deposition. Basically, there are two types of flushing operations with, and without drawdown, and optional techniques can be used with the complete drawn flushing as shown in Figure 1.

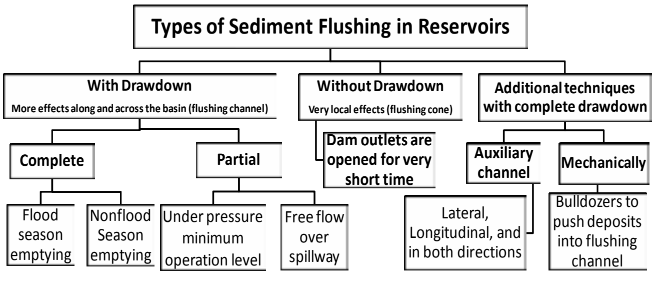

Figure 1. Classification of sediment flushing techniques

Drawdown is the lowering the water levels in a reservoir. Hydraulic flushing involves reservoir drawdown by opening the bottom outlet to generate and accelerate unsteady flow towards the outlet (Morris and Fan, 1998). This accelerated flow possesses an increased stream power and consequently eroding a channel through the deposits and flushing the fine and coarse sediments through the outlet. During this process a progressive and a retrogressive erosion patterns can occurs in the tail and delta reaches of the reservoir, respectively (Batuca and Jordaan, 2000). Among reviewed literature, sediment removal from reservoirs (White, 2001) generally only affords the problem of sediment flushing inside the reservoir. However, there is scarce information about experiences on prototypes and especially in respect to flushing channel formation. One of the phenomena in reservoirs that is not well investigated and theoretically explained is the formation of flushing channels in the delta of the reservoir (Sloff et al., 2004). In many reservoirs these channels can be found, e.g. see Figure 2, as they are a common feature of deltaic deposition in wide reservoirs.

Figure 2. Flushing channel in reservoir upstream of Gebidem dam during drawdown operation

1.2 *Relevant Parameters for Flushing Channel*

The characteristics of the flushing channel when the reservoir is fully drawdown are location, width, side and longitudinal slopes, and shape. Some of these characteristics are investigated experimentally in shallow reservoir geometries with different shapes (Kantoush and Schleiss, 2009). The width of the flushing channel W_f is estimated as proposed by the World Bank RESCON model, (2003) (REServoir CONservation), and Atkinson (1996). To predict W_f, Atkinson, (1996) suggests the empirical relationship ($W_f = K\,Q_f^{0.5}$) based on prototype measurements in four reservoirs of China, United States, and India. In this equation, W_f (in meters) is the flushing-channel width, K is a coefficient depending on bed material (in this case K is 12.8) and Q_f is the discharge (in $m^3 \cdot s$-1) that will form the channel.

1.3 *Aim of the Study*

The lack of knowledge regarding flushing channel evolution and its morphological processes, initiated a study to channel formation, applied to flushing processes in Dashidaira and Unazuki reservoirs in Japan. The study aims at investigating the causes of these observed behaviors, and find measures to control and predict the channel characteristics. Therefore this study is focusing mainly on track the patterns of reservoir erosion through field and experimental modeling. Finally, quantitatively and qualitatively monitoring techniques during flushing are discussed.

2 CASE STUDY OF THE KUROBE RIVER

Japan has geologically young mountains, steep and short rivers with flashy flow regimes, and densely populated floodplains. Japan suffers from frequent heavy storms. The combination of steep catchments and heavy storms results in widespread hill slope failures and landslides and extensive flood discharges.

2.1 *Study Area*

The Kurobe River originates in mountainous areas with peaks elevation above 3,000 m. The main river flows for about 85 km into Toyama Bay as shown in Figure 3. The average river bed slope ranges from 1/5 to 1/80 is about 1/30. The mean annual precipitation ranges from 2400 mm to 4100 mm. Figure 3 shows an outline of the Kurobe River System.

The Kurobe River is the only river in Japan where full scale dam-linked sediment flushing is done by performing sediment flushing well linked to sediment flushing at an electric power dam (Dashidaira Dam) installed upstream from the Unazuki Dam. Both dams have an extremely large amount of sediment inflow; therefore, they were the first in Japan which was built with sediment flushing facilities (sediment flushing gates).

