Hydrological Research Letters **11**(2), 114–120 (2017)
Published online in J-STAGE (www.jstage.jst.go.jp/browse/hrl). DOI: 10.3178/hrl.11.114

Effects of sediment replenishment on riverbed material size distribution and attached algal biomass in the downstream reaches of a dam

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Abstract:

Sediment replenishment is an effective method for resupplying depleted sediment and detaching overgrown algae in the downstream reaches of a dam. In this study, we used empirical data to examine the effects of sediment replenishment on bed material size and algal biomass in the downstream reaches of the Futase Dam, Chichibu City, Saitama Prefecture, Japan. Assuming that algae detach from bed materials when they are moved by water flow, we calculated the tractive force on the riverbed (τ) and allotted a threshold bed material size in motion (D_{cri}) for each given τ. The resulting bed material in the downstream reaches of the dam in any year was typically finer than that in the previous year when flooding in the rainy season transported a large volume of sediment. Algal biomass was lower when monthly D_{cri} exceeded 2 mm, versus when it was less than 2 mm. These results suggest that replenishment of fine bed materials accelerates algal detachment and restricts the accumulation of algal biomass by reducing bed stability.

KEYWORDS attached algae; sediment deficiency; riverbed disturbance; flow; detachment; tractive force

INTRODUCTION

In downstream reaches of a dam, flows are more stable and sediment transport is more limited than in the upstream reaches. The downstream reaches often exhibit sediment deficiency, which causes riverbed degradation (Erskine, 1985; Kondolf, 1997). Under such conditions, the movement of sediment particles and detachment of algae are reduced, leading to algal overgrowth (Biggs and Close, 1989). Thick mats of algae are for the most part not edible by grazing animals (e.g. Heptageniid mayflies and Japanese Ayu fish), because the mats consist of older algae with high silt content and are of low nutritional quality (Graham, 1990).

Bed load and sediment management have been conducted in many Japanese reservoirs to improve the state of sediment deficiency in downstream reaches. Sediment replenishment is one such effective management tool. In this method, a quantity of sediment is excavated from an upstream reservoir, transported to downstream channels, and then flushed by the flooding of the channels (Kantoush *et al.*, 2010). Sediment replenishment supplies sediment to deficient areas with the added effect of detaching overgrown algae.

There are several principal factors controlling the loss of algal biomass in streams (Figure S1). Algal biomass is usually measured using the proxy of the primary photosynthetic pigment, chlorophyll-a (chl-*a*), the unit for which is mg/m^2 (Stevenson, 1996). Loss can occur via two distinct pathways: (1) external forces (e.g. hydraulics; Biggs, 1996); and (2) internal activities (e.g. self-generated detachment; Bouletreau *et al.*, 2006). The sediment replenishment method facilitates algal detachment by exerting an external force of dynamic friction between bed and saltating particles during bed load transport. A previous study, which involved experiments using a flume, reported that simultaneous velocity elevation and solid addition produced instantaneous algal loss rates approximately double those with a velocity increase alone (Horner *et al.*, 1990). An increased quantity of detached algae has also been reported *in situ* in the downstream reaches of Managawa Dam, Fukui Prefecture, Japan after sediment replenishment.

In Japan, replenished sediment typically flows into the downstream reaches of a dam in the rainy season, which usually occurs in spring or summer (Figure S2). The total volume of sediment that flows in depends on several factors, including the volume of replenished sediment, degree of water discharge, and the location of sediment placement (Ock *et al.*, 2013). Furthermore, the extent of downstream transport for a set volume of replenished sediment depends on the distance from the replenished site (Lisle *et al.*, 2001). The combination of these factors complicates the prediction of sediment flow patterns.

The Unified Gravel-Sand (TUGS) model has been developed for simulating sediment transport and bed material size distribution in gravel-bed rivers (Cui, 2007). However, the downstream interval of the model is very short compared with the downstream reaches of most dams. To analyze the effects of river flow regime and distance from the replenished site on sediment deposition downstream, several years of data on replenishment sediment volume, dam discharge, and riverbed material size are needed. However, existing data of this type only span a few years.

Because fine particles are more easily transported by

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Received 31 January, 2017
Accepted 11 April, 2017

river flow than coarser ones (Wilcock *et al.*, 2003), replenishment with fine sediment may disrupt established bed load transport frequencies and induce algal detachment. The effects of the dynamic frictional force exerted by sediment grains on attached algae during the rainy season are not permanent, as algae can recover their biomass within one month after detachment (Biggs *et al.*, 1999). However, the sediment deficiency may be improved over the longer term if the replenished sediment particles remain within the riverbed throughout the dry season. To evaluate the extent of these benefits, the degree of riverbed disturbance must be observed and quantified daily for one month prior to the measurement of algal biomass. The algal biomass calculations can then be compared with the degree of disturbance and the flow regime in the area to determine the factors responsible for algal detachment. There are, however, few peer-reviewed investigations that fit this description.

