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Sharing Water: Multi-Purpose of Reservoirs and Innovations

Study on the Koshibu Dam sediment bypass tunnel operation based on sediment transport monitoring in upstream reaches

Étude sur l'exploitation de la galerie de dérivation des sédiments du barrage de Koshibu, basée sur la surveillance du charriage en amont

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Abstract. SBTs (sediment bypass tunnels) are a leading technique to mitigate reservoir sedimentation. SBTs consist of a tunnel connecting the upstream and downstream reaches of a dam and diverts sediment-laden flood directly during flood events. A difficulty in operating SBTs is to reduce sediment inflow into the reservoir effectively, and simultaneously sustaining dam functions such as flood mitigation and hydropower generation. To optimize the problem in controlling the timings required in opening and closing the gates in the SBTs, which are governed by the hydrograph and inflow sediment data. Despite many studies on SBT operations considering hydrograph, there are few of those on the temporal change of sediment inflow. Ultimately, this study aims at improving SBT operations by understanding sediment inflow from upstream reaches using an indirect bedload monitoring system called an impact sensor. For this study, the Koshibu River basin was chosen because impact sensors are already placed in several locations around the basin including inside of the SBT. This observation has revealed the amount of transported sediment during each season in a year, are shown with relations between hydrograph and sediment inflow, and the spatial transient of sediment transport peak levels. According to these observations, desirable rules for SBT operations are suggested.

Résumé. Les galeries de dérivation des sédiments (en anglais Sediment Bypass Tunnels ; SBT) sont une technique de pointe pour limiter l'envasement des retenues. Les SBT consistent en une galerie reliant les zones amont et aval d'une retenue et détournant directement l'eau chargée de matériaux solides lors des crues. Une des difficultés du fonctionnement des

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SBT est de réduire efficacement l'apport des sédiments dans le réservoir tout en maintenant les fonctions du barrage : gestion des crues et production d'énergie hydroélectrique. Ces exigences régissent un problème d'optimisation qui détermine le moment d'ouverture et de fermeture des vannes des SBT en tenant compte de l'hydrogramme et des apports de sédiments. Malgré de nombreuses études sur le fonctionnement des SBT en tenant compte de l'hydrogramme, peu d'entre elles portent sur le changement temporel de l'apport de sédiments. En conséquence, cette étude vise à améliorer le fonctionnement des SBT en comprenant l'apport de sédiments en amont grâce à un système de surveillance indirect du charriage appelé plaques d'impact. Pour cela, le SBT du barrage de Koshibu (Japon) a été choisi parce que des plaques d'impact sont déjà placées à plusieurs endroits du bassin versant, ainsi qu'à l'intérieur du SBT. Cette observation a révélé la quantité de sédiments transportés à chaque saison de l'année, la relation entre l'hydrogramme et l'afflux de sédiments, et le transitoire spatial des pics de transport de sédiments. Selon ces observations, des règles souhaitables pour le fonctionnement des SBT sont suggérées.

1 Introduction

In Japan, many reservoirs are suffering from progressing reservoir sedimentation. Although a part of reservoir volume is allocated for future reservoir sedimentation, fast sedimentation rate beyond expectation causes for some of dams to experience almost 100 % of sedimentation rate. Reservoir sedimentation is regarded as an urgent problem because this induces the following troubles: water intake clogging, efficient volume reduction, and sediment shortage in the downstream reaches. Dams play an important role in society and has multi purposes, hence the situation naturally requires strategies to mitigate sedimentation to prolong dam lifespan.

Among many sedimentation mitigation measures, such as dredging, dry excavation, sluicing, and flushing, the sediment bypass tunnel (hereafter abbreviated to SBT) is a leading technique used in Japan, Switzerland, and Taiwan. The main part of an SBT is a tunnel connecting the upstream and downstream reaches of a dam, which bypasses sediment-laden flood to the downstream reaches, thus incoming sediment to the reservoir is reduced. Generally, the inflow discharge into SBTs is controlled with inlet gate operation.

One advantage of the SBTs over others are its sustainability both by financial and environmental aspects. Financially, SBTs is a semi-permanent countermeasure for reservoir sedimentation. Once a SBT is constructed, few operation costs are needed unlike dredging. The other unique merit is that SBTs can contribute to restore the environment of the downstream reaches in respect of sediment supply. Because the SBT connects upstream and downstream reach of the dam directly, it can supply natural flood water directly without including unnaturally concentrated sediment flow likewise flushing nor lowering water level affecting hydropower generation.