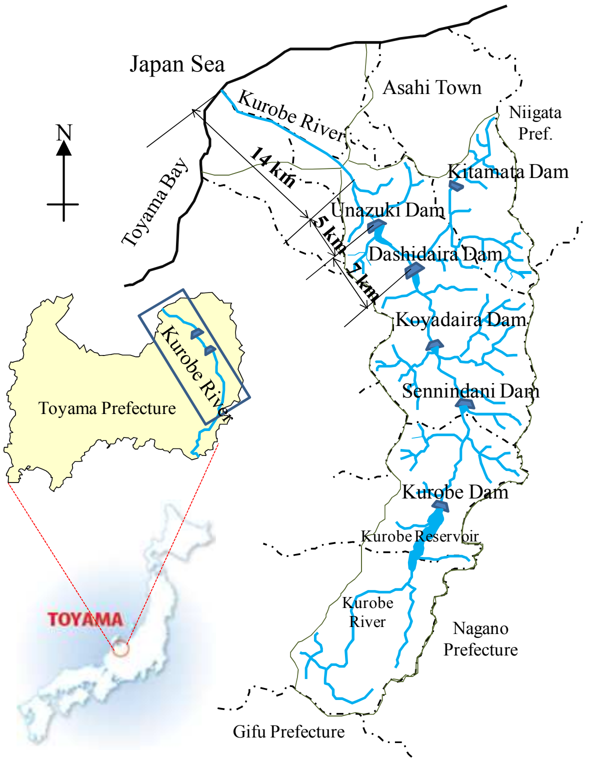

Figure 3. Kurobe River site map and location of Dashidaira and Unazuki dams

2.2 *Dashidaira dam and its flushing facility*

Figure 4(a) shows the Dashidaira reservoir, dam site, and downstream reach during flood. The concrete gravity dam with a height of 76.7 m is providing 124 MW. The dam is located 26 km upstream the river mouth. Dam was constructed by Kansai Electric Power Company in 1985. Figure 4(b) shows the topography of the Dashidaira reservoir with initial gross and effective capacities of 9.01 MCM and 1.66 M.m^3, respectively. The small capacity reservoir has an elongated shape with quasi-uniform width.

The Unazuki Dam is a multipurpose dam planned mainly to prevent floods on the Kurobe River. The dam height is 97.0 m, completed in 2001 by the Ministry of Land, Infrastructure and Transport. The upstream side of the Unazuki dam and inlet of two sediment scouring gate are shown in Figure 5(a), during draw down. The sediment scouring channels are both equipped with flushing gates with dimension of 5.0 m x 6.0 m. The three gates in upstream, intermediate, downstream sides are high pressure slide gates. The purposes of flushing facilities are to sustain the original functions of the dam and maintaining sediment routing system within the reservoir. Unazuki reservoir (Figure 5(b)) has larger gross and effective capacities comparing with Dashidaira of 24.7 MCM and 12.7 MCM, respectively.

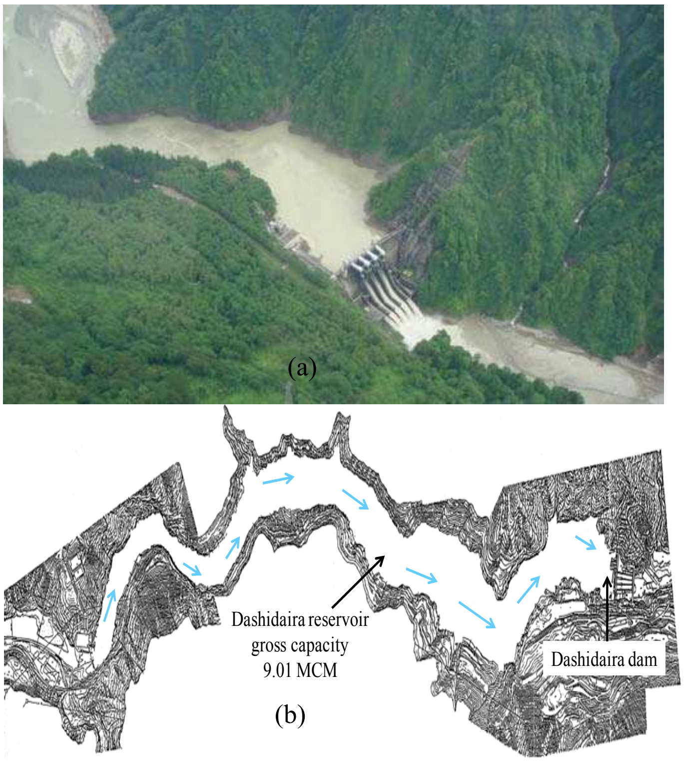

Figure 4. (a) Photo of Dashidaira dam during draw down flushing; (b) Plan view of Dashidaira reservoir topographic map

