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THE EFFECT OF SEDIMENT FLUSHING AND ENVIRONMENTAL MITIGATION MEASURES IN THE KUROBE RIVER *

Tetsuya SUMI
Associate professor, Dr. of Engineering
Department of Civil and Earth Resources Engineering, Kyoto University

Shin-ya NAKAMURA
Former Head of the Kurobe River Work Office, Dr. of Engineering
Ministry of Land, Infrastructure, Transport and Tourism

Kyuichi HAYASHI
Chief Manager, Engineering Group
Hokuriku Branch, Kansai Electric Power Co., Ltd.

JAPAN

1. INTRODUCTION

The Kurobe River in the eastern region of Toyama Prefecture is a representative steep river in Japan which stretches over 85 km in a 682 km^2 drainage basin (Figs. 1 and 2). The Unazuki Dam (completed in 2001, height: 97 m, gross capacity of reservoir: 24,700,000 m^3), which is under the control of Ministry of Land, Infrastructure, Transport and Tourism, is located at the farthest point downstream of the Kurobe River. The Dashidaira Dam (completed in 1985, height: 76.7 m, gross capacity of reservoir: 9,010,000 m^3) owned by Kansai Electric Power Co. Ltd. is located at the upstream of the Unazuki Dam. These two dams have an extremely large amount of sediment inflow compared to their gross storage capacity of reservoir; therefore, they were the first in Japan which was

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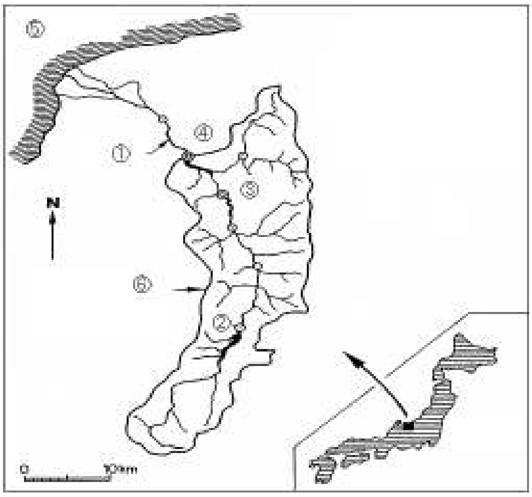
* *Les effets de la chasse de sédiments et des mesures de gestion environnementales dans la rivière kurobe*

built with full-scale sediment flushing facilities (sediment flushing gates). Sediment flushing has been conducted on the Dashidaira Dam since 1991. Since 2001, when the Unazuki Dam was completed, sediment flushing and sluicing have been conducted coordinately for the two dams (Photo 1).



① Kurobe river
② Kurobe dam
③ Dashidaira dam
④ Unazuki dam
⑤ Toyama bay
⑥ Catchment area 617.5km²

① *Rivière Kurobe*
② *Barrage de Kurobe*
③ *Barrage de Dashidaira*
④ *Barrage d'Unazuki*
⑤ *Baie de Toyama*
⑥ *Superficie du basin hydrographique 617.5km²*

Fig.1
Kurobe river basin
Bassin de la rivière Kurobe

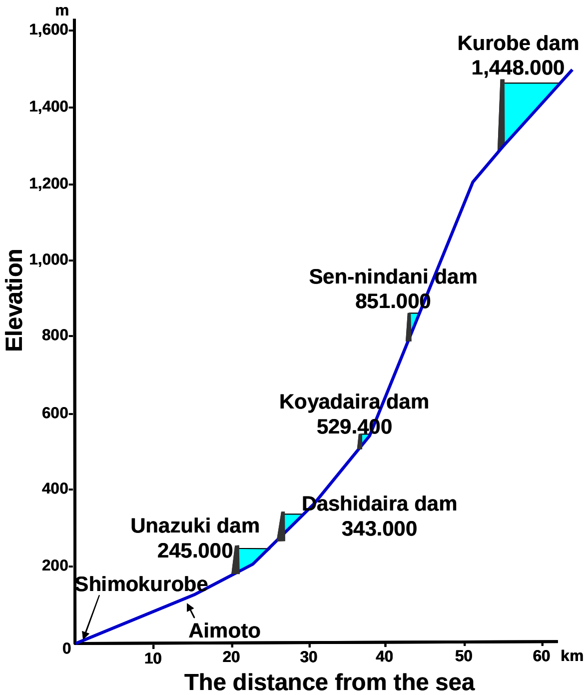


Fig. 2
Longitudinal profile of the Kurobe River
Profil longitudinal de la rivière Kurobe

Unazuki dam
Barrage d'Unazuki

Dashidaira dam
Barrage de Dashidaira

Photo 1
Unazuki and Dashidaira dam during coordinated flushing
Barrages Unazuki et Dashidaira lors de chasses coordonnées de sédiment

Kokubo[1], Liu[2] and Sumi[3] and others have presented an overview of coordinated sediment flushing operations at the Dashidaira and Unazuki Dams, which are typical sediment flushing sites in Japan. In this paper we analyze sediment flushing operations to date, and describe the effects of sediment flushing on the sediment continuity in the river basin and physical environment on the river. We also describe technological initiatives to make the sediment flushing operations more sophisticated, and environmental protection initiatives to minimize the impacts of sediment flushing on the downstream river environment.

2. ANALYSIS ON COORDINATED SEDIMENT FLUSHING OPERATIONS

While it is important to maintain high sediment flushing efficiency in a sediment flushing operation, it is also necessary to minimize the downstream impact of flushed sediment.

2.1. CRITERIA FOR CONDUCTING SEDIMENT FLUSHING AND SLUICING

Since the completion of the Unazuki Dam in 2001, seven sediment flushing and seven sediment sluicing operations have been conducted. When a flood in excess of 300 (250 in some special case) m^3/s of inflow occurs at the Dashidaira Dam at the first time of the year between June and August, a coordinated sediment flushing is performed. Whenever a flood in excess of 480 m^3/s occurs at the Dashidaira Dam after sediment flushing, a sediment sluicing is performed. These sediment flushing and sluicing practices have been taken place by agreement in the Kurobe River Sediment Flushing Evaluation Committee and the

Kurobe River Sediment Management Council, considering the natural flow regime in the Kurobe River as well as the impacts of sediment discharge downstream.

Fig. 3 shows the frequency distribution of discharges when the flood peaks in each year since 2001. Fig. 4 shows the average rainfall in the river basin and the inflow discharge to the Dashidaira Dam in 2006, as an example. The floods occur primarily due to melting snow in May and the rainy season from June to August. The flushing period of June to August was chosen by considering these natural flow regime and the impacts on fishing and agricultural water use both in the downstream river and the connected sea shore area. In recent years, water flow in excess of 300 (250 in some special case) m^3/s of inflow at the Dashidaira Dam has been occurring several times a year, and a flood in excess of 480 m^3/s has been occurring about once a year. The threshold values are considered to be appropriate to perform sediment flushing operations regularly.