One difficult point in using SBTs is how to decide the timing of opening and closing the tunnel gate. Inlet gate opening is required when we decrease sediment incoming to the reservoir, and, in contrast, gate closing contributes to divert flood water to the reservoir to mitigate downstream flooding or store water in the reservoir. Therefore, the timing decision of switching these two conflicting operations is a key to using SBTs efficiently [1].

Incidentally, sediment incoming rate into dams is inconstant, and it is important for advanced reservoir management to monitor sediment transport at the upstream regions. In Japan, these monitoring are often carried out by Sabo (erosion control) offices, but few of them collaborate with dam offices [2]. Although annual sedimentation bathymetric measurement is conducted at large reservoirs, no bedload monitoring is utilized for reservoir management.

In Japan, the Asahi Dam SBT and Miwa Dam SBT have been operated more than ten years and they contribute to mitigate reservoir sedimentation. The Koshibu Dam SBT, the newest SBT in Japan was built in 2016 and various monitoring are being conducted [3]. Koshibu Dam is a large dam in Japan and plays important roles for hydroelectricity, agricultural water supply, and flood mitigation, thus the lack of the dam function due to sedimentation is a critical problem for downstream areas. In the upstream of the Koshibu Dam, a Sabo (erosion control) office deploys several continuous sediment transport monitoring stations with turbidity meters, Japanese Pipe Microphones, and Impact Plates. Although many studies have dedicated for these monitoring systems in Sabo study [4, 5], the observation is not used for dam management.

This study aims at extracting useful information from the bedload observation for better Koshibu SBT operation. In particular, we focus on temporal sediment transport change in different types of flood hydrographs.

2 Sediment transport monitoring

2.1 Location

The Koshibu Dam is a multi-purpose dam constructed on the Koshibu River, a tributary of the Tenryu River, in the Nagano Prefecture, Japan. This dam is equipped with an SBT from 2016 for dealing with severe reservoir sedimentation. The SBT is supposed to start bypassing flood water when the inflow discharge to the reservoir exceeds 100 m^3/s. Two sediment transport monitoring stations, which are concerned in this study, locate in the Koshibu River basin (288 km^2) as in Figure 1. The Ogawara station (Figure 2(a)) has a 134.8 km^2 upstream basin, 60 m width, and 1/70 bed slope, and the Kashio station (Figure 2(b)) has a 52.3km^2 upstream basin, 31.7 m width, and 1/31 bed slope.

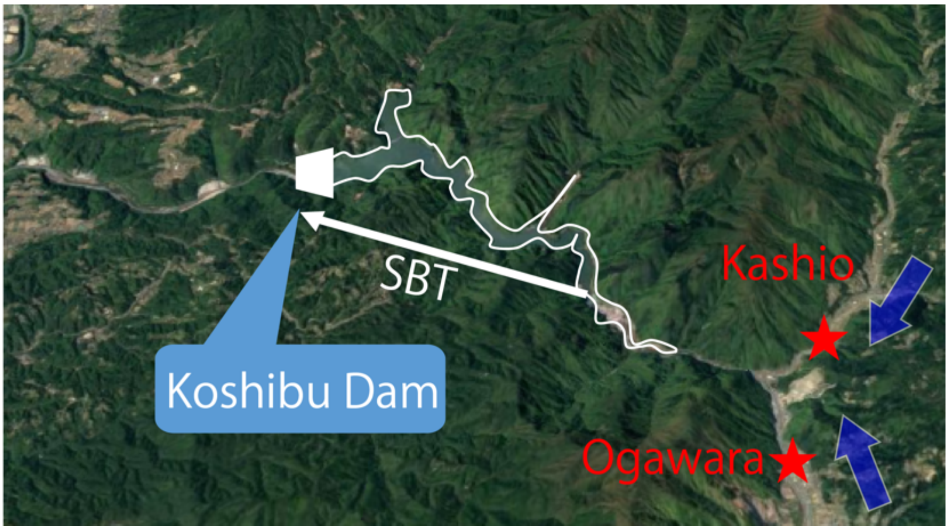

Fig. 1. The Koshibu Reservoir and bedload monitoring stations.

