Sediment Replenishing Measures for Revitalization of Japanese Rivers below Dams

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Abstract: *In Japan an effective means for reservoir sediment management is to excavate the accumulated sediment and replenishing the downstream reaches of the dam. In an effort to restore the lower reach of the river to a more natural ecosystem an artificial flood release was designed to flush the replenished sediment at the banks of Uda River downstream of Murou dam. In order to evaluate the effect of the sediment replenishment on the river morphology, LSPIV and IC-Tag technology are undertaken to monitor surface velocity and gravel movements on the river bed. Since 2006, six attempts of sediment replenishment for rebuilding vital sediment sand bars below Murou dam are in progressing. Pre- and post- sediment replenishing measurements clarified the effect of the new improvement in riverbed formation. The results indicate that the replenished sediment volumes and flushing discharges were not sufficient to enhance the downstream bed morphology and the biodiversity of Uda River. Moreover, the interval between flushing flows should be reduced when higher sediment volumes are supplied.*

Keywords: *Sediment management techniques, sediment excavation, reservoir sedimentation, sediment replenishment, river morphology.*

1. BACKGROUND

Sustainable management of sediment in river basins must be done on a regional basis, restoring the continuity of sediment transport where possible and encouraging alternatives to river-derived aggregate sources. An effective means of such comprehensive reservoir sediment management is to excavate and transport part of coarse sediment, which accumulated in reservoirs to the river channels downstream, and then the sediment will be transported by flushing flows of artificial or natural floods. Different management and ecological restoration measures to compensate the sediment deficit downstream from dams were conducted in some rivers (Kondolf, 1997). For instance, controlled flow releases (flushing flows) and beach nourishment with imported sediment dredged from reservoirs and harbours were implemented along many rivers (Inman 1976; Everts 1985; Sumi & Kanazawa 2006; Kantoush *et* al 2009). These measures range from optimising the compensation discharges, and artificial sediment feeding (sediment replenishment).

The effects of sediment replenishment must be investigated through studies and local tests before large-scale operations, and by detailed monitoring after such operations. Even if some reports of past test are available, the state-of-the-art is not consolidated enough to draw general guidelines. There are gaps to quantitatively assess the sediment deficit volume caused by large dams on a large river system, based upon regular, systematic and extensive direct measurements of total load (both in suspension and as bed load) upstream and downstream of the reservoirs. Recently, the Radio Frequency Identification (RFID) method was successfully employed in various streams using mobile antennas to determine the displacement of single transponders-tagged particles. The RFID tracer method in bed load transport monitoring with mobile antenna systems was successfully implemented by several research groups (Lamarre *et* al. 2005; Schneider *et* al. 2010, Sumi *et* al. 2010). The standard PIV method was applied to velocity measurements for larger scales, commonly named as Large Scale Particle Image Velocimetry (LSPIV) (Kantoush & Schleiss 2009)

In Japan, Europe, and USA, large rivers are often trained to a large extent, to maintain services such as navigation, hydropower generation and flood defence. Okano *et* al., (2004) summarized sediment replenishment projects in large Japanese Rivers such as Tenryu, Otakine, Abukuma, Ara, Oi, Naka, Kuzuryu, Yodo, Kanna, and Tone. Sediment treatment system was applied by Sumi *et* al. (2009), to produce appropriate grain sized material with less turbidity. Effects of sediment replenishment downstream of Yahagi dam was analysed and investigated by Seto *et* al., (2009). Large European rivers such as the Rhône, the Rhine, or the Danube, have been undergoing ecological and hydraulic restoration measures, especially in reaches bypassed by hydraulic structures. Today, rehabilitation of damaged and modified aquatic ecosystems has become an integral part of catchment and river management. Sediment transport and associated channel bed mobility are recognized as key processes for creating and maintaining physical habitats, aquatic and riparian ecosystems. In this context, various river restoration projects were initiated or implemented in many countries. Some examples include creation of secondary channels along the Rhine River (Simons et al. 2001), reconnecting the Danube side-arm system to the main channel (Tockner *et* al. 1998), removing bank protection structures to initiate sediment transport in the Mur River (Kloesch *et* al. 2008), and artificial gravel supply in the Ain River (Rollet *et* al. 2008).