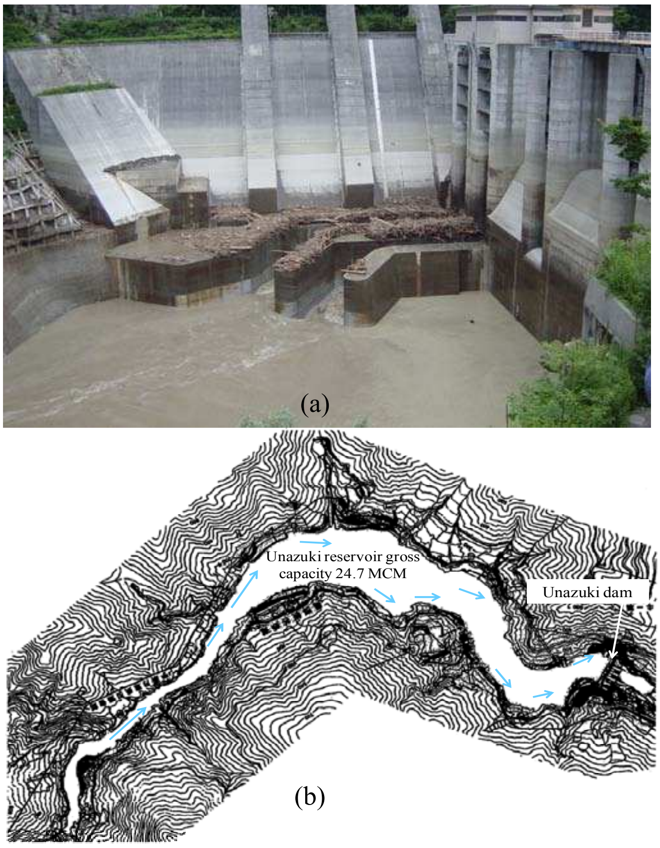

Figure 5. (a) Photo of Unazuki dam during drawdown flushing; (b) Plan view of Unazuki reservoir topographic map

2.3 *Monitoring techniques for sediment flushing*

Innovative methods for sediment monitoring techniques should be developed in order to evaluate environmental influences and effectiveness of sediment flushing. Several parameters are measured during and after flushing, namely: 3D topography, 2D surface velocities, cross section bathymetry, turbidity, and sediment transport rate. More details about these techniques are shown and explain by (Sumi et al., 2004, 2005). Figure 6 shows field measurement of channel evolution and morphological processes during a coordinated sediment flushing operation at the Unazuki Dam reservoir in 2006. These measurements included surface velocity using LSPIV (Large Scale Particle Image Velocimetry) performed by using CCTV camera, in combination with geographic feature measurement with a 3D laser scanner. A high concentrated SSC is also observed downstream of the dam.

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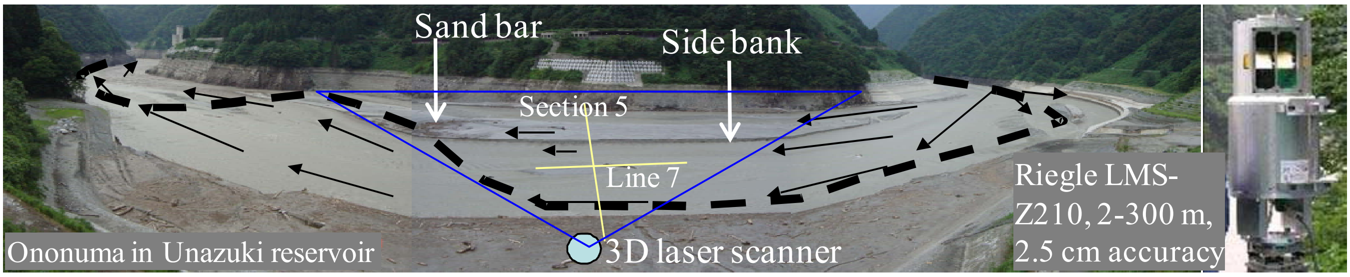

Figure 6. Photo of monitoring measurements within Unazuki reservoir by using 3D laser scanner (Sumi et al., 2004)

2.4 *Analysis of coordinated sediment flushing operations of Dashidaira and Unazuki dams*

Based on laboratory tests, numerical simulations, and previous engineering practices at Dashidaira dam; the coordinated sediment flushing operation rules for Dashidaira and Unazuki reservoirs are established. Since 2001, when the Unazuki Dam was completed, sediment flushing and sluicing have been conducted coordinately for the two dams. Dashidaira dam previously completed has been executed sediment flushing in single since 1991. The coordinated sediment flushing would be carried out when the inflow at Dashidaira reservoir become firstly larger than the designated discharge of 250 m^3/s in the rainy season around June to July. In the next flood events after flushing, whenever a flood excess of 480m^3/s, sediment sluicing is performed.

Figure 7 shows actual sediment flushing operation performed in July 2006. Erosion phase with free flow state is lasting for 12 hours to flush out sediment volume of 0.24 MCM. The flushing time from the beginning of drawdown to the end at Dashidaira dam is 51 hrs and 60 hrs at Unazuki dam. It is a key to the coordinated sediment flushing and sluicing to do these operations at the same time in Dashidaira and Unazuki dams that are located longitudinally.