(a)
(b)

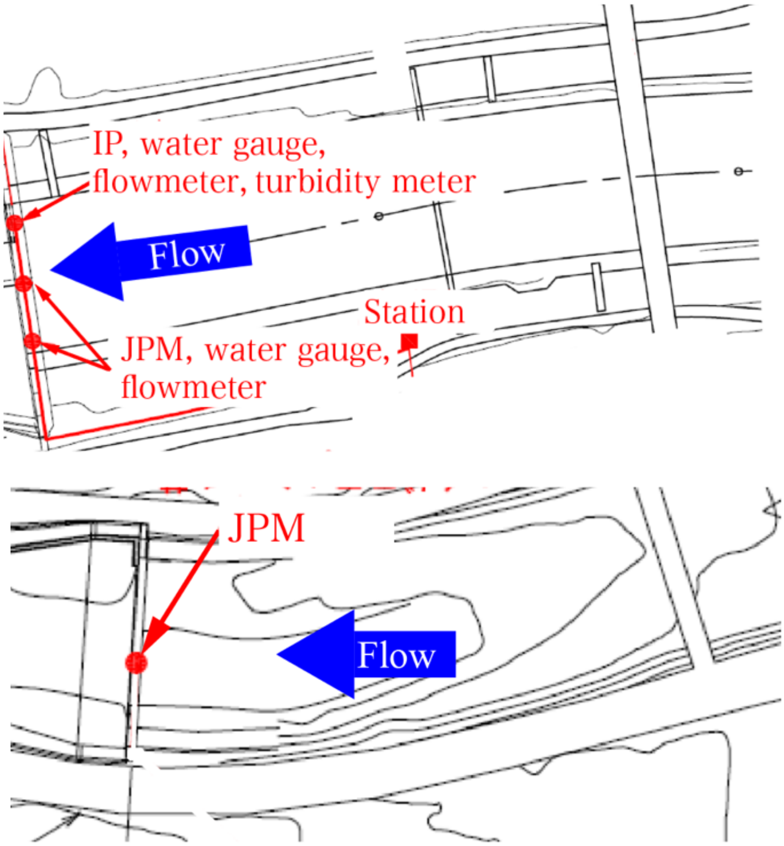

Fig. 2. Monitoring systems on the Koshibu River. (a) The Ogawara monitoring station, (b) the Kashio monitoring station.

2.2 Bedload monitoring systems

At the two stations, surrogate bedload monitoring systems called the Japanese Pipe Microphone and Impact Plate, hereafter referred as JPM and IP respectively, are employed. These systems consist of a steel pipe for the JPM and a steel plate for the IP embedded on river bed, and a microphone attached the inside of them (Figure 3). The systems register the acoustic energy caused by sediment collision on the pipe or plate. We can obtain the information about sediment transport by analyzing the obtained acoustic signal [4, 5]. These systems enable us continuous and indirect bedload monitoring even in rivers with high flow velocity and bedload transport rate (BTR).

Many approaches to analyze the signal have been proposed in the study of bedload surrogate monitoring. Particularly in Japan, the pulse method is of practical use [4]. The method counts the number of spikes being over a predefined threshold as the number of pulses. Then, the regression relationship between the number of pulses and BTR is developed. At the two stations, continuous BTR is estimated using an on-site calibrated regression curve.

The JPM and IP have respective merits and demerits. The JPM has higher sensitivity because of its convex shape to which gravels are easy to collide, while the system easily deforms and it results in abnormal signal. By contrast, the IP is duller for sediment impact than the JPM, and gravels' simultaneous impact on the plate causes signal overlapping [6].

The IP is tough, however, hence, favorable for long-term use without maintenance. In normal rivers in Japan, JPMs are mainly used, but IPs are used in rivers with high flow velocity or sediment transport rate including SBTs [6].