In Japan, sediment replenishment projects are undertaking with different configurations and characteristics of sediment and discharges. Some of these projects are successfully implemented since all the placed sediments were eroded during high flood flows. However, some other part of these projects, the placed did not mobilize or transport according to the post- project monitoring measurements. The central challenge in sediment replenishment research is to determine sediment and flow characteristics, and how to determine sediment replenishment volume.

Indeed, river morphodynamics is a complex process that involves a high degree of interactions between the flow and sediment transport. Several significant gaps in the scientific understanding of these processes remain, particularly concerning the morphological riverbed features that are influenced by changes in flushing flow discharge and sediment replenishment volume. Replenishment scenarios may, therefore, induce undesirable morphological and ecological consequences as well as significant channel adjustments that can result in failure of the restoration project itself. That is, it is necessary to better understand the reversibility, direction and time scale of changes, and the sustainability of a replenishment intervention before it is implemented.

2. FIELD METHODS

The supplied sediment for this study was placed by the Japan Water Agency (JWA), on right side bank of Uda River downstream of Murou dam, Nara prefecture (Figure 6). Moreover, planning, design, and long-term monitoring of replenishment tests were guided by JWA. Photographs in Figure 1 show the 2010 field test of Murou dam stilling basin and the placed sand at downstream reach about 150 m from the dam site. The cross section of the placed sediment geometry is a trapezoidal shape with a groove channel near river right bank, see Figure 1.

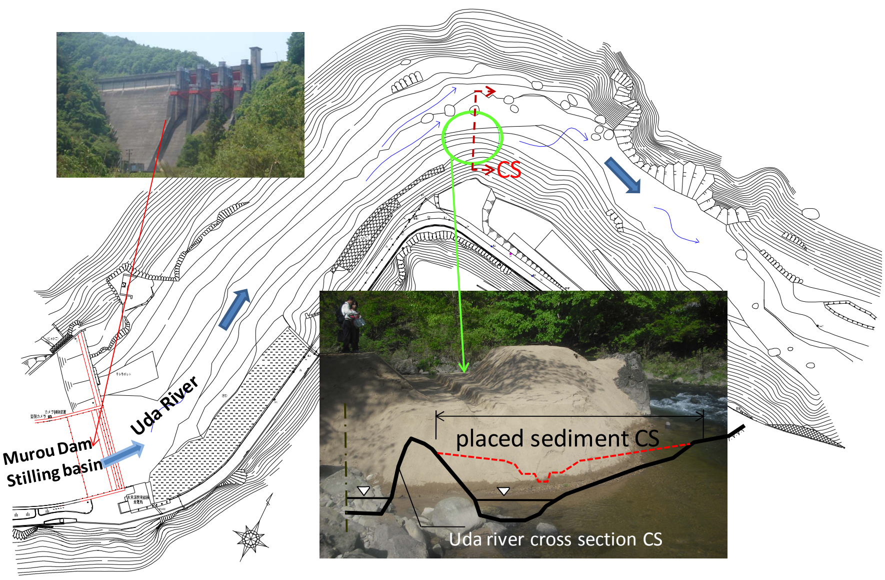


Figure 1 Sediment replenishment site in Uda River downstream reach of Murou dam.

2.1. Records of sediment replenishment downstream Murou dam

Various sediment volumes since 2006 have been supplied to Uda River downstream of Murou dam. Tracking the history and performance of these projects helps to clarify the objective of such project. Table 1 summarizes the replenishment history, type of flushing flow and sediment characteristics. The volume of placed sediment was limited to several hundred cubic meters each time. Two types of flow were used to erode the supplied sediment by using natural flood and artificial flushing flows (Table 1). Several considerations have to be given to environmental problems in the lower river basins, occurrence of turbid water, and safety risks due to sediment deposition in the channel. Concrete means are being explored, taking into consideration sediment particle sizes and the scale of flood that is suitable for safe implementation.