3 LABORATORY EXPERIMENTS

3.1 *Experimental facility installation and setup*

Laboratory experiments for Dashidaira and Unazuki reservoirs are set up to examine the flushing processes and channel formation. Four sets of experimental tests are administered in Dashidaira reservoir after two years of dam completed. The purposes of Dashidaira physical models are to predict the sediment and flow patterns in equilibrium state during flushing especially with wash load effect, and moreover, to examine different test procedures and find the optimal sediment material can be used for Unazuki dam. The test concept and the bed material initial conditions are shown in Figure 8. The initial sedimentation condition is built in the model with silica sand and styropor granulate as shown in Figure 8. The diameter of the silica as bed load is the same as the prototype. The styropeor material was selected as wash load due to the similarity in density and size with the field.

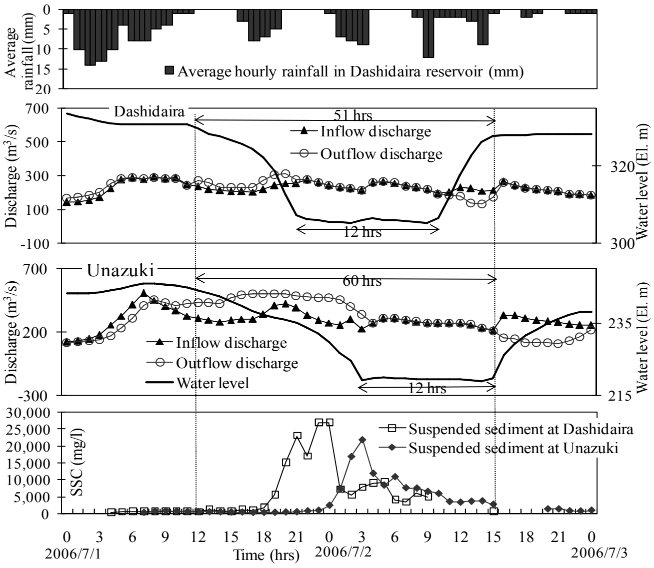

Figure 7. Coordinated Sediment flushing operation in 2006

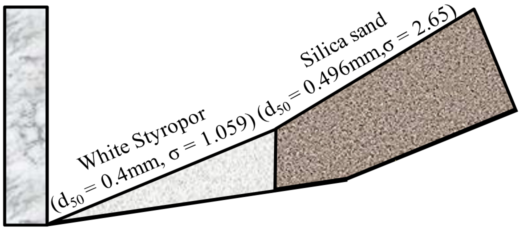

Figure 8. Initial bed condition and sediment material

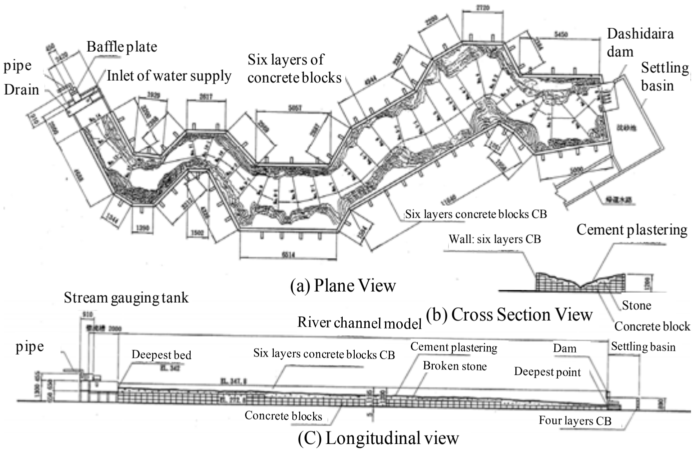

Figure 9. Dimensions and laboratory setup of Dashidaira dam (a) Plan view; (b) Cross section; (c) Longitudinal view

The experiments were carried out at PWRI, Public works Research Institute, the Ministry of Construction, Japan. Schematic view of the experimental setup and cross section of Dashidaira reservoir are shown in Figure 9. The model scale of Dashidaira and Unazuki dams is 1:62.5. Two different test procedures with several clear water inflows and flushing durations are used in both dams. A discharge of 200 m^3/s imposed without sediment. By the flushing inflow, a channel is eroded in the sediment layer. The physical model of Dashidaira reservoir was constructed only for flushing test experiments. Therefore, the original bed profile is apparently different from the field profile (Figure 10). But, the initial bed deposition profile before flushing is the same as the actual one. The result of the flushing test is shown in Figure 10.