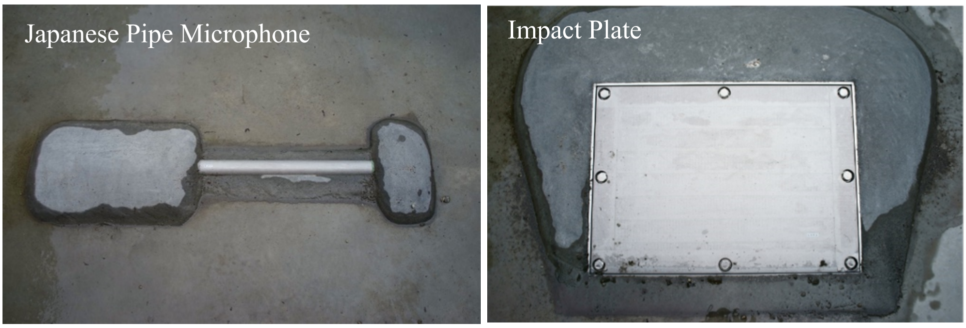

Fig. 3. The Japanese pipe microphone and Impact plate installed on a river bed.

2.3 Bedload monitoring station

Both of the stations are conducting hydrological and sediment monitoring every one minute since 2016. Three bedload monitoring systems are placed at the Ogawara station: an IP on the right bank, and two JPMs on the center and left bank. At the Kashio station, one JPM is used. The plate of IPs measures a 50 cm of width, 20 cm of length along the water-flow direction, and 3 - 4 mm of thickness. The pipe of JPMs measures a 50 cm of width, 48.6 mm of length along the water-flow direction, and 12 mm of wall thickness.

Their measurement items are water level, flow velocity, turbidity, and BTR.

3 Results and discussion

3.1 Flood events discussed in this paper

We focus on observed data from January 2016 to October 2018 as the data in 2019 contain many missing and error values. In particular, in this paper, we discuss data in 2018 because flood discharges in the year vary from low to high values.

3.2 Comparison of bedload transport data by two JPMs and an IP

The water discharge (hereafter blue line in Figures) and total BTR (hereafter red line in Figures) at the Ogawara station of three flood events in 2018 are shown in Figure 4, Figure 5, and Figure 6: during snowmelt season, frontal rain season, and typhoon season, respectively. The total BTR is the sum of BTR measured by three monitoring systems multiplied by the ratio of river width in the summed monitoring system widths. The timing of the hydrograph peak is indicated with ▼ symbol, and the period before ▼ is defined as a hydrograph rising limb and after ▼ is defined as falling limb. Figure 4 shows, in snowmelt season, BTR decreases as hydrograph decreases. In other seasons, by contrast, the decrease speed of BTR is slower than that of the hydrograph (Figure 5, Figure 6).

Next, we see the data obtained by the JPM and IP at the Ogawara station separately. Figure 7 exhibits observation by the JPM, which locates in the left bank side of the river, during a flood with 25 m^3/s of peak discharge (Figure 7(a)) and 100 m^3/s (Figure 7(b)). When the flood scale is low (25 m^3/s), temporal variation of discharge and BTR synchronize, whereas when the flood scale is high (100 m^3/s), BTR appears to be almost constant. It is reported that the JPM's high sensitivity causes output signals to be saturated [4], and the saturation seems to occur in Figure 7(b).

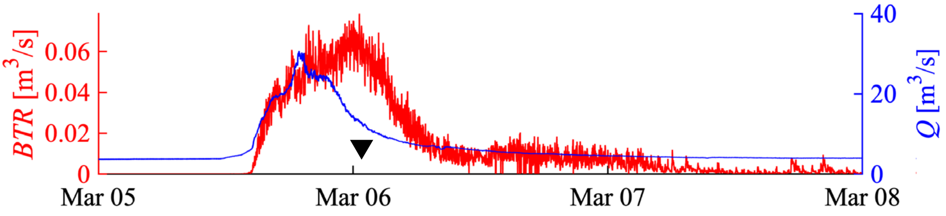

Fig. 4. The discharge and total BTR at the Ogawara station in March 2018 (snowmelt season).

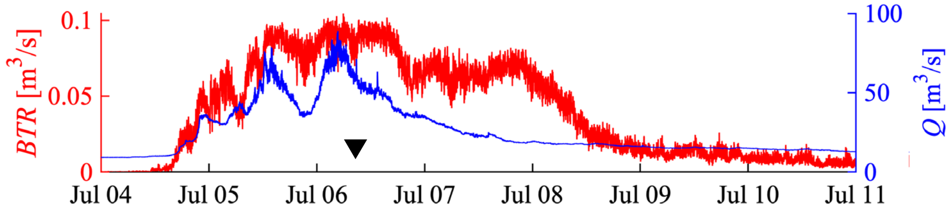

Fig. 5. The discharge and total BTR at the Ogawara station in July 2018 (frontal rain season).