Table 1 History of the sediment replenishment tests downstream of Murou dam

Year	Setting and placing sediment period	Time of artificial or natural flow	Type of flushing flow	Volume of placed sediment (m^3)	Volume of sediment transport
2006	From 12-5-2006	13,14-5-2006	Natural flood	90	90
	To 16-5-2006	17,18-5-2006	Natural flood	50	50
2007	From 8-5-2007	18-5-2007	Artificial flushing	250	150
	To 10-5-2007	24-5-2007	Natural flood		100
2008	From 12-5-2008	16-5-2008	Artificial flushing	230	170
	To 15-5-2008	25-5-2008	Natural flood		60
2009	From 7-5-2009	14-5-2009	Artificial flushing	280	230
	To 12-5-2009	31-5-2009	Natural flood		50
2010	From 13-5-2010	17-5-2010	Artificial flushing	200	165
	To 16-5-2006	24-5-2010	Natural flood		35

2.2. Monitoring techniques

Innovative methods for sediment replenishment monitoring techniques should be developed in order to evaluate environmental influences and effectiveness of replenishing. These monitoring efforts pre- and post- replenishment methods show the effect of improvements in riverbed formation, riverbed materials, benthic organisms, and algae. Several parameters were measured during and after replenishing, namely: cross section bathymetry, 2D surface velocities, and tracing bedload transport. Figure 2 shows the placed sediment geometry with the installed RFID system and LSPIV camera.

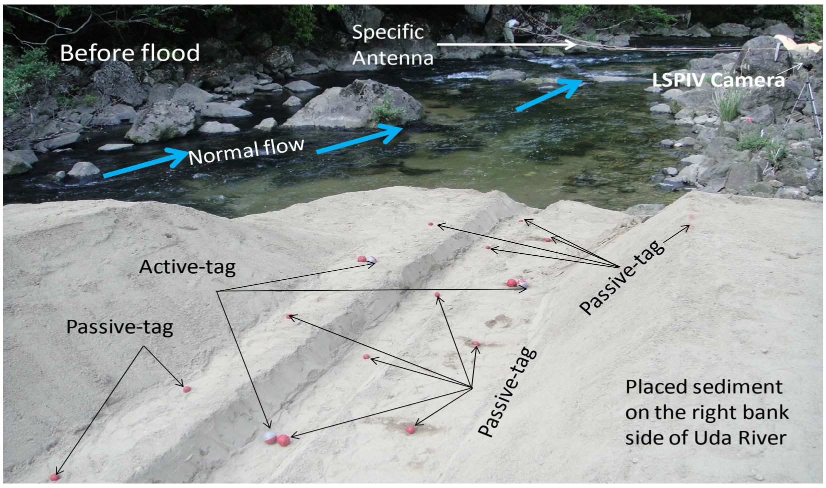


Figure 2 Picture of monitoring techniques before flushing flow below Murou, 16 May 2010.

The RFID system consists of reader and control unit, antenna and transponder (tags) used for tagging the object of interest. In the study five active and 20 passive-tags were used as shown in Figure 2.

Several types of passive and active tags were developed see Table 2. The active tags have battery inside, which increase the reading distance for 5m as for RUBEE type (Table 2). The TI-RFID and RUBEE tags were investigated under water conditions in a series of laboratory experiments (Table 2). The operating frequencies of the system used in this study are 131 kHz for RUBEE-tag and 134.2 kHz for TI-RFID tag as shown in Figures 3(a, b), which is the Low-Frequency (LF) category. Compared to High-Frequency, the LF signal can be used under water conditions since the signal can pass through water, rock, concrete, wood and mud.

Table 2 Different IC-Tag system comparison used for bed load movement tracking

IC-Tags Type	Passive Tag			Active Tag	
Name	TI-RFID	FeliCa	μ-chip	RUBEE	ZigBee
Frequency(Hz)	134.2k	13.56M	2.45G	131k	2.4G
Reading distance	1m	10cm	30cm	5m	Ca.10m
Age of battery	—	—	—	5 yrs	1 yrs
Underwater conditions	water and air	air	air	water and air	air

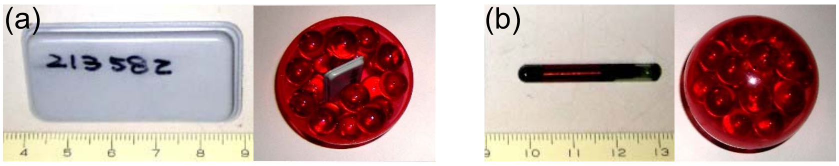


Figure 3 (a) RUBEE- Tag (50mm×25mm, 3mm), (b) Passive TI-RFID(φ3.85mm 32mm)

For LSPIV technique, a Sony camera was used to record images with 30fps and 740 by 480 pixels. Naturally occurring turbulence, sediment clouds, differences of watercolour and bed features reflections on the flow surface were used as seeding tracers. The combination of these tracers was present during flushing that facilitating the LSPIV measurements in a situation where none of the other techniques can be used due to safety. Dantec's FlowManager software was used to perform the necessary calibration, correlation functions, filtering, and statistical calculations on images to generate the resolved velocity fields. Raw pixel displacement fields were computed using a standard cross-correlation algorithm.

