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Case Report

Heavy flooding generating a precipitous decrease of fine particles along a riverbed: the case of a downstream reach of the futase dam

Abstract

Sediment replenishment is a technique employed to prevent sediment deficiency in riverbeds. The distribution of sediment in a riverbed is affected by the volume of replenished sediment, in addition to the flood discharge. We examine the effects of flood discharge on the riverbed material distributions by analyzing a case of sediment replenishment in the Futase Dam in Saitama Prefecture, Japan. Specifically, we compared data from 2003 to 2013 on the annual volume of flushed sediment (Sf), the annual maximum flood discharge (Q_{max}), and the proportion of particles less than 100 mm in diameter ($P_{<100mm}$). Results showed that the annual $P_{<100mm}$ at the downstream site may decrease following heavy flooding (i.e., Q_{max} reaches a ten-year high) possibly as a result of fine particles on the riverbed being carried away by flood water. Alternatively, the area covered by the replenishing sediment may be limited when Q_{max} is at a ten-year low. Thus, in the case of the Futase Dam, a moderate degree of flooding may facilitate sediment transport at the downstream reach and distribute fine particles on the riverbed.

Keywords: Sediment, Replenishment, Flood discharge, Riverbed material disturbance, Tractive force

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Introduction

Dams and their reservoirs are operated for multiple purposes, including flood protection.[1] However, all dams trap sediment and inevitably lead to downstream physical and ecological changes.[1] In the downstream reaches, flows are more stable and sediment transport is more limited than in those upstream.[2] This can cause several problems in downstream reaches including sediment deficiency and riverbed degradation.[3] To compensate the sediment deficit downstream and reduce ecological damage, sediment replenishment is sometimes performed.[3] Specifically, a certain amount of sediment is excavated from an upstream reservoir, transported to downstream channels, and then flushed via channel flooding.[4] However, the total volume of sediment transported downstream is influenced not only by the annual volume of replenished sediment, but also by the flood discharge. The combination of these factors complicates prediction of sediment flow patterns. Analysis of a range of flood discharge rates and sediment flow data over many years at a single site is required in order to better predict these sediment flow patterns. However, existing data of this type spans only relatively short time periods (a few years at most). In this study, we examine the impacts of flood discharge on fine material on a riverbed by investigating the effects of sediment replenishment in the Futase Dam in Saitama Prefecture, Japan.

Case presentation

The Futase Dam is located in the Arakawa River in Chichibu City, Saitama Prefecture, Japan. Sediment from upstream has been deposited in the reservoir at this site since the dam was constructed in 1961, leading to sediment deficiency in the downstream reaches. To mitigate degradation of the channel, sediment replenishment has been carried out annually in the dry season since 2003. Since 2004, flooding in the rainy season has typically flushed the sediment further downstream. The average replenished sediment was approximately 10,000m^3/year, which amounts to 10% of the total volume deposited in the reservoir.[5] In this study, there are five stations; one at the site where sediment replenishment takes place; three survey sites downstream termed St.1,2,and3; a point where the Arakawa River joints the Nakatsu River (Figure 1). These sites are located 0.2,0.7,1.8,2.7, and 4.0km downstream of the dam respectively (Figure 1). In this area, there are no large sub-streams or tributaries supplying sediment. We evaluated the annual volume of flushed sediment (Sf in m^3/year) and the degree of flooding via measurement of the annual maximum flood discharge (Q_{max} in m^3/s). These data, recorded from 2003 to 2013, was obtained from the Ministry of Land, Infrastructure, Transport, and Tourism at the Kanto Regional Development Bureau, Futase Dam Management Office (Table 1). To examine the annual fluctuation in the ratio of coarse to fine material along the riverbed, we determined the proportion of particles less than 100 mm in diameter ($P_{<100mm}$ in %). Given that the size of the replenished components was less than 100 mm, we predicted that the distribution or outflow of replenished materials along the riverbed would alter $P_{<100mm}$. In addition, to assess the degree of riverbed disturbance occurring during the annual maximum flood discharge, we calculated the tractive force acting on the riverbed (τ) at St.1 (the site nearest the dam) using equation1.[6]

$$\tau = \rho\left(\frac{\kappa u}{\ln\left(10h/D_{84}\right)}\right) \tag{1}$$

Where ρ is the density of water (1000 kg/m^3); κ is Karman's constant (0.4); u is the average flow velocity (m/s); h is the depth (m); and D_{84} is the 84% passing size of bed material size (m). The data on riverbed material distribution at Sts.1−3 and on flow at St.1 were obtained. We then compared annual changes in Sf, Q_{max}, and $P_{<100mm}$ at Sts.1–3, and compared the annual maximum τ (mτ in kg/m^2/s), at

St.1 to daily flow. At all sites, $P_{<100mm}$ was found to have increased in 2005, 2006, 2010, and 2012, but to have unexpectedly decreased in 2007 and 2011 (Figure 2). We note that in 2007 and 2011, Q_{max} was particularly high, and almost double that in 2004, the year with the third highest value (Table 1). In 2009, $P_{<100mm}$ increased at St.1, but decreased at the other sites (Figure 2). The lowest Q_{max} was recorded in 2009 (Table 1). The mτ value measured at St.1 was highest in 2007 and 2011, and lowest in 2009, when Q_{max} also reached its highest and lowest values.