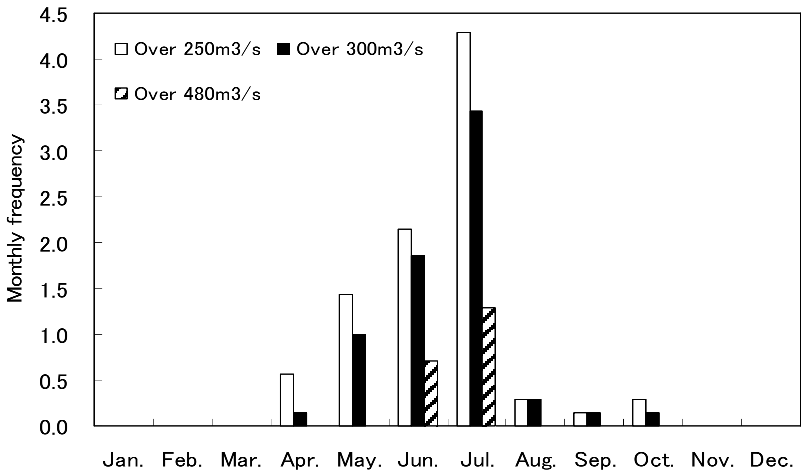


Fig. 3

Monthly frequency for every inflow rates to the Dashidaira Dam since 2001

Fréquence mensuelle pour chaque débit entrant dans le barrage Dashidaira depuis 2001

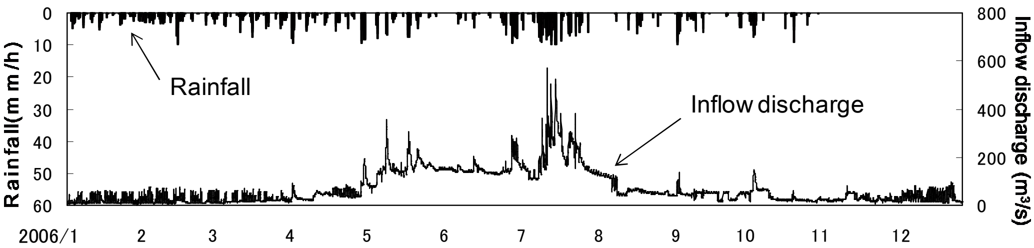


Fig. 4

Average rainfall in the river basin and inflow discharge to the Dashidaira Dam in 2006

Précipitation moyenne dans le bassin de la rivière et évacuation du débit entrant au barrage Dashidaira en 2006

The basic sequence of operations for sediment flushing is: drawing down the reservoir water level, keeping free flow state in several hours and recovering water level. The amount of time for the free flow sediment flushing depends largely on the target amount of sediment to be flushed, which is planned prior to a sediment flushing operation. Fig. 5 shows actual sediment flushing operation performed in July 2006, as an example. Free flow state was continued for 12 hours to flush out deposited sediment of 240,000 m^3.

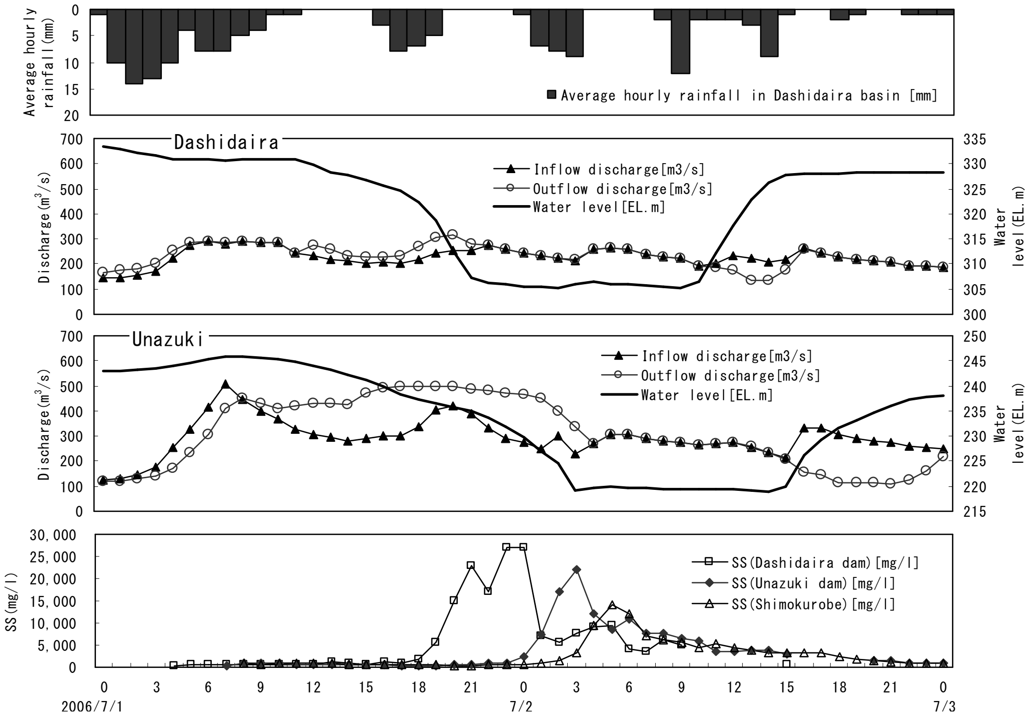


Fig.5

Coordinated sediment flushing operation in 2006

Opération coordonnée de chasses de sédiments en 2006

2.2. Actual Sediment Flushing and Sediment Flushing Efficiency

Table 1 shows the actual amount of sediment flushed out of Dashidaira Dam since 2001. Flooding events when sediment flushing took place were those with about 500 m^3/s of discharge for sediment flushing, and about 700 m^3/s for sediment sluicing. The flushing volume data was obtained by measuring the cumulative amount of sediment in the dam reservoir after the previous year's sediment flushing operation to the end of May. This quantity fluctuates depending on flooding events out of the sediment flushing season from autumn to spring.

Fig. 6 shows the relationship between the quantity of flushed sediment and the quantity of water used during sediment flushing operations. To measure the quantity of water used, we calculated the total discharge in two periods: (1) from the start of drawing down reservoir water level to the completion of recovering water level, and (2) from the start to the end of the free flow flushing phase. As shown in Fig. 6, duration of sediment flushing namely the total discharge is planned to be longer depending on the quantity of sediment to be flushed as seen at 2005 flushing example.

Table 1
Actual sediment flushing and sluicing operations at the Dashidaira Dam
Opérations réelles de chasse et d'écoulement au barrage Dashidaira

	Maximum Discharge Inflow (m^3/s)	Average Discharge Inflow (m^3/s)	Flushing Volume (10^3 m^3)	Maximum SS (mg/l)	Average SS (mg/l)
2001 Flushing	333	277	590	90,000	15,000
2001 Sluicing	491	273		29,000	6,700
2002 Flushing	362	215	60	22,000	4,500
2003 Flushing	777	217	90	69,000	7,100
2004 Flushing	356	229	280	42,000	10,000
2004 Sluicing	1,152	281		16,000	7,300
2005 Flushing	958	290	510	47,000	17,000
2005 Sluicing 1	835	275		90,000	16,000
2005 Sluicing 2	790	250		40,000	7,300
2006 Flushing	308	246	240	27,000	6,500
2006 Sluicing 1	378	203		12,000	2,500
2006 Sluicing 2	685	264		27,000	5,200
2006 Sluicing 3	529	196		7,400	1,800
2007 Flushing	418	245	120	25,000	3,500
Average of Flushing	502	246	270	46,000	9,100
Average of Sluicing	694	249		31,600	6,700
Average of All Data	598	247	270	38,800	7,900

Fig. 7 shows sediment flushing efficiencies at the Dashidaira Dam, which are calculated by the quantity of flushed sediment and the quantity of water used defined by the above two periods. The sediment flushing efficiency which is calculated by the quantity of water used during the free flow phase was about 0.01 to 0.03. As shown in the Figure, the sediment flushing efficiencies became much higher in 2007. In this year, relatively lower water level operation was maintained for a long time prior to the sediment flushing. This operation pushed the accumulated sediment to the dam prior to the free flow operation, which made the flushing more efficient than usual during the free flow operation.