2.3. Characteristics of the flow and supplied sediments

Figure 4 shows the monthly inflow and outflow discharges of Murou reservoir in 2009, with the reservoir storage capacity. The reservoir has the highest flow discharges during July and October. The post-dam hydrograph shows a significant reduction in flood peaks and the maximum use of the outflow discharge is about 14.0 m^3/s. The timelines of sediment supply, placement, starting of artificial flushing, and monitoring measurements are shown in Figure 4. There are three monitoring phases; before artificial flushing, after artificial flushing, and after natural flood. Dam gate was opened from 8:00 with 1.34 m^3/s and gradually increased till reach to peak at 12:00 with 14m^3/s.

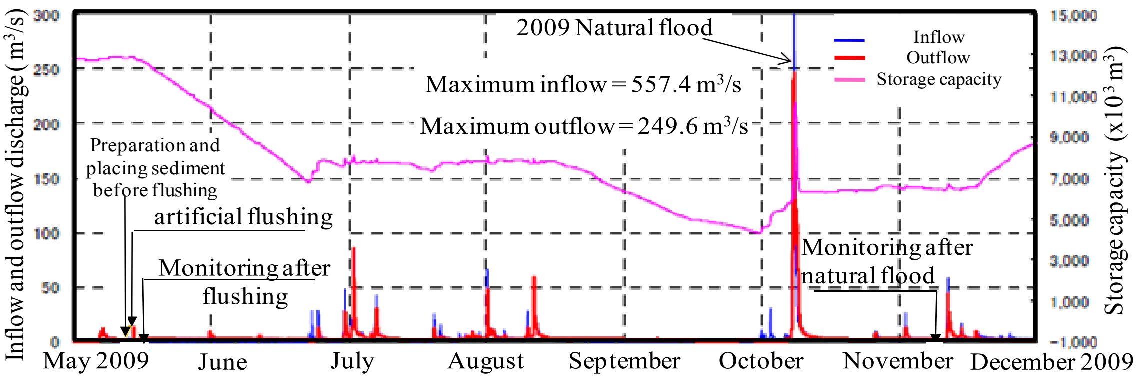


Figure 4 Flow duration curves before and after flushing and flood discharges at the Murou dam

The supplied sediment is composed of sand and gravel with grain size of 19 mm or less. There are a lot of medium gravel with size of 10 mm and medium sand size of about 0.25 mm. The placed sediment median grain size d_{50} is 1.25 mm as shown in Figure 5. The grain distribution is well sorted.

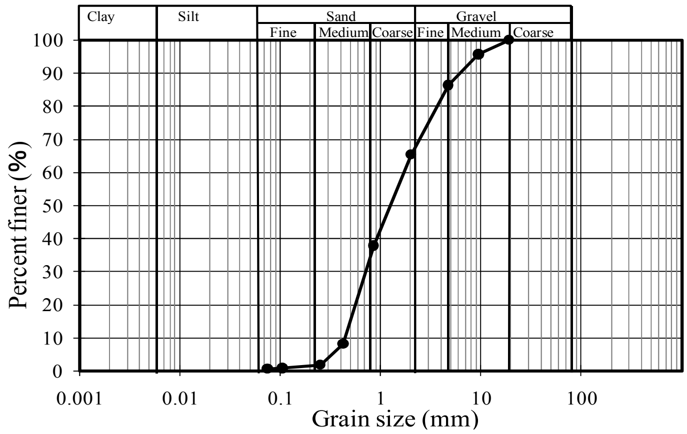


Figure 5 Grain size distribution of the placed sediment used for replenishment in Uda River

3. RESULTS

The evolving bed topography and grain size distribution were monitored, along with water surface, velocities and bedload movement at the downstream end of the river. Measurements were performed at various cross sections along the river. With the field experiments the processes were directly visible and a wealth of valuable data was obtained, and thereby will be used for further investigations.