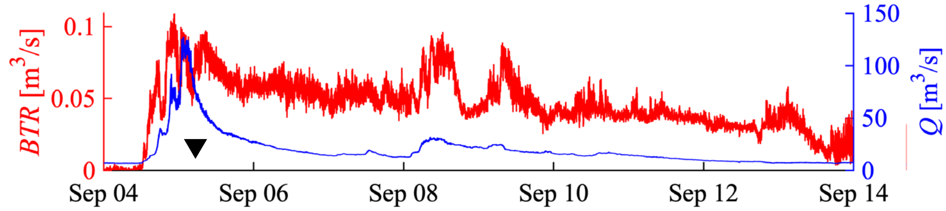

Fig. 6. The discharge and total BTR at the Ogawara station in September 2018 (typhoon season).

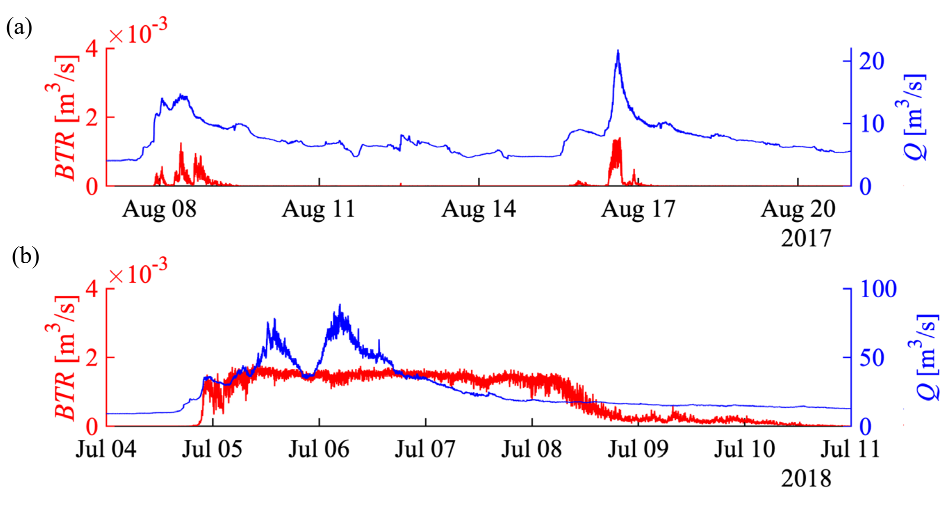

Fig. 7. Discharge and BTR observed by the left bank JPM. (a) Maximum discharge is 25 m^3/s, (b) maximum discharge is 100 m^3/s.

Figure 8 exhibits observation by the IP, which locates in the right bank side of the river, during a flood with 25 m^3/s of peak discharge (Figure 8(a)) and 100 m^3/s (Figure 8(b)). The IP also provides good synchronization between discharge and BTR under low discharges. It should be noted that, in Figure 8(b), the BTR changes along discharge much clearer than the JPM observation does.

The comparison of the JPM and IP above implicates that both of the systems are applicable for small and middle-scale of flood events monitoring, while, for large scale flood events, the IP is better.

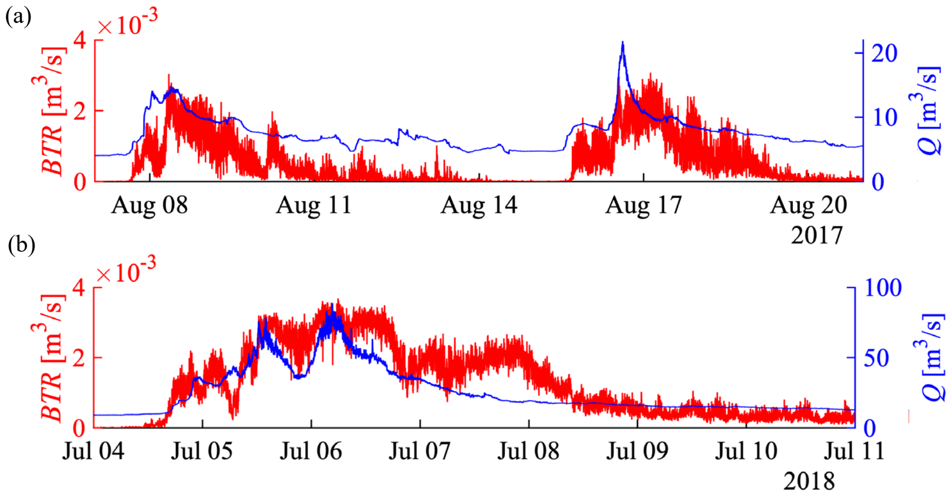

Fig. 8. Discharge and BTR observed by the right bank IP. (a) Maximum discharge is 25 m^3/s, (b) maximum discharge is 100 m^3/s.