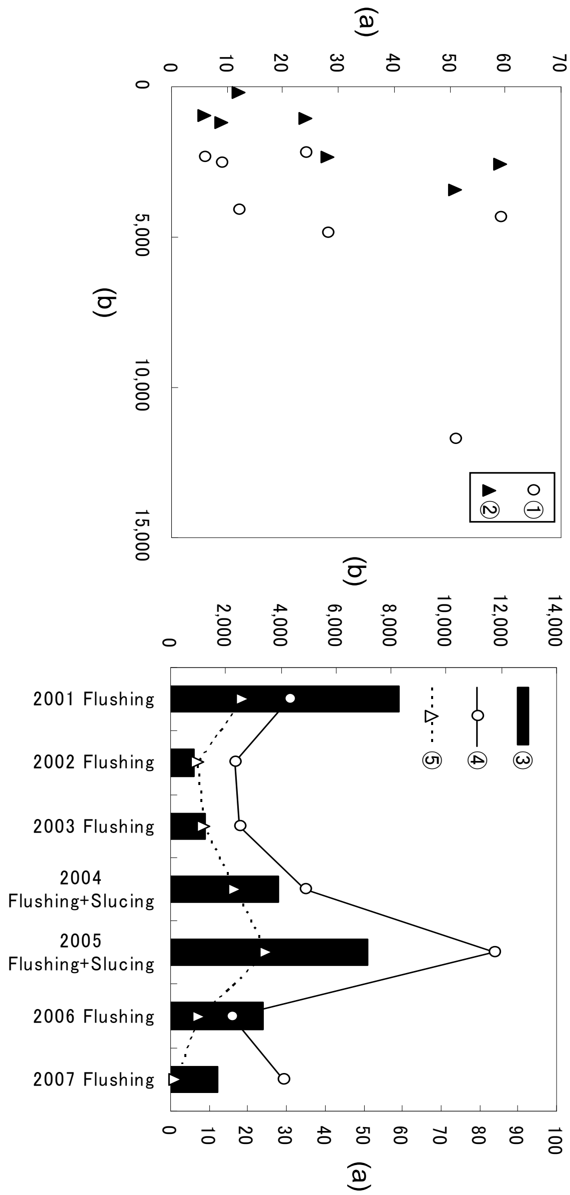


Fig. 6

Relationship between the quantity of water used and the quantity of flushed sediment

Relation entre la quantité d'eau utilisée et la quantité de sédiment chassé

(a) Quantity of flushed sediment (×$10^4 m^3$)

(b) Quantity of water used (×$10^4 m^3$)

① From start of water level draw down to the end of water level recovery

② From start to the end of free flow phase

③ Quantity of flushed sediment

④ From start of water level draw down to the end of water level recovery

⑤ From start to the end of free flow phase

(a) *Quantité de sédiment chassé (×$10^4 m^3$)*

(b) *Quantité d'eau utilisée (×$10^4 m^3$)*

① *Du début de la baisse du niveau amont jusqu'à la fin du remplissage du réservoir*

② *Du début à la fin de la phase d'écoulement libre*

③ *Quantité de sédiment chassé*

④ *Du début de la baisse du niveau amont jusqu'à la fin du remplissage du réservoir*

⑤ *Du début à la fin de la phase d'écoulement libre*

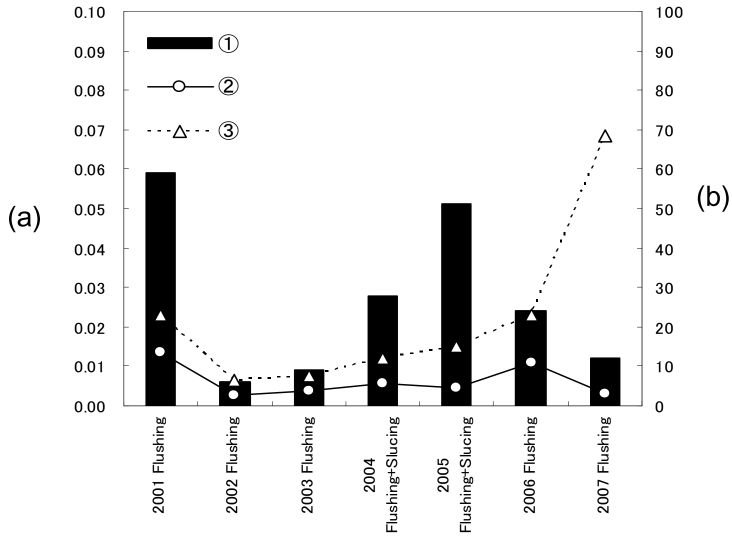


Fig. 7
Sediment flushing efficiency
Efficacité de la chasse de sédiment

(a) Sediment flushing efficiency
(Flushed sediment / Used water)
(b) Quantity of flushed sediment (×$10^4 m^3$)
① Quantity of flushed sediment
② From start of water level draw down to the end of water level recovery
③ From start to the end of free flow phase

(a) *Efficacité de la chasse de sédiment*
(Sédiment chassé / eau utilisée)
(b) *Quantité de sédiment chassé (×$10^4 m^3$)*
① *Quantité de sédiment chassé*
② *Du début de la baisse du niveau amont jusqu'à la fin du remplissage du réservoir*
③ *Du début à la fin de la phase d'écoulement libre*

2.3. SS DISCHARGE AND CONTROLLING FACTORS

Fig. 8 shows the changes in SS discharge during each sediment flushing operation plotted with the peak time set to zero, while Table 1 shows the maximum and average amount of SS. Unlike sediment sluicing, sediment flushing flushes the accumulated sediment since the last year's sediment sluicing all at once, with high SS discharge peaks.