3.1. Flow field

The time variant surface velocities measured by LSPIV at three different positions are shown in Figures 6 (a, b, c and d). Figures clearly depict the variations between velocity magnitudes in normal and peak flow phases. It appears that changes of water levels from normal to peak stages are significantly influence the direction and magnitude of flow, especially for the placed sediment erosion processes. In Figure 6 the flow fields are plotted superimposed on the eroded sediment picture (left side) and the corresponding colour contours of velocity magnitudes (right side). In the upstream part of the placed sediment at time t_0 flow was forced to diverge laterally to left side and a large circulation cell on right side was formed (Figure 6(a)).

Flow moved out with low velocity about 0.75 m/s and erodes the front face of placed geometry as shown in Figure 6(b). At higher discharges t_1, the placed geometry was partially submerged and the flow velocities were increased to 1.25 m/s as shown in Figure 6(b). When the discharge lasted for long duration the, most of the placed sediment was eroded as shown in Figure 6(c). The flow velocities at this time t_2 downstream of the placed sediment were much higher than during the same discharge on the upstream region. Figure 6(d) shows velocity field further downstream of the placed sediment and near the antenna of RFID system. Most of the active and passive tags showed in Figure 2 were detected during and after the artificial flushing. It is interesting to see in Figure 6(d) that the tracked tags followed a very similar trajectory with higher velocity magnitudes of 2.0 m/s. During the flushing, movements of three active-Tags were detected by antenna. The other two active tags were apparently trapped by large rocks or pools on the side of the Uda River. It indicates that the travel distance of the placed sediment were more than 10 m during the flushing period. Moreover, with the natural flood event most of deposited sediments were transported farther downstream.

3.2. Morphological evolution processes

To understand the process of scouring and deposition during 2009 flushing, series of pictures were taken at different times and different discharges as shown in Figure 7. The erosion at the base of the placed sediment caused the sand mass of placed sediment bank to slide downward and deposit. The deposited sand mass was then flushed due to the higher velocity at peak discharge. The width of the erosion during whole flushing periods was one to three times the height of the placed sediment. The erosion region developed from a straight bank line into the crenulated shaped (half moon shape) as seen in Figure 7 (b). At the peak discharge the water level increased at t_3 produce a greater erosion area and the water enters the grove channel in the placed sediment as shown in Figure 7(c).

Artificial flushing increased the erosion rate and transported the sediment out of the region. The peak discharge lasted for two hours and permits a deeper cut in the placed sediment bank. With peak flow, the eroded volumes increased in the range of 45 percent. Reduction of discharge at t_5 reduced the erosion rate, therefore 50 m^3 of the placed sediment remain as shown in Figure 7(f). By looking downstream in Figure 7, the erosion started at the inner bank of the placed sediment till the half moon shape is formed due to gradually increase of the discharge at t_1 and t_2, see Figure 7(a, b). Looking upstream to the dam side, during the peak discharge one part of the placed sediment was isolated and collapsed as a block. Apparently, 20 percent of the placed volume that were placed in higher elevation on right bank was not transported because of low water level during peak flow.