3.3 Q-Qs relationship and hysteresis

The relationship between discharge and BTR, so called Q-Q_s relationship, in the three flood events corresponding to Figure 4, Figure 5, and Figure 6 is shown in Figure 9. Data with the maximum discharge recorded are indicated with ▼ symbol. Bluer data are in rising limbs and redder data are in falling limbs. These plots reveal the Q-Q_s relationship has an anti-clockwise hysteresis, which means more sediment were transported in falling limbs than in rising limbs.

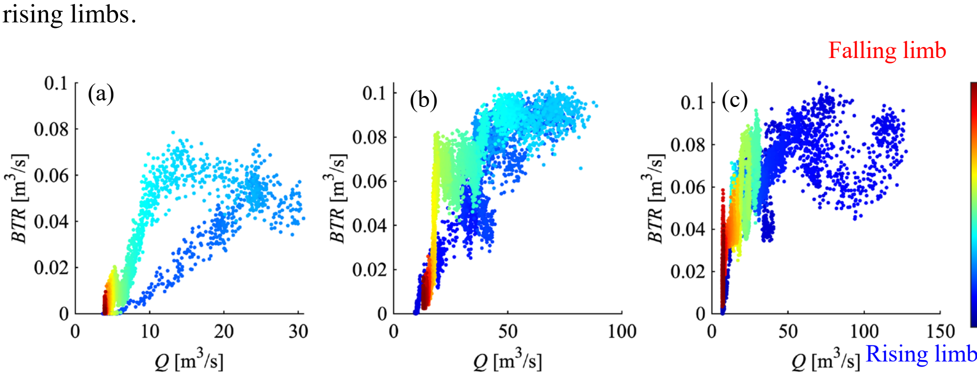

Fig. 9. The relation between discharge and BTR at the Ogawara station in 2018. (a) snowmelt season, (b) frontal rain season, (c) typhoon season.

Washload is known to have a clock-wise hysteresis generally, whereas the loop direction of bedload varies according to the source of bedload supply [7]. In the upstream areas of the Koshibu reservoir, the hysteresis mainly exhibits anti-clockwise direction. This tendency is more significant in earlier periods of a year. Therefore, we can summarize that bedload transport shift in this area tends to be behind of hydrograph.

Figure 10(a) and Figure 11(a) are Q-Qs relationship with three flood events combined at the Ogawara and Kashio stations, respectively. Additionally, the plots are separated into rising limbs (Figure 10(b) and Figure 11(b)) and falling limbs (Figure 10(c) and Figure 11(c)). Overall, bedload increases as discharge increases.

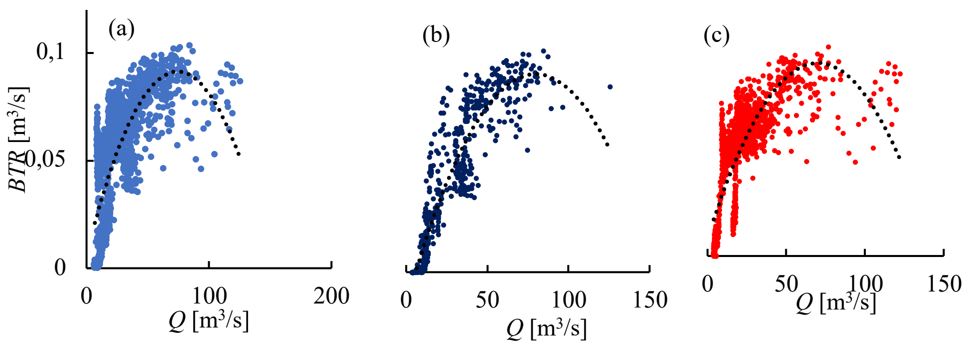

Fig. 10. The relation between discharge and BTR at the Ogawara station in 2018. (a) snowmelt season, (b) frontal rain season, (c) typhoon season.