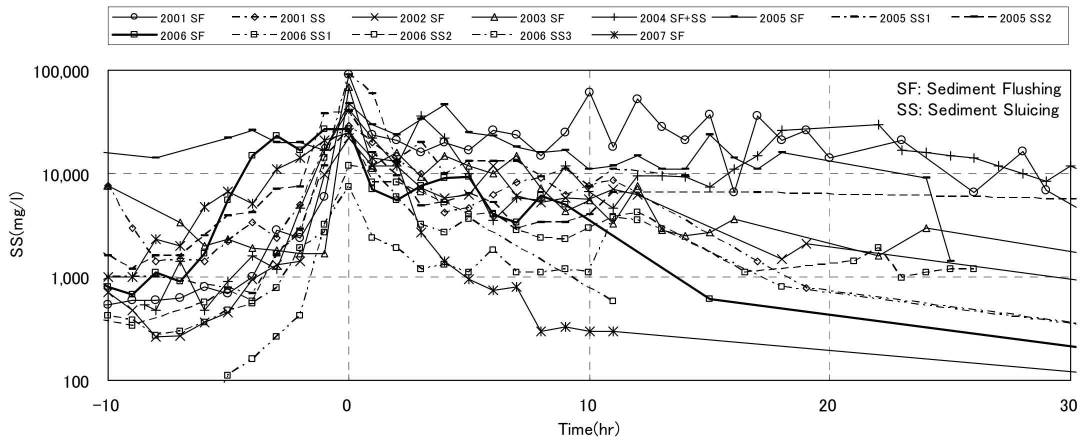
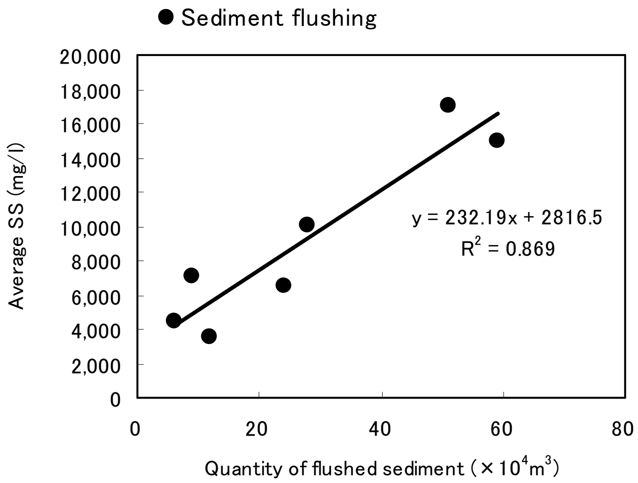


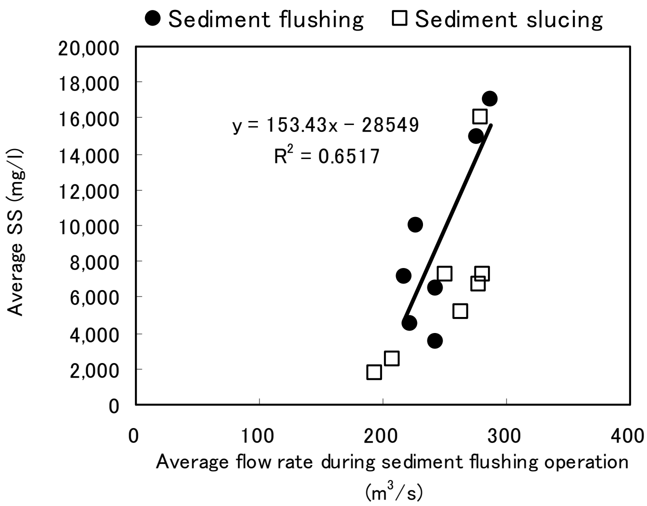
Fig. 8
Changes in SS (Dashidaira dam)
Modification des MES (barrage Dashidaira)

We will now discuss the factors that affect the SS. Figs. 9 (a) to (c) show the relationship between the average SS and the quantity of flushed sediment and the average flow rate during the sediment flushing operation, and the maximum SS and reservoir water level draw down speed, respectively. Generally speaking, as Fig. 5 shows, the amount of flushed SS during a sediment flushing operation increases from starting point when the reservoir water level is drawn down to the start of the free flow phase. As shown in Fig. 9, the average SS is higher for a larger quantity of flushed sediment, and for a larger average flow rate during a flushing operation. We attribute this to the fact that a larger quantity of sediment is flushed downstream, and that the sediment concentration flowing in is also higher. The maximum SS values, although they fluctuate, tend to be high when the speed of drawing down the reservoir water level is high. This is presumably due to the fact that, as the water level is drawn down, part of a reservoir becomes a river state again, which increases the flushing power, pushing the accumulated tiny sedimentary particles downstream all at once. To plan sediment flushing operations that are less taxing on the environment, we need to forecast these effects and adjust for them with dam operations such as controlling the speed of drawing down the reservoir water level.



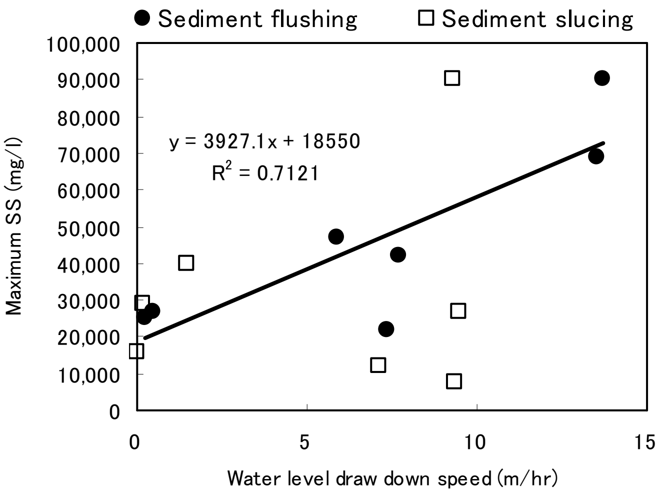
(1) Relationship between average SS and quantity of flushed sediment

Relation entre la moyenne des MES et la quantité de sédiment chassé



(2) Relationship between average SS and average flow rate during sediment flushing operation

Relation entre la moyenne des MES et la moyenne de débit durant l'opération de chasse de sédiment



(3) Relationship between the maximum SS and water level draw down speed

Relation entre le maximum des MES et la vitesse de baisse du niveau d'eau

Fig. 9

Relationship between SS during a sediment flushing operation and controlling factors
Relation entre les MES pendant une opération de chasse de sédiment et les facteurs contrôlant

3. EVALUATION OF SEDIMENT FLUSHING EFFECTS

The effects of sediment flushing in the Kurobe River should be evaluated in three locations: the river downstream, at the mouth of the river, and at the neighboring sea shore. Also, since the Dashidaira and Unazuki Dams were completed in different years, we need to consider each of the following time periods: (a) before the completion of the Dashidaira Dam (before 1985), (b) before the start of sediment flushing at the Dashidaira Dam (1985-1990), (c) before the completion of the Unazuki Dam (1990-2000), and (d) the present period when coordinated sediment flushing has been performed. Items to be evaluate include (1) physical environment (riverbed level (average and deepest point), composition of the riverbed materials, amount of sediment transport, change in the shoreline, etc.), (2) water environment (water quality, quality of the bottom sediment, etc.), and (3) biological environment (algae, benthos, fish, birds, etc.). Such considerations are in progress by the Kurobe River Dam Sediment Flushing Evaluation Committee.

In addition to these items, we will discuss the sediment balance to maintain the continuity of sediment transport in the river basin, change in physical environment in the river channel, and the environmental conditions at the bottom of reservoir.

3.1. SEDIMENT BALANCE DUE TO SEDIMENT FLUSHING

Fig. 10 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 its equilibrium state. In contrast, because the Unazuki Dam was completed only recently, the accumulation of sediment is currently still in progress mainly with coarse sediment that was brought by sediment flushing from the Dashidaira Dam as well as from the Kuronagi River which is a tributary of the Kurobe River. The accumulation of sediment at the Unazuki Dam was being reduced in 2006, and as the size of sediment materials is now being 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.