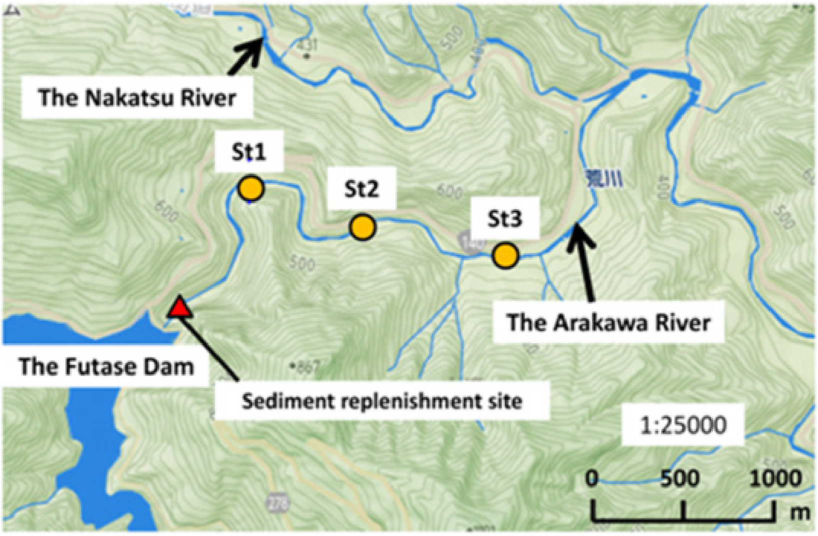

Figure 1 Map showing relevant downstream reaches of the Futase dam.

Table 1 Annual Sf, Q_{max}, mτ, and $P_{<100mm}$ for St.1-3 from 2003 to 2013

Year	Sf (m3/year)	Qmax (m³/s)	mτ (kg/m²/s)	P<100mm (%)		
				St.1	St.2	St.3
2003	0	74	179	2	N.D.	2
2004	13,000	159	296	2	5	8
2005	11,700	81	187	15	12	10
2006	5,400	108	319	55	25	60
2007	5,300	337	360	10	25	18
2008	5,000	69	175	22	10	23
2009	14,700	27	149	50	5	10
2010	12,400	57	283	70	55	33
2011	4,100	281	450	15	8	15
2012	3,900	71	176	30	25	38
2013	2,400	108	220	40	30	30

Sf, annual volume of sediment flushed from the replenishing site; Qmax, annual maximum flood discharge from the Futase Dam; mτ, annual maximum tractive force acting on the riverbed at St.1. N.D.

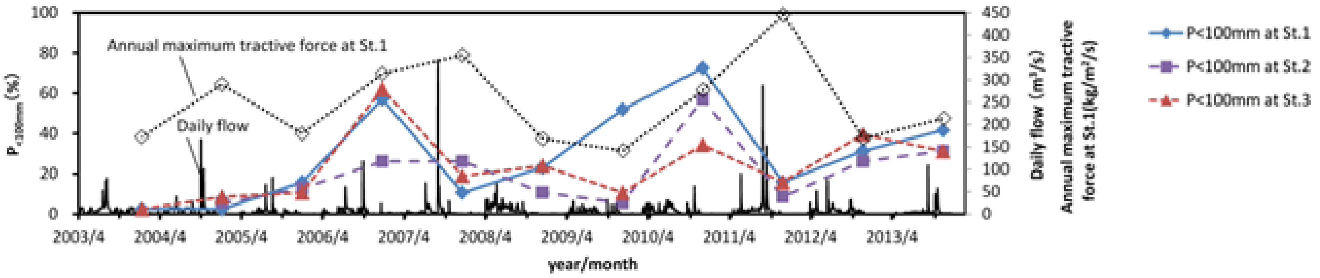

Figure 2 Annual $P_{<100mm}$ fluctuation at Sts.1-3, and mτ at St.1 relative to daily flow.

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Discussion

Our results indicate that the annual $P_{<100mm}$ downstream of a dam may decrease following heavy flooding (i.e., Q_{max} reaches a ten-year high). Heavy flooding may generate strong tractive force along the riverbed; consequently, although sediment is replenished and deposited on the riverbed before the flood, nearly all fine particles at this site may be carried further downstream. Regarding the lower Sf in 2007 and 2011 (approximately 5,000 m^3/year), the heavy flooding may have caused the precipitous displacement of sediment from the replenishing site. It is unclear whether $P_{<100mm}$ would increase if the sediment volume was higher and the sediment at the replenishing site was not carried away by flood waters. The replenished sediment may have reached only St.1 by 2009, given that the values of Q_{max} and mτ were at ten-year lows and that $P_{<100mm}$ only increased at St.1. However, it is possible that the sediment was transported to St.2 and St.3 in the following year and helped to mitigate channel degradation. In the case of the Futase Dam, it is likely that fluctuations in the fine material ratio along riverbeds within a year are dependent on the extent of annual maximum flood discharge, particularly in the case of heavy flooding. These fluctuations are also affected by mτ, which is determined by the flood discharge and bed material distribution. In addition, Sf was found to have a weaker relationship with the fine material ratio than Q_{max}. In summary, we note the importance of an enhanced understanding of the effects of sediment replenishment, given that the high costs of sediment excavation and transportation limit the volume of sediment that can feasibly be replenished, and given that it is difficult to ensure replenishment of the specific target areas. Our results demonstrate that proper sediment management downstream of a dam must consider not only the sediment volume, but also the flood discharge rate.

Acknowledgement

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Conflict of interest

None.

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