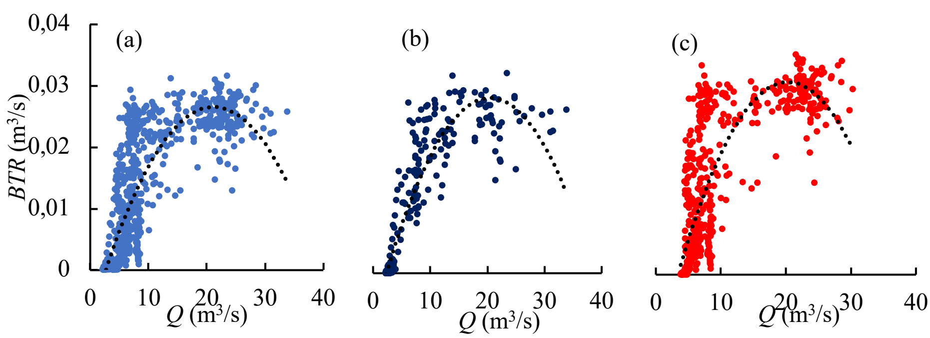

Fig. 11. The relation between discharge and BTR at the Kashio station in 2018. (a) snowmelt season, (b) frontal rain season, (c) typhoon season.

3.4 Inter-season characteristics of bedload transport

The annual temporal discharge and bedload data at the Ogawara and Kashio stations are shown in Figure 12 and Figure 13, respectively. The data later than August at the Kashio station are missing. Both of the figures are classified to snowmelt, frontal rain, and typhoon seasons as in the figures. It is natural that most sediment were transported during frontal rain, and typhoon seasons, but it should be noted that the total volume of sediment yield from snowmelt runoff accounts for 25 % of the annual sediment inflow to the Koshibu reservoir.

The Koshibu SBT is supposed to operate only during frontal rain, and typhoon seasons, because other seasons are thought of involving few sediment supplies. However, this result connotates that sediment yield during snowmelt season is not ignorable

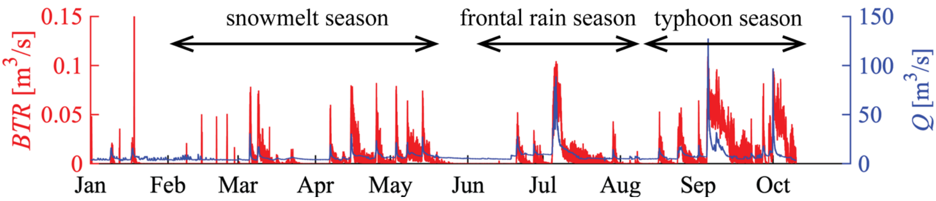

Fig. 12. Temporal change of discharge and BTR at the Ogawara in 2018.

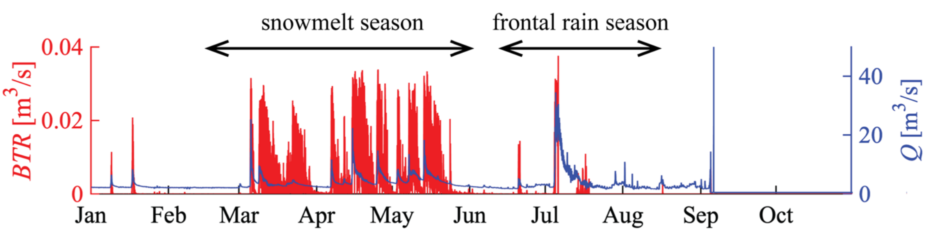

Fig. 13. Temporal change of discharge and BTR at the Kashio in 2018.