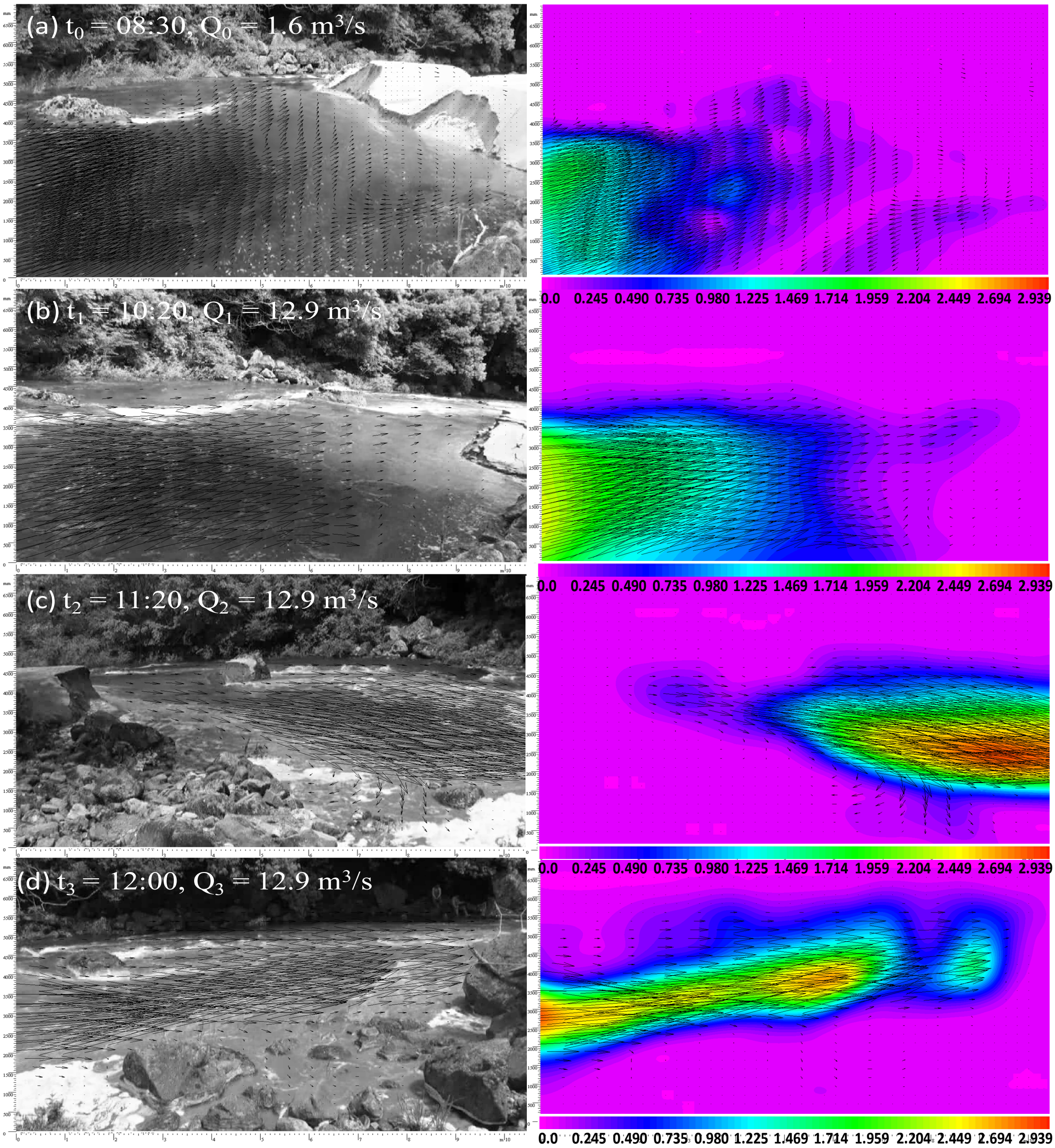
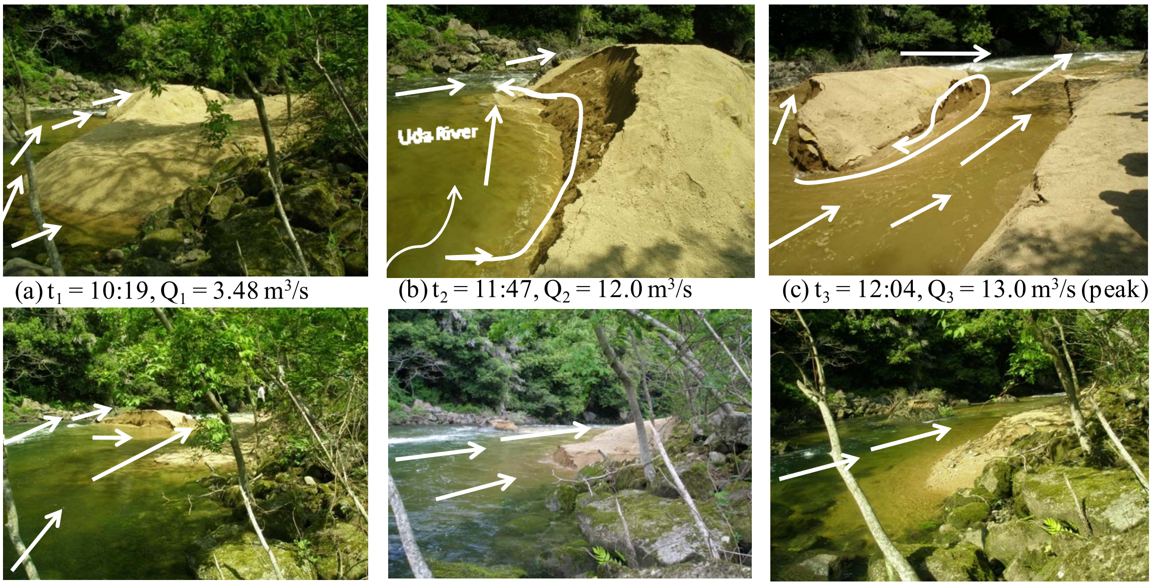