In this study, we examined the effects of sediment replenishment on the physical characteristics and algal biomass of bed material in the downstream reaches of the Futase Dam, Saitama Prefecture, Japan. We accomplished this by quantifying the degree of riverbed disturbance caused by the supplied sediment and then relating this disturbance metric to the particle size distribution and algal biomass data measured during annual field surveys.

STUDY AREA AND METHODS

Collection of field monitoring data

We focused on the Futase Dam, an upstream dam on the Arakawa River in Chichibu City, Saitama Prefecture, Japan. Sediment from upstream has been deposited in the reservoir here since the dam's construction in 1961, causing sediment deficiency in the downstream reaches. To mitigate degradation of the channel, sediment replenishment has been carried out once annually in the dry season (Figure S2) by excavating, transporting, and depositing reservoir sediment downstream. Flooding in the rainy season typically flushes the sediment further downstream (Figure S2). The volume of replenished sediment has varied annually from 5,000 m^3 to 15,000 m^3.

Each year, the replenishing sediment was deposited 0.2 km downstream of the dam. Three survey sites, herein termed Stations 1, 2, and 3 (St1, St2, and St3, respectively), were located no further than 4 km downstream of the replenishment site (0.7, 1.8, and 2.7 km, respectively), where a tributary, the Nakatsu River, joins the main trunk of the Arakawa River (Figure 1). The volume of sediment flushed from the sediment replenishment site was estimated in m^3/yr from the difference between the sediment storage before and after the rainy season. These data were available from the Ministry of Land, Infrastructure, Transport, and Tourism at the Kanto Regional Development Bureau, Futase Dam Management Office. The water flow at each site was estimated based on the outflow discharge of the dam and the Ochiai Gauging Station, located downstream (Ministry of Land, Infrastructure, Transport, and Tourism, 2017). The flows at St1, St3, and St2 were defined as the outflow discharge of the dam, the outflow discharge of the Ochiai Gauging Station, and the average of St1 and St3, respectively. The bed material size distribution was measured at each site once annually, in the dry season (Figure S2).

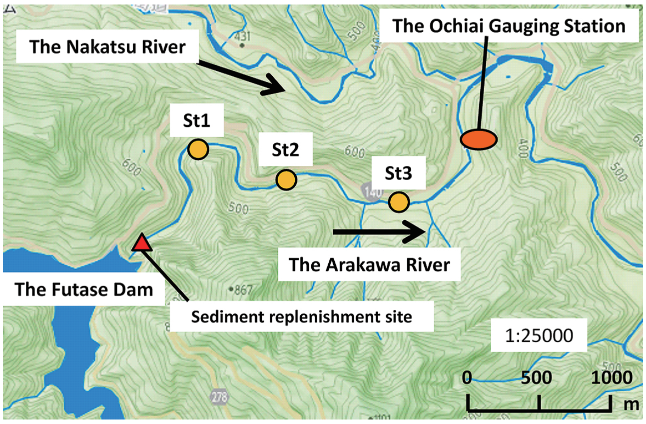

Figure 1. Map of the study area in the downstream reaches of the Futase Dam

Algal biomass was measured up to three times per year at each site from 2004 to 2013, in the dry season, using the proxy of the primary photosynthetic pigment chl-*a* in mg/m^2. To measure chl-*a*, four stones of moderate size (150–200 mm) were collected from riffles in the river. The algae were then scraped from the surface of each stone in a 5 × 5 cm quadrat using a nylon brush. The chl-*a* content of each algal sample was measured via high-performance liquid chromatography (HPLC) (Shioi *et al.*, 1983). The dominant species of algae in each sample were determined using a microscope to identify any changes in species composition during the overgrowth phase.

Analysis of the relationship between independent and dependent variables

This study aimed to determine the sediment-related annual changes in the river bed material downstream of the Futase Dam, and the extent to which flood disturbances contributed to these annual changes between 2003 and 2013. To accomplish these goals, we established two independent variables: (1) the annual volume of sediment flushed from the sediment replenishment site (Sf in m^3/yr); and (2) the annual maximum daily flow (Q_{max} in m^3/s), an index of annual changes in flood disturbance. These variables directly affect the volume of sediment flushed and the degree of riverbed disturbance (Ock *et al.*, 2013). Variable (1) was collected from annual reports on the Futase Dam (Civil Engineering and Eco-Technology Consultants, from 2004 to 2014), and variable (2) was calculated using the daily flow data at St1, St2, and St3 (Ministry of Land, Infrastructure, Transport, and Tourism, 2017). We then established various physical characteristics of the bed material as dependent variables. One was representative bed material size (D_{60}, the 60% passing size of the bed material [mm]). The other was the proportion of particles less than 100 mm in diameter ($P_{<100mm}$ in %), because the size of the replenished components was less than 100 mm, and we assumed that the proportion of these particles in the riverbed would be changed when replenished materials were supplied. To identify inter-annual changes in the size distribution of the bed material, differences were calculated between D_{60} of the present year and D_{60} of the previous year, and between $P_{<100\text{mm}}$ of the present year and $P_{<100\text{mm}}$ of the previous year:

$$cD_{60} = (D_{60}) - (D_{60} \text{ previous year}) \tag{1}$$

$$cP_{<100\text{mm}} = (P_{<100\text{mm}}) - (P_{<100\text{mm}} \text{ previous year}) \tag{2}$$