A one-dimensional river bed evolution model has been constructed for the Kurobe River in order to forecast the amount of sediment and to evaluate its effect on the downstream river bed, taking into consideration the sedimentation and sediment flushing at the reservoirs. Fig. 11 shows the inflows and outflows of sediments for different grain sizes in July 2006, which contains one sediment flushing and two sediment sluicing operations, by comparison with data such as measured SS values and change of sedimentation at the reservoirs

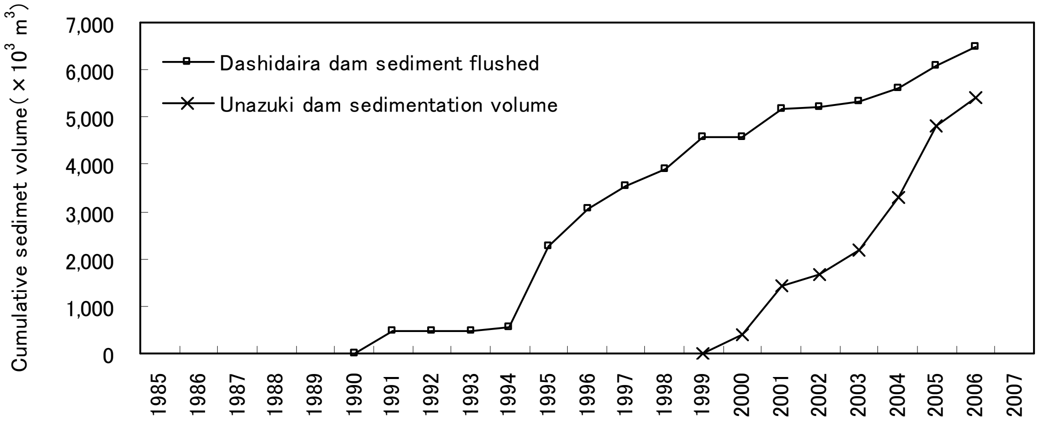
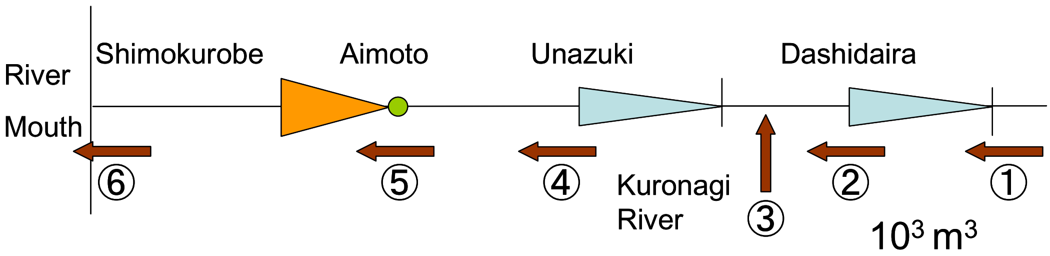


Fig. 10

Amount of flushed sediment at the Dashidaira Dam and accumulated sediment at the Unazuki Dams

Quantité de sédiment chassé au barrage Dashidaira et sédiment accumulé au barrage Unazuki



	①	②	③	④	⑤	⑥
70mm <	37	93	50	0	4	0
2-70mm	54	165	108	18	60	80
0.2-2mm	123	279	213	479	386	312
< 0.2mm	201	371	97	513	564	556
Total	416	909	468	1,010	1,013	948

Fig. 11

Inflows and outflows of sediment of different grain sizes in July 2006

Débits entrants et sortants de sédiment de différentes granulométries en juillet 2006

According to this chart, the Dashidaira Dam flushes out 910,000 m^3 of sediment which includes 420,000 m^3 of newly inflowing sediment. The Unazuki Dam has an inflow of 1,380,000 m^3 of sediment which includes 470,000 m^3 from the Kuronagi tributary. From this inflow, the dam is passing through 1,010,000 m^3, or 73%, which mainly consists of fine sediments smaller than 2 mm. The amount of coarse sediments larger than 2 mm passing through the Unazuki dam is only 20,000 m^3, or 10%, and 90% is currently trapped at the reservoir. In the river channel downstream, it is estimated that there is almost the same quantity of sediment load as the one flushed out from the Unazuki Dam. Among this sediment load, the wash load component, which is smaller than 0.2 mm, is washed out directly to the sea. While a part of the 0.2-2 mm diameter component of this sediment load is trapped on the riverbed, we believe that some amount of river bed materials larger than 2 mm is washed downstream. We further expect that the passing of the coarse sediment component from the Unazuki Dam will increase in the future, and accordingly it will further be supplied downstream.

3.2. PHYSICAL ENVIRONMENT CHANGES IN THE DOWNSTREAM RIVER CHANNEL

In the Kurobe River downstream, 0-6 km from the river mouth is braided channel, and 6-13 km from the river mouth is single bar. Fig. 12 shows the average riverbed level for each section from year to year based on the one in 1980 before the Dashidaira Dam was completed. While the riverbed degradation had been occurred over all sections of the downstream river channel, after sediment flushing was begun, the riverbed began to rise again, mainly in the sections closest to the river mouth. Slightly riverbed degradation started again after the Unazuki Dam was completed, but we can now notice the riverbed aggradations again, reflecting the coordinated sediment flushing.