Figure 6 Flow field and velocity (m/s) during 17 May 2010 artificial flushing of Murou dam



(a) t_1 = 10:19, Q_1 = 3.48 m³/s (b) t_2 = 11:47, Q_2 = 12.0 m³/s (c) t_3 = 12:04, Q_3 = 13.0 m³/s (peak)

(d) t_4 = 12:34, Q_4 = 13.0 m³/s (peak) (e) t_5 = 14:26, Q_5 = 5.0 m³/s (f) t_6 = 15:05, Q_6 = 2.5 m³/s

Figure 7 Morphological evolutions during 14 May 2009 artificial flushing of Murou dam

3.3. Changes in river bed materials

The effects of sediment replenishment are investigated on cross section bed deposition, grain size distribution, water quality and organisms. Thirteen monitoring points below Murou dam are investigated and their locations are shown in Figure 9. The distribution of river bed materials are analysed by visually determining the sizes of river bed material in quadrates of 1 to 2 m in dimensions and preparing a two dimensional map, which enabled changes in distribution before and after sediment replenishment to be compared. Figure 8 presents the changes in the river bed material before and after sediment replenishment and after natural flood. By comparing Figure 8(a) and 8(b), a significant riverbed changes can be identified from cross sectional surveys, and visual inspections. But after the natural flood the newly deposited sediment grace to the replenishment is eroded again and replaced by a larger boulders and rocks.

(a) before flushing (b) after flushing and replenishment (c) after natural flood

Figure 8 Photographs of Uda river bed depositions in different months in 2009

Figure 9 shows bed material size in three different monitoring times and 13 observation points along the river. Before sediment replenishment in point No 2 and No 2-1, the material is coarser gravel than in the farther downstream points No 4 and No 7 (Figure 9(a)). After flushing, the fine material content of the channel deposits strongly increased. The sediment deposition in point No 2 and No 2-1 after replenishment consist of a nearly continuous layer of fine sand, but no change occurs further downstream (Figure 9(b)). But after natural flood where a less placed sediment volume, the bed material is transported and much of the coarsest sediment is supplied to point No 2, and No 4 (Figure 9 (c)). The mount of supplied sediments is not effectively influenced on the river bed after natural flood occurs.

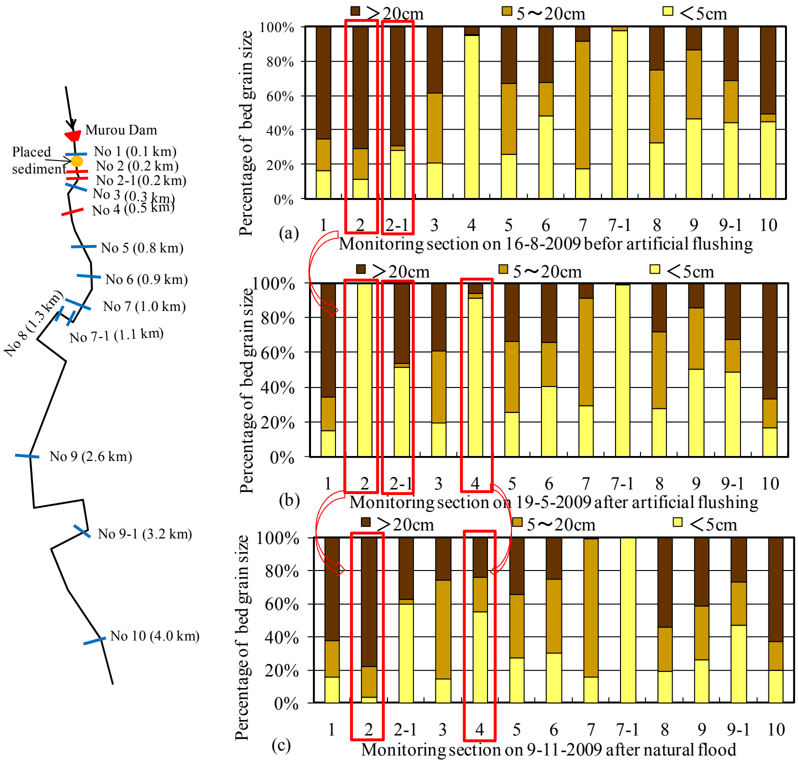


Figure 9 Variations of river bed material size in 13 cross sections along Uda River

4. DISCUSSIONS

The first results of ongoing research on the artificial sediment replenishment downstream dams are presented. This paper has pointed out the alteration of sediment transport and, subsequently, of the fluvial dynamics due to dam impacts in a large river system. The downstream sediment replenishment method is currently being field tested at Murou dam, but so far not enough knowledge has been accumulated about its influence on lives in rivers and coastal areas.