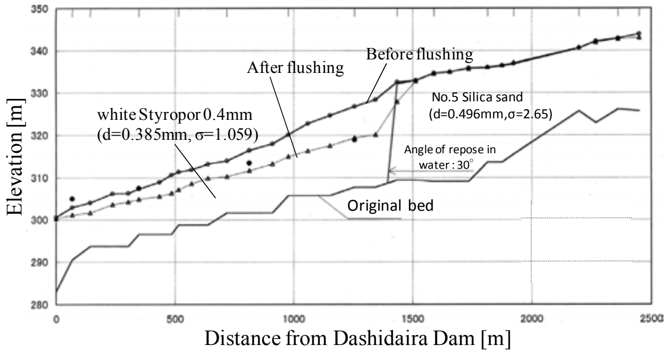

Figure 10. Longitudinal bed profiles before and after flushing laboratory test along Dashidaira reservoir

3.2 *Erosion and flow patterns during flushing*

The final bed morphology obtained from experiment is used as the initial topography for clear water test. Here, clear water without sediment is introduced into the basin to investigate the further bed evolution. Figure 11 shows the flow with vectors and the bed topography after 11.9 hrs of flushing. Reduction of water surface generates high flow velocity near the outlet; the flow starts to erode a wide channel. At that stage, a significant amount of sediment deposits was flushed through the reservoir, and the initial channel deepened as a result of the strong jet flow and erosion.

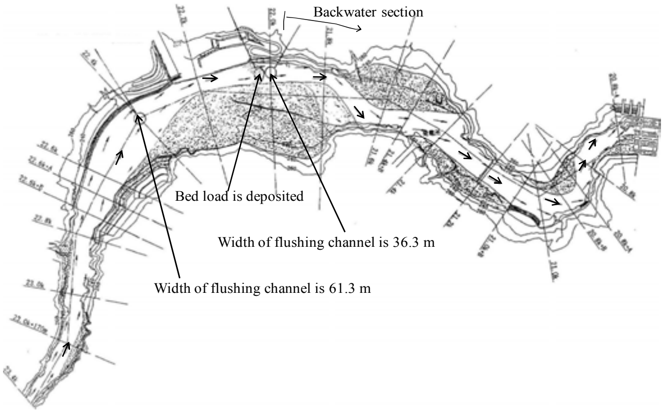

Figure 11. Morphological patterns after flushing within Unazuki reservoir after t =11.9 hrs

The flushing channel location was clearly visible by the re-suspended sediment which was rapidly released during 11.9 hrs (Figure 11). The flow trajectory path is eroded until the scouring channels bottom outlet. Fine suspended sediments were carried and deposited on the right and on the left sides along the reservoir. After the channel is formed its location is rather stable, and difficult to shift as its depth enforces the flow pattern to follow the channel path.

3.3 *Comparison of laboratory and field data*

Within Dashidaira reservoir, the actual and laboratory test of flushing channel is schematically shown in Figure 12.

By the clear-water inflow a channel is eroded in the placed sediment layer. The actual and laboratory has almost the same channel formation way, except at the wider section before dam. The meandering behavior at the wider location within reservoir has opposite direction of the channel. The location of the channel is difficult to be predicting in the wider region within the reservoir. Moreover, the bank failure of the flushing channel creates relatively steep side slopes as shown in Figure 13. The side slope is almost constant within Dashidaira reservoir. Bank failure caused by hydraulic overpressures associated with rapid drawdown. The eroded channel profile has a trapezoidal cross section (Figure 13).

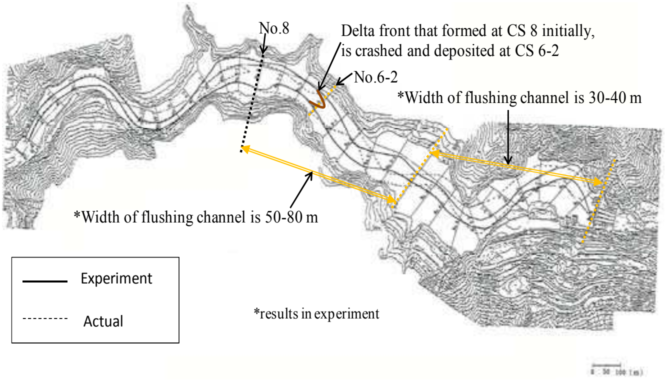

Figure 12. Comparison between experimental and actual flushing channel formation within Dashidaira reservoir

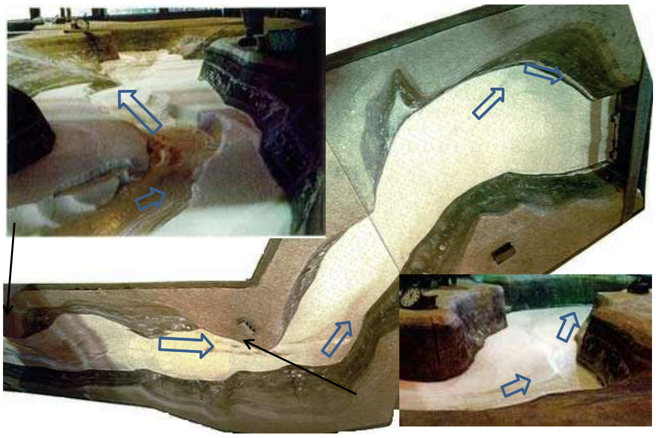

Figure 13. Photograph, looking downstream, of eroded channel at the end of experiments of Dashidaira reservoir