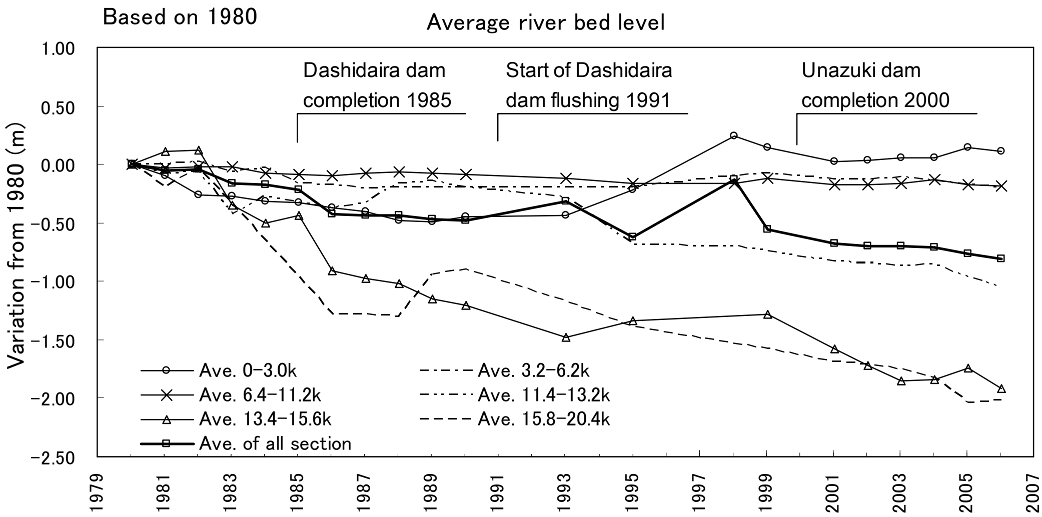


Fig. 12

Relationship between river bed level and sediment flushing

Relation entre le niveau du lit de la rivière et la chasse de sédiment

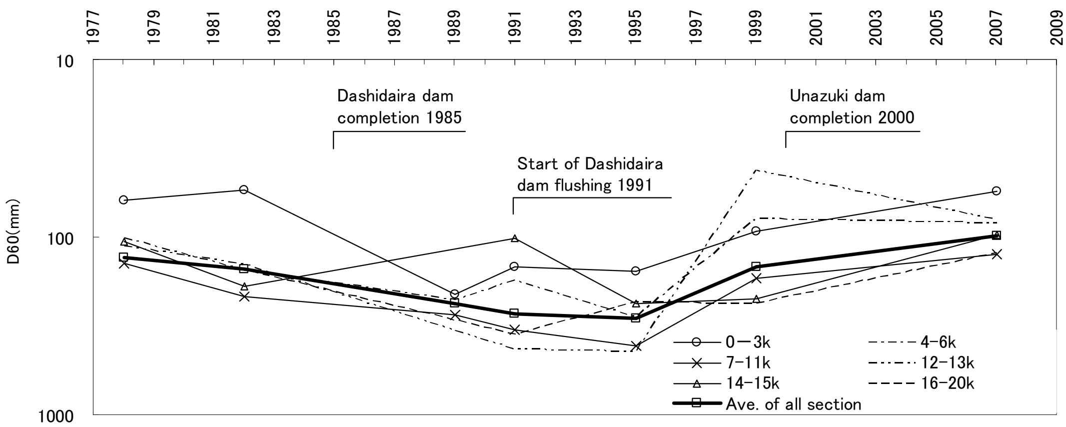


Fig. 13
Relationship between representative grain size (D_{60}) and sediment flushing for different sections
Relation entre les grosseurs représentatives (D_{60}) et la chasse de sédiment pour différentes sections

Fig. 13 shows these changes in terms of the riverbed materials. This figure indicates that for a representative grain size of D_{60}(mm), the riverbed materials had generally been getting larger after the completion of the Dashidaira Dam by “armoring”; however, after the start of sediment flushing, they began to get smaller in all sections. This is considered to be due to the supply of the sand component.

3.3. QUALITATIVE CHANGES OF SEDIMENT IN THE RESERVOIRS

We conducted surveys of quality of bottom sediments in the Dashidaira Dam reservoir. These surveys were conducted at five locations before the sediment flushing season (May), immediately after the sediment flushing season (July) and after the sediment flushing season (September). Reservoir bottom sediments were analyzed for appearance, smell, pH, COD (Chemical Oxygen Demand), IL (Ignition Loss), TOC (Total Carbon), T-N (Total Nitrate), T-P (Total Phosphorus), ORP (Oxidation-reduction Potential), sulfide and grain size distribution.

The analysis of reservoir bottom sediments before and after sediment flushing in 1998 and later generally reveal the following characteristics: Organic material indices (COD, IL and TOC), T-N and T-P dropped after sediment flushing, and then rose in September to about the same level as before sediment flushing. Average sediment size (D_{50}) increased after sediment flushing, and decreased in September to about the same size as before sediment flushing. Although Reduction Index (ORP) showed an oxidizing tendency immediately after sediment flushing, it showed about the same level of reduction tendency in September as before sediment flushing.

Based on the above analysis, we can say that the bottom sediments of the Dashidaira Dam reservoir follow a cycle associated with sediment flushing. Sediment flushing flushes out fine particles, and then reduces the organic materials indices and the eutrophication index. As new sediment, which includes fine particles, is accumulated, the organic materials indices and eutrophication index are increased back to their original levels. In other words, sediment flushing has the effect of replacing the surface layer of the reservoir bottom sediments so that fresh sediment only accumulates all time.

4. TECHNOLOGICAL DEVELOPMENT OF SEDIMENT FLUSHING OPERATIONS

Among the initiatives employed to make the sediment flushing operations more advanced at the Kurobe River are the following: 1) forecasting of rainfall and runoff, 2) monitoring of sediment transport in the reservoirs, and 3) monitoring of highly turbid water and amount of sediment transport rate.

4.1. FORECASTING OF RAINFALL AND RUNOFF [4]

In order to minimize the impacts of sediment flushing on the environment at the Kurobe River, sediment flushing is performed to coincide with natural flood events. In order that, it is essential to forecast the amount of rainfall and runoff as accurately as possible. To manage the sediment flushing operations in a more sophisticated manner, we have developed a rainfall-runoff forecast model which takes into account the effect of geographical features of the surrounding mountains. These models have been applied to the Dashidaira dam to forecast real-time inflow discharge.

The rainfall model employs kinematic methods based on radar data, and physical methods based on local weather models. This system forecasts the amount of rainfall in a 2.5 km x 2.5 km grid placed to cover the Sen'nindani Dam, Koyadaira Dam, and Dashidaira Dam every ten minutes, up to six hours in advance. The runoff model forecasts the amount of runoff discharge up to six hours in advance, using the forecasted rainfall data, the slopes of the mountains, and the water discharge in the river channels. The steep and complicated geographic features of the Kurobe River were taken into consideration, and we employ Kalman filtering to the water flow calculation models to improve the accuracy of the forecast.

4.2. Monitoring of Sediment Transport in the Reservoirs [5] [6] [7]

For a successful sediment flushing operation, it is important to increase the sediment flushing efficiency (ratio of flushed sediment to the quantity of water used) and the sediment flushing effect (relationship between the flushed sediment to the accumulated sediment before a sediment flushing operation). It is also important to forecast how the sediment erosion channel is formed due to the water level change and how highly concentrated SS occurs during the sediment flushing operation.

In order to monitor them, we conducted field measurements during a coordinated sediment flushing operation at the Unazuki Dam reservoir in 2006. These measurements included a flow velocity measurement using PIV (Particle Image Velocimetry) performed on images from CCTV cameras, in combination with geographic feature measurement with a 3D laser scanner located within the reservoir. We analyzed the flow velocity and the discharge of fine sediments during the water level draw down associated with a sediment flushing operation.

A highly concentrated SS downstream of the dam was observed immediately before the start of the free flow phase and its maximum value is related to the speed of drawing down the reservoir water level. To protect the river environment, it is necessary to develop an optimal operation scheme for the flushing gate, taking into account the flow of water within the reservoir during the drawing down operation as well as the sediment transport characteristics.

4.3. Monitoring of highly turbid water and amount of sediment transport rate [8]

In order to evaluate environmental impacts of sediment flushing by discharging highly turbid water downstream and to assess sediment transport during the operation, various types of sediment monitoring techniques should be developed. We are applying several new monitoring instruments such as SMDP (Suspended Sediment Concentration Measuring System with Differential Pressure Transmitter), turbidimeter designed for high sediment concentrations using glass fiber probe, and a multiple pipe sediment sampler to collect bed load and suspended load at one time.

The SMDP makes it possible to monitor suspended sediment concentration by measuring density of water directly with differential pressure transmitter. Two pressure detectors are placed vertically with some interval, e.g. H=1,000mm, and connected by small pipes filled up with water to the differential pressure transmitter mounted at the center of the system. It has an advantage in high turbidity measurement without any errors caused by properties of sediments such as grain size, color and so on.

5. DEVELOPMENT OF TECHNOLOGIES TO MITIGATE ENVIRONMENTAL IMPACT OF SEDIMENT FLUSHING

At the Kurobe River, technologies have been developed and implemented to mitigate the environmental impacts of sediment flushing on the river channel downstream. These include “rinsing discharge” and “evacuation channels for fish and other creatures”.