3.5 Comparison of observed BTR and theoretical values

3.5.1 Dimensionless bedload transport rate

To evaluate the observed BTR for their ratio to potential volume, we computed the dimensionless BTR using the Ashida-Michiue formula. First, we obtained critical Shield's stress (τ_*) with

$$\tau_* = \frac{u_*^2}{\left(\sigma/\rho - 1\right)gd} = \frac{Ri_e}{\left(\sigma/\rho - 1\right)d}, \tag{1}$$

where, u_* is friction velocity (m/s), σ is specific gravity of sediment (2.65), ρ is specific gravity of water (1), g is gravitational acceleration (9.8m/s^2), d is representative particle diameter (m), R is hydraulic radius (m), i_e is energy gradient (m/m). The value d is defined to be 2 mm which is the minimum detectable grain size of the IP, R be water depth, and i_e be river bed gradient. Then, dimensionless BTR (q_b^*) is calculated from

$$q_b^* = \frac{q_b}{\sqrt{\left(\sigma/\rho - 1\right)gd^3}}. \tag{2}$$

Where, q_b is BTR observed by the JPM or IP.

3.5.2 Comparison of observed and calculated BTR

The relation between τ_* and q_b^* obtained by the bedload monitoring systems and the Ashida-Michiue formula [8] (short dashes line) in 2016, 2017, and 2018 at the Ogawara station is in

Figure 14. The data of each year contains three floods in snowmelt, frontal rain, and typhoon seasons introduced in section 3.2. Generally, the observed values approach the equilibrium sediment transport rate by Ashida-Michiue formula at around the peak time. By contrast, this tendency cannot be seen at the Kashio station, and so, the bedload transport characteristics differs even between close tributaries. This high sediment yield in the Ogawara station is probably attributed to that the Koshibu River locates on a huge fault, so called the Median Tectonic Line.

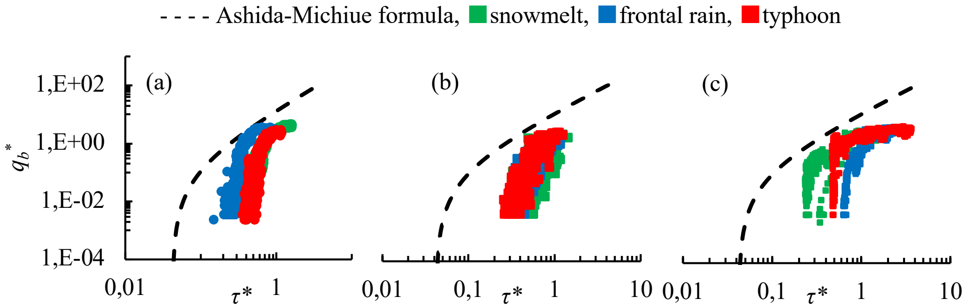

Fig. 14. The relation between critical Shield's stress (τ_*) and dimensionless BTR (q_b^*) obtained by the bedload monitoring systems and the Ashida-Michiue formula (short dashes line). (a) 2018, (b) 2017, (c) 2016.

Focusing on seasonal difference, most sediment were observed during frontal rain and typhoon seasons in 2016 and 2017. In 2018, however, sediment yield in snowmelt season is dominant. It is known that BTR is governed not only by flow discharge or the scale of preceding flood events, but also large-scale flood events caused in past years. Accordingly, the high sediment yield in snowmelt season, 2018, is likely to be induced by the last typhoon in 2017 and small several floods from Autumn 2017 to Spring 2018. This kind of long-term impact to bedload transport hysteresis is also important to be noted for better reservoir management.

4 Conclusion

In the upstream areas of the Koshibu Dam and its SBT, advanced hydrological monitoring and bedload transport monitoring are conducted. Considering the use of these observation data is helpful for dam management, we analyzed the data with respect to following topics: comparison between the JPM and IP bedload monitoring systems, the characteristic of temporal BTR in different scales or seasons of floods, bedload transport at around the flood peak time. We conclude:

- IPs are widely applicable for small and mid-scale floods to large-scale floods.
- Water discharge has higher correlation with washload than with bedload, because the peak time of BTR tends to be later than that of water discharge. In flood hydrograph falling limbs, in addition, the decrease speed of BTR is slower than that of the hydrograph. The reason is that the river bed was plenty of sediment even in falling limbs due to a great deal of sediment supply during flood events.
- At present, the Koshibu SBT is not used in Autumn to Spring season. However, the total volume of sediment yield from snowmelt runoff accounts for 25 % of the annual sediment inflow to the Koshibu reservoir.
- The relationship between water discharge and sediment transport rate might be affected by the scale of preceding flood events.

For improving SBTs operation, it is important to consider the characteristic of inflowing sediment transport. Also, this information should be utilized combining with the study of sediment movement in the vicinity of the diversion wear and inlet gate.

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