4 FIELD OBSERVATION AND DATA

4.1 *Evaluation of sediment flushing effects*

The effects of sediment flushing in the Kurobe River should be evaluated. The suitable condition to perform the flushing operation is the taking place of a natural flood more than a constant scale. The previous and present longitudinal sediment profiles of Dashidaira and Unazuki dams are shown in Figures 18(a) and (b), respectively. Dashidaira dam was constructed fourteen years before Unazuki dam. Therefore, the Dashidaira Dam is currently at an equilibrium state in terms of its sediment, and the quantity of passing through is approximately one million cubic meters yearly. However, sediment is still being accumulated at the Unazuki Dam. While the majority of sediments of grain size larger than 2 mm are trapped at the reservoir, about 70% of the sediment that has grain size smaller than 2 mm, is sluiced.

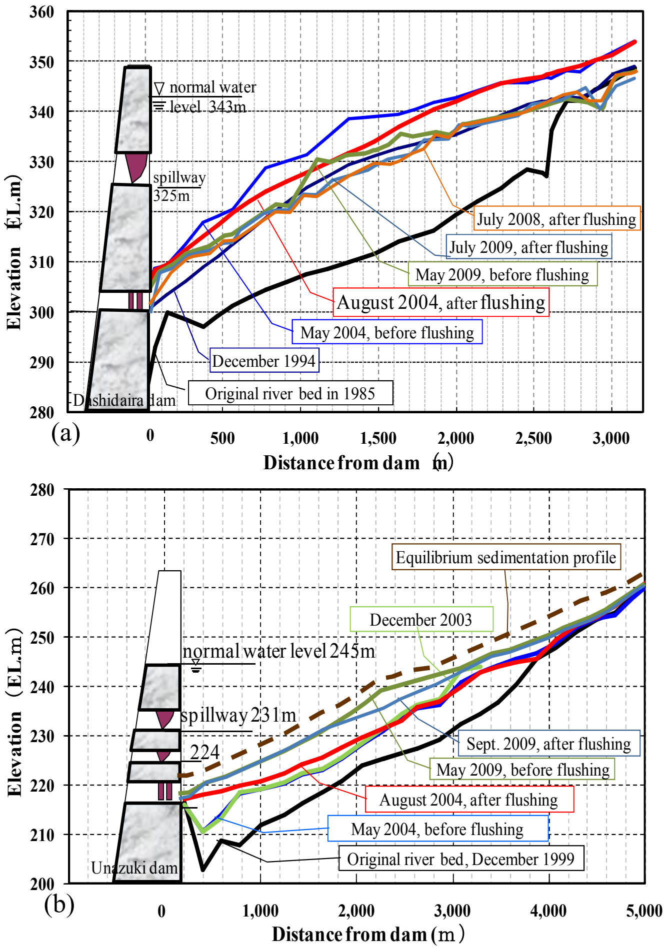

Figure 14. Actual field longitudinal bed profiles variations in time along (a) Dashidaira reservoir; (b) Unazuki reservoir

High sediment deposition is formed in May 2004 within Dashidaira reservoir as shown in Figure 14(a). Afterward in August 2004, by continuous sediment flushing another bed profile is formed. Longitudinal profiles before and after flushing in 2009 are shown in Figure 14(a). On the other hand in Figure 14(b), the sedimentation in Unazuki dam progresses mainly by the coarse sediment inflow from both sediment flushing of Dashidaira dam and a tributary river. The flushing efficiency calculated from the water consumption including the discharge during drawdown and the sediment volume flushed out is about 2%. For this reason, it can be estimated that sediment flushing by using a natural flood discharge in the rainy season is executed regardless of the previous year's amount of sedimentation to prevent the sediment from changing in quality in the reservoir every year, and in that case while doing an enough dilution.

Figure 15 shows the amount of flushed sediment from the Dashidaira Dam and the amount of accumulated sediment at the Unazuki Dam for each year. Due to regular sediment flushing, the Dashidaira Dam has been maintaining present sedimentation volume equivalent to about 45% of the gross storage capacity, which is equilibrium state. The accumulation of sediment at the Unazuki dam is reduced in 2006, and as the size of sediment materials is stabilized, coarse sediments are reaching up to the dam. Therefore, these coarse sediments are also beginning to pass through the dam in addition to the fine sediments produced upstream.