By replenishing sand at different locations of the Uda River within the downstream reaches, the replenishment may direct future supplements for a more widespread dispersal of suitable sand for fish spawning. In order to put the downstream sediment replenishment method to practical use, it is also important to share information with the people concerned in the same river basin, such as fishery workers associations and environmental groups, and endeavour to make the method socially acceptable. Sediment replenishment for the purpose of keeping a dam functional needs to be performed semi-permanently. There is a need to increase the amount of the supplied sediment and artificial flow discharge every year. The increasing amount of flushing flow discharges should erode the placed sediment and move typical size gravel of 10 cm.

Furthermore, the flushing period and flushing interval should be increased. The artificial flushing duration for Murou dam is approximately 10 hours, including peak discharge of 3 hours. Neither the flushing discharge nor the flushing period is able to transport all the placed sediment volume. The remained sediment was transported during the natural flood periods that have large discharge and period. Therefore, a combination between artificial and natural flow should be planned and designed. The flood is expected once every summer season; therefore sediment replenishment should be implemented just before this flood event. Moreover, sediment placement should be planned in the combination of lower channel and higher side bank levels (direct and indirect sediment supply). The most reliable way for establishing the discharge of flushing flow requirements is to observe the studied river or stream at various flow levels. By periodically increase the discharge either artificially or naturally, as illustrated in Figure 10, is required to distribute previously deposited sediment to far downstream channel following natural morphological features.

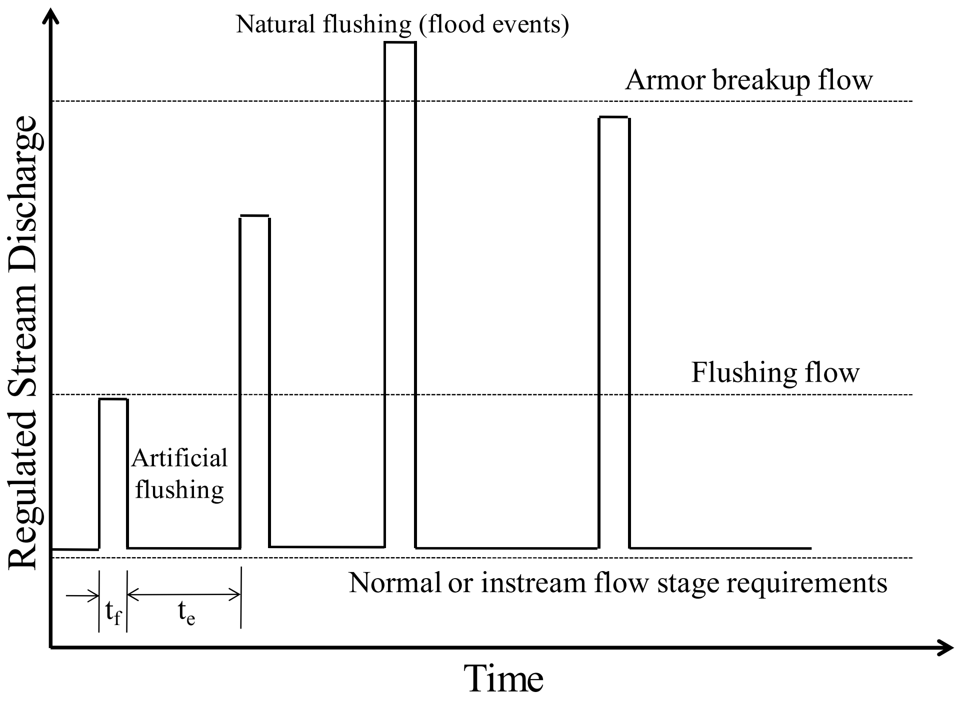


Figure 10 Schematic of the artificial and natural discharge required for sediment replenishment of Murou dam (Here t_f is the duration of the flushing flow, t_e is the interval between flushing)

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