In summary, the dependent variables were bed material characteristics (D_{60}, cD_{60}, $P_{<100\text{mm}}$, $cP_{<100\text{mm}}$), while the independent variables were $Q_{\max}$ and *Sf*. Annual measurements of these variables from 2003 to 2013 were analyzed using Pearson's correlation coefficient to determine the strength of linear relationships between the dependent and independent variables. p-values of 0.05 for Pearson's correlation coefficient were established to indicate statistical significance.

Comparing flow and detachment force with attached algal biomass

The tractive force acting on the riverbed (τ) was calculated daily as follows (Wilcock, 1996):

$$\tau = \rho\left(\frac{\kappa u}{\ln\left(10h/D_{84}\right)}\right) \tag{3}$$

where ρ is the density of water (1,000 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 the bed material (m). We assumed that algae detach from bed materials when water flow moves the bed materials. Sand, with a diameter of around 2 mm (Bain *et al.*, 1985), is often used as the smallest size category of bed material in Japan, when measuring bed material size distribution (e.g. Katano *et al.*, 2009). Because fine particles, and not simply suspended solids, promote the detachment of algae (Horner *et al.*, 1990), we determined that algae detach when materials with a diameter greater than 2 mm were moved by water flow. We then calculated the threshold bed material size for motion (D_{cri}) for a given τ using Equation (4) (Tanaka and Furusato, 2014).

$$D_{cri} = \left(\frac{\tau}{0.045 R_s g D_{50}^{0.6}}\right)^{2.5} \tag{4}$$

where R_s is the specific gravity of bed material in water (1.65), g is gravitational acceleration (9.8 m/s^2), and D_{50} is the 50% passing size of the bed material (m).

Because algal biomass was determined one month after the flood in most cases (Biggs *et al.*, 1999), algal detaching events that occurred within a month might be related to the measured algal biomass. Then D_{cri} was calculated for one month prior to the measurement. To determine the degree of riverbed disturbance for the month, the maximum D_{cri} value for the month (MD_{cri}) was identified. Maximum daily flows throughout the month (*Mdf*) were also identified.

Algal biomass measurements were classified into two groups according to the relative degree of disturbance. Biomass measurements taken when MD_{cri} was below or above 2 mm were classified as G1 or G2, respectively. In a second classification scheme, algal biomass measured when *Mdf* was below or above 5 m^3/s (the average daily flow from 2003 to 2013) was classified into R1 or R2, respectively. Combining the two schemes, algal biomass in G1 and R1 (G1R1), in G2 and R1 (G2R1), and in G2 and R2 (G2R2) were then established (note, there were no algal biomass measurements in G1 and R2). One-way analysis of variance (ANOVA) was then used to determine whether algal biomass differed between each of the groups at all levels of classification (G1 vs. G2; R1 vs. R2; and G1R1 vs. G2R1 vs. G2R2). The one-way ANOVA was followed by Tukey's Honest Significant Difference (HSD) multiple comparison test to identify differences among the groups (G1R1 vs. G2R1 vs. G2R2). p-values of 0.05 for the one-way ANOVA and 0.016 for the Tukey's HSD test were established to indicate statistical significance.

RESULTS

Relationships between flow, sediment, and bed material

At all sites, D_{60} decreased and $P_{<100\text{mm}}$ increased, especially in 2010, but $P_{<100\text{mm}}$ exhibited a sudden decrease in 2007 and 2011 (Figure 2). There were several differences between sites with regard to inter-annual changes. For example, the bed material size was finer only at St1 in 2009 (Figure 2). Both cD_{60} and $cP_{<100\text{mm}}$ variables exhibited a linear relationship with Q_{max} (cD_{60} $p < 0.04$; $cP_{<100\text{mm}}$ $p < 0.001$), while D_{60} and $P_{<100\text{mm}}$ did not (Figure 3a, b, c, and d, respectively). Variable cD_{60} was the only one to exhibit a linear relationship with *Sf* ($p < 0.003$; Figure 3f). Most cD_{60} values were positive and most $cP_{<100\text{mm}}$ values were negative in 2007 and 2011, when Q_{max} was at its two highest values, and $P_{<100\text{mm}}$ exhibited sudden decreases (Figure 2). These values are termed Group P1 in Figures 3b and 3d. Most cD_{60} values were negative and most $cP_{<100\text{mm}}$ were positive in 2004, 2005, 2009 and 2010, when *Sf* exceeded 10