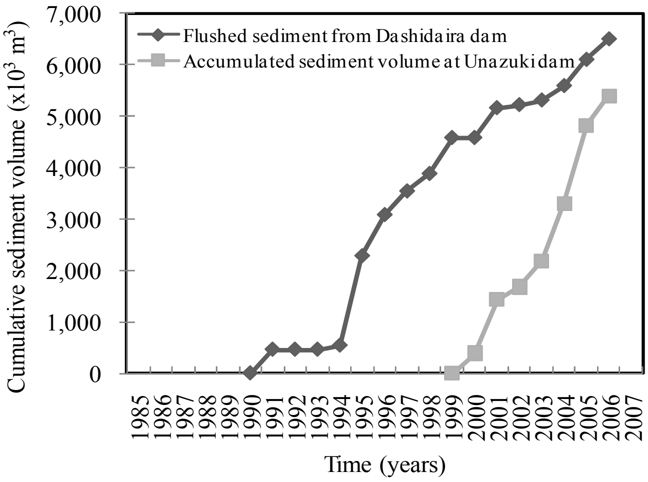

Figure 15. Comparison of flushed sediment volume at Dashidaira dam and accumulated sediment at Unazuki dam

4.2 *Morphological process of Dashidaira*

The 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. During flushing processes two types of erosion pattern can occurs; a progressive erosion in the tail reach of the reservoir, and a retrogressive erosion in the delta reach of the reservoirs. In order to predict the flushing channel width and location, it is important to understand the erosion process of sediment within reservoir.

Figure 16 shows erosion process of deposited sediment in Dashidaira reservoir in 2004. It can be found that longitudinal and lateral erosions created by river bed degradation and side bank erosion. A meandering flushing channel in the accumulated sediment is also formed. Not all the sediment is flushed out during the free flow duration. However, the sediment on both banks is gradually fall down by the stream bank erosion. During very high discharges in 2004 the channel was able to break through the sand bar with bend cut-off and forming a wide channel section. Nevertheless, these cut-off events can only occur when water levels at the dam are not completely draw down, because then the flow becomes concentrated in the existing deep channel. The flushing operation has a significant contribution to the maintenance of the reservoir capacity to extend the dam life time.

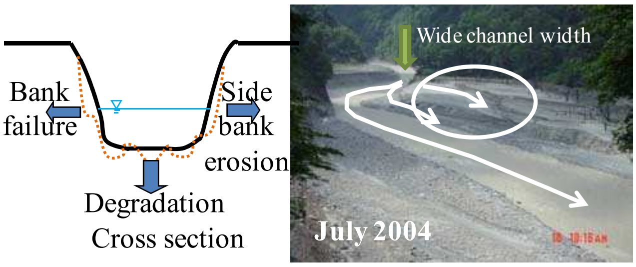

Figure 16. Flushing channel formed in Dashidaira reservoir

4.3 *Evolution of flushing channel formation inside Unazuki reservoir*

Several field measurements are conducted in order to evaluate channel formation during drawdown flushing within Unazuki reservoir. By using 3D laser scanning technology (Sumi et al., (2004), Sumi et al., (2005)), erosion-deposition process of sediment in reservoirs and rivers are measured as shown in Figure 6. Moreover, morphological changes in river channels during and after flushing are investigated.

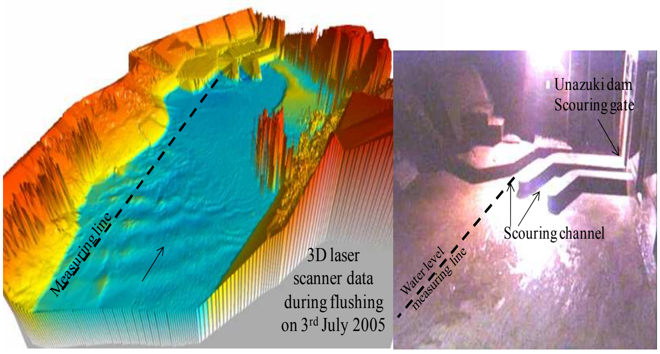

Figure 17. 3D laser scanner measurements of deposition and water surfaces within Unazuki reservoir

The morphological topography with the water surface is clearly visible in Figure 17. Field measurement of time and spatial variations of water surface during drawdown flushing in night time is also conducted. Figure 18 reports a snapshot in terms of water elevation profiles within Unazuki reservoir along the scouring channel. The water surface elevation along the measuring line is shown in Figure 18. This figure shows how the shock waves generated by the scouring gate propagated over the sediment bed. The observed flushing wave propagates along the measuring line at different time steps. Figure 18 indicates the 3D laser scanner capability to reproduce the global evolution of the sediment profile as a function of the flushing durations, with high accuracy.