5.1. CHANGES IN THE SEDIMENTARY FINE PARTICLES IN THE RIVER BED DUE TO THE RINSING DISCHARGE

The rinsing discharge has been practiced at the Kurobe River in order to wash away locally remaining fine sediment in the riverbed downstream using relatively clear water after the free flow phase, for the purpose of maintaining the habitat for fish and other creatures in spite of the sediment flushing. In 2007, rinsing discharge was performed for three hours with a flow rate of about 300 m^3/s. In order to understand the effects of the rinsing discharge, we conducted surveys on the fine sediments accumulated on the surface layers of the riverbed on two occasions; one immediately after the sediment flushing operation and the other immediately after the rinsing discharge operation. The location of the survey was in a section 4-5km from the river mouth where the river bed slope becomes very gradual and fine sediments may accumulate on the river bed. The visual classification was according to the simplified classification, and resulted in a distribution diagram describing four levels of surface coverage by both sand and mud as shown in Table 2. The survey revealed that the change in the fine sediment distribution due to the rinsing discharge was such that the mud component was reduced from 7% to 3% overall. The grain size distribution showed that a change was observed from mud to sand in two locations, and that the grain size became larger at four locations as shown in Fig. 14. These measurements confirmed the effect of the rinsing discharge.

Table 2

Coverage classification of fine sediment particles
Classification de la couverture par les particules fines de sédiment

Coverage of river bed surface	0–25%	25–50%	50–75%	75–100%
Sand (0.125–4mm)	Sand 1	Sand 2	Sand 3	Sand 4
Silt and Mud (<0.125mm)	Mud 1	Mud 2	Mud 3	Mud 4

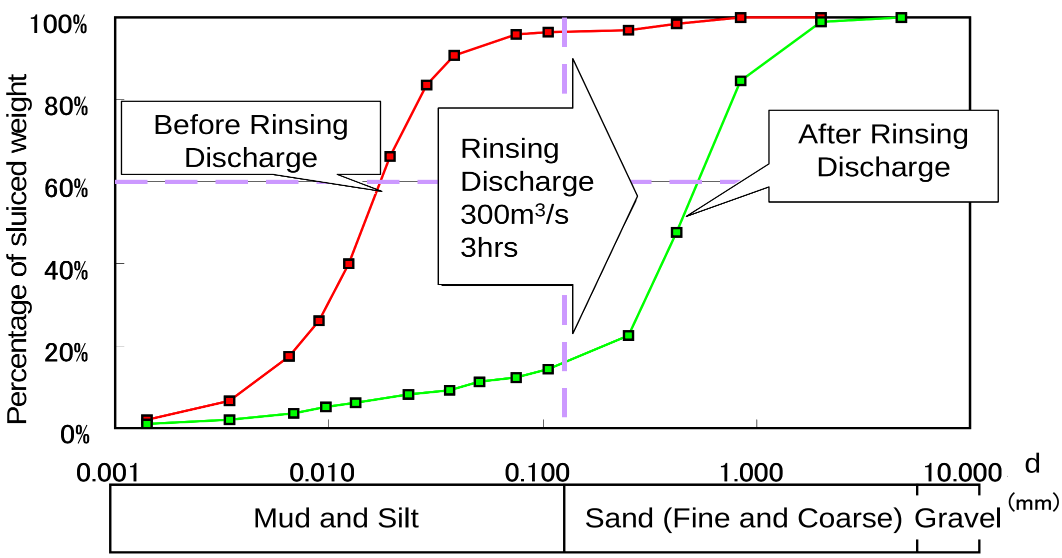


Fig. 14

Changes in grain size of river bed material on surface layer at 4.9 km from river mouth

Modification de la granulométrie du matériau de la couche de surface de la rivière, à 4,9 km de son embouchure

5.2. IMPLEMENTATION AND EFFECT OF THE EVACUATION CHANNELS FOR FISH AND OTHER CREATURES

Evacuation channels for fish and other creatures are implemented at the Kurobe River in order to protect them from an increase in the SS concentration in the river associated with sediment flushing. These channels take water from agricultural water and spring water, and maintain a lower SS concentration than the main river channel during a sediment flushing operation. There are currently nine channels at both sides of the river and we conducted surveys between 2003 and 2007 in order to verify their effectiveness.

The surveys were conducted at eighteen locations in the river including the evacuation channels in three locations by quantitative collections using a cast net during the flooding period (draw down period of the water level) and immediately after sediment flushing operation (recovery period of the water level). There were differences in the number of fish between the flooding period and immediately after sediment flushing operation at each location. In particular, the largest number of fish was collected immediately after a sediment flushing operation at one evacuation channel.

We think that this is because this channel maintained a lower SS concentration and a higher water temperature than the main river. Therefore, we need to consider the use of infiltrated water and the possibility of leading water collected from porous pipes buried underground to secure clear water in the evacuation channels as shown in Fig. 15.

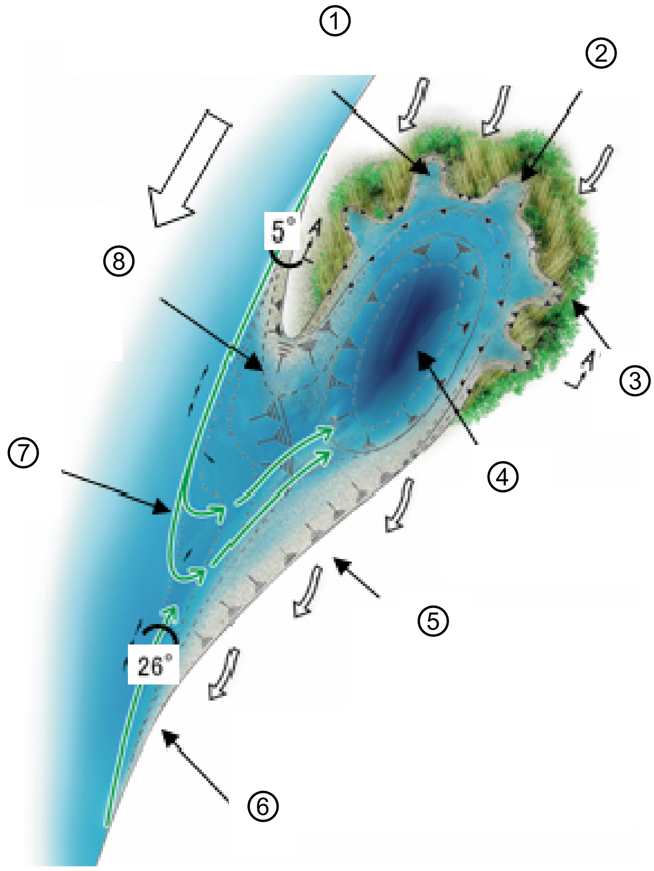


Fig. 15
Conceptual schematics of evacuation facilities
Schéma conceptuel des installations d'évacuation

① Shallow area appropriate for hatching and still-water fish
② Complex features of the shoreline to accommodate varied environmental conditions
③ Immersed plant growth
④ Depth and body of water to secure sinking sand and subsoil water

⑤ Slope of moving water (underground water)
⑥ Slow and long sloped opening to be able to bring in fish going up and down the stream

⑦ Movement of fish up and down the stream
⑧ Slightly angled in order to reduce the generation of separating current at the entrance

① *Eaux peu profondes pour éclosion et poissons d'eau calme*
② *Caractéristiques complexes de la berge pour créer des conditions variées de l'environnement*
③ *Croissance de plantes submergées*
④ *Eau profonde afin de garantir un fond sablonneux et la recharge du sous-sol.*

⑤ *Pente de l'eau en mouvement (eau souterraine)*
⑥ *Ouverture longue, progressive et inclinée afin d'amener le poisson se déplaçant en aval et en amont du cours d'eau*
⑦ *Mouvement des poissons se déplaçant en amont et en aval*
⑧ *Légèrement à angle afin de réduire la production d'un courant séparateur à l'entrée*

CONCLUSIONS

The major conclusions of this paper are as follows.

1) At the Kurobe River, both sediment flushing and sluicing are performed approximately once a year without major environmental impacts by restricting sediment flushing operations to appropriate sediment flushing seasons (June to August), and times when natural water flow rate exceeds a certain level, 300 (250 in some special case) m^3/s or more for sediment flushing, and 480 m^3/s or more for sediment sluicing.

2) The sediment flushing efficiency at the Dashidaira Dam, which is calculated by the quantity of flushed sediment and the quantity of water used during the free flow phase, was about 0.01 to 0.03. Drawing sediment by means of lower water level operation before to the sediment flushing is effective in improving flushing efficiency.

3) Discharged SS at the Dashidaira Dam during a sediment flushing operation was 8,000mg/l on the average (40,000mg/l peak), averaged over 14 sediment flushing operations. The average SS values are closely related to the quantity of flushed sediment as well as the quantity of water used during a flushing operation, and the peak SS values are closely related to the speed of drawing down the reservoir water level.

4) The Dashidaira Dam is currently at an equilibrium state in terms of its sediment, and the quantity of passing through sediment is approximately one million cubic meters yearly. In contrast, 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, which is mostly of grain size smaller than 2 mm, is sluiced.

5) Active shifting of sand bar and water path locations are frequently seen in the river channels downstream, which is considered to be the positive effect by the maintenance of sediment supply due to the coordinated sediment flushing of two dams. In particular, mainly by the supply of sand materials, the lowering of the river bed in some sections has been reversed and “armoring” in the riverbed materials where the coarse sediment component increased after the completion of the dams is being alleviated in all sections.

6) The sediment flushing operation ensures that the surface layer of accumulated sediment on the bottom of the reservoir is continually replaced with fresh sediments, decreasing the organic materials and the eutrophication indices.

7) To make the sediment flushing operation more sophisticated at the Kurobe River, work is in progress to develop rainfall-runoff models using radar

data, to monitor sediment transport using 3D laser scanners and PIV technology, and to monitor highly turbid water and the sediment transport rate.

8) In order to prevent accumulation of residual fine particle sediment on the sand bars in the river channel after sediment flushing operations, the rinsing discharge is practiced. This is particularly effective after a sediment flushing operation when a large quantity of fine sediments, such as silt, has been discharged, and has proved to be an effective means to reduce the environmental impact.

9) The evacuation channels have been proven to be effective in reducing the environmental impact since many species of fish are evacuating when the turbidity of the main river rises due to the sediment flushing. It is essential to secure clear water sources to these channels.

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SUMMARY

The Unazuki Dam (completed in 2001, height: 97 m, gross capacity of reservoir: 24,700,000 m^3), which is under the control of the Ministry of Land, Infrastructure, Transport and Tourism, is located at the farthest downstream point of the Kurobe River, which is one of the typical steep rivers in Japan. The Dashidaira Dam (completed in 1985, height: 76.7 m, gross capacity of reservoir: 9,010,000 m^3) is owned by Kansai Electric Power Co., Ltd. These two dams have an extremely large amount of sediment inflow compared to their gross capacity of reservoir; therefore, they were the first in Japan to be built with full-scale sediment flushing facilities. Sediment flushing has been conducted on the Dashidaira Dam since 1991. Since 2001, when the Unazuki Dam was completed, sediment flushing and sluicing have been conducted at coordinated times for these two dams. This paper covers an analysis of sediment flushing operations to date, the effect of sediment flushing on the river's sediment balance and physical environment, technological initiatives to make the sediment flushing operations more sophisticated, and environmental protection initiatives in order to harmonize with the downstream river environment.

In the Kurobe River, sediment flushing and sediment sluicing have each been effectively conducted roughly once per year by restricting sediment flushing and sluicing operations to times when there is natural flooding above a certain scale in the summer period from June to August. The sediment flushing operation limits sediment accumulation volume and quality deterioration of accumulated sediments in the reservoirs. Downstream sand bars and water courses are changing frequently before and after a flood, which is considered to be the result of maintaining the sediment supply from the dams by sediment flushing. In order to make the sediment flushing operations more sophisticated, work is in progress on the development of rainfall-runoff models, as well as on monitoring sediment transport, highly turbid water and so on. The rinsing discharge and the evacuation channels for fish and other creatures are utilized in order to mitigate the environmental impact on the downstream river channels, and they have proven to be effective.

RÉSUMÉ

Le barrage Unazuki (achevé en 2001, hauteur : 97 m, capacité globale du réservoir : 24 700 000 m^3), lequel est sous la juridiction du *Ministère des terres, infrastructures, transport et tourisme*, est situé au point le plus en aval de la rivière Kurobe, laquelle est une des rivières abruptes typiques du Japon. Le barrage Dashidaira (achevé en 1985, hauteur : 76,7 m, capacité globale du réservoir : 9 010 000 m^3), est la propriété de Kansai Electric Power Co., Ltd. Ces deux barrages ont un extrêmement grand débit entrant de sédiment comparativement à

la capacité globale de leur réservoir ; conséquemment, ils furent les premiers au Japon à être construits avec des installations de débit à pleine échelle pour chasse de sédiment. La chasse de sédiment est effectuée au barrage de Dashidaira depuis 1991. Depuis 2001, lorsque le barrage d'Unazuki a été achevé, la chasse (*flushing*) et l'écoulement (*sluicing*) de sédiment ont été effectués à des moments coordonnés pour ces deux barrages. Cet article couvre une analyse des opérations de chasse de sédiment réalisées à ce jour, les conséquences de la chasse de sédiment sur l'équilibre du sédiment de la rivière et de l'environnement, les initiatives technologiques afin de rendre les opérations de chasse de sédiment plus sophistiquées, et les initiatives de protection de l'environnement afin d'harmoniser la chasse de sédiment avec l'environnement en aval de la rivière.

Dans la rivière Kurobe, la chasse et l'écoulement de sédiment ont effectivement été faits approximativement une fois par année, en limitant les opérations de chasse et d'écoulement de sédiment à des moments où il y a des inondations naturelles dépassant une certaine échelle, durant la période d'été de juin à août. L'opération de chasse de sédiment limite l'accumulation de volumes importants de sédiment et la détérioration de la qualité des sédiments accumulés dans les réservoirs. Les bancs de sable et cours d'eau en aval changent fréquemment avant et après une inondation, ce qui est considéré comme étant le résultat du maintien de la source de sédiment en provenance des barrages par chasse de sédiment. Afin de rendre les opérations de chasse de sédiment plus sophistiquées, des travaux sont en cours pour le développement de modèles d'écoulement d'eau de pluie, ainsi que pour la surveillance du transport de sédiment, de l'eau très turbide et ainsi de suite. Le rinçage de décharges et les canaux d'évacuation pour les poissons et autres créatures sont utilisés afin d'atténuer l'impact sur l'environnement des canaux des rivières en aval, et ils se sont avérés efficaces.