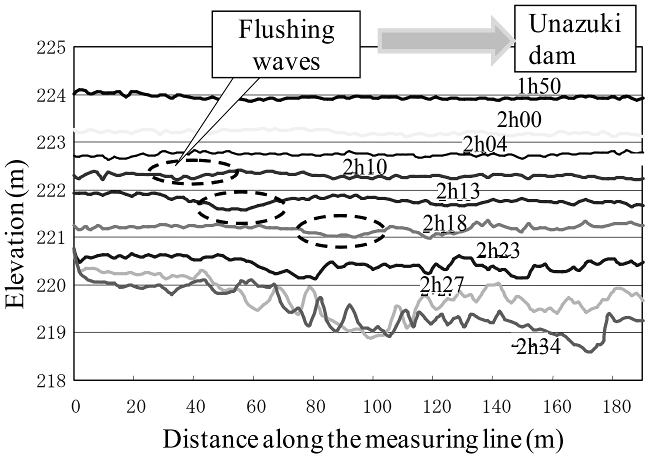

Figure 18. Time series of measured water surface elevations

Time and spatial variations of reservoir surface velocities during drawdown and flushing period were also measured by LSPIV. 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. Side bank erosion process of the sand bar formed in the Unazuki reservoir and water surface profiles nearby banks are shown in Figure 19. The location of the measured cross section (section 5) is shown in Figure 6. Based on these results, it can estimate the height of side bank of 1.0-1.2 m is eroded with the speed of 7.5 m/hr. Slope of water surface is also estimated as 1/75 and water waves generated by the antidune are also observed.

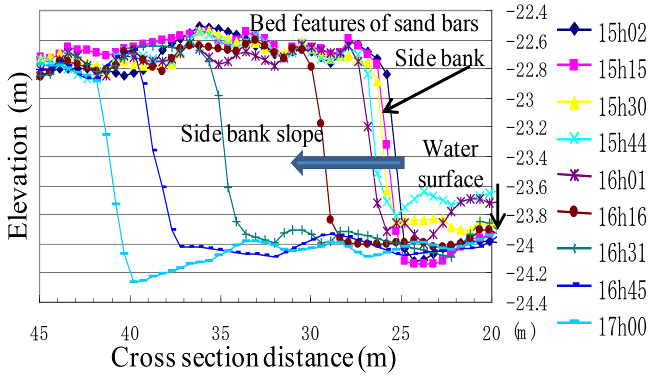

Figure 19. Time series of flushing channel side bank erosion processes within Unazuki reservoir

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. Based on field observation of turbidimeter, movement of the suspended sediment load discharged from Unazuki dam during flood, flushing and sluicing periods are clarified.

5 DISCUSSIONS

Laboratory and field measurements for a large V shape gorge reservoir show that channel formation in reservoirs is particularly controlled by the flow and deposition patterns. It is therefore highly dependent on the boundary conditions, the initial flow conditions and the geometry. On the other hand, the sensitivity of flow patterns creates opportunities to redirect the channel direction by means of small interventions in the flow field (e.g., operation of water-levels at gates, or constructions that redirect the flow within the reservoir).

Channels formed by flushing in reservoir sediment deposits correlate well with flushing discharge. Figure 20 shows the relationship and the comparison of observed flushing channel widths in Dashidaira and other four reservoirs. The fitted line is described by $W_f = K\,Q^{0.5} = 12.8\,Q^{0.5}$ (section 1.2), where the width is determined by the flow and is independent of sediment size. The flushing channel width in Dashidaira reservoir is 170 m at distance of 640 m from the dam and flushing discharge of 250 m^3/s. Therefore, Sumi and Iguchi (2005), suggest that K value for Japanese reservoirs is 6.4, to be reduced by twice.

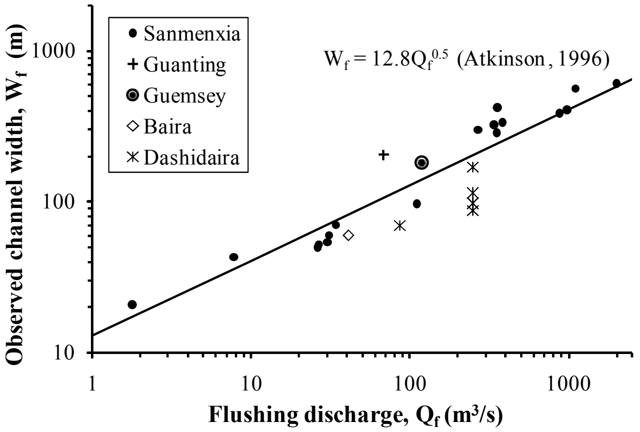

Figure 20. Comparison of Dashidaira dam flushing channel width with Atkinson relationship of four dams

To successfully apply the channel formation processes for removing deposits, the location of the channel and its width can be changed by modifications of the flow pattern. Before a channel is formed these interventions can be much smaller than that after its formation, because the channel attracts the main flow, and stabilizes the flow pattern. The present study has new information regarding the dimensions of channels of Dashidaira dam, in the laboratory and the field. The width of the channel is in accordance with the riverine width, flow pattern, water depth, discharge, and the bottom outlet arrangement. A larger volume in the reservoir generally generates a higher flushing flow depth and velocity in the flushing channel.

Reservoir sedimentation management in Japan is entering a new era. Although there are still technical problems to be solved, it is believed that the importance of 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, an effective sediment management plan should be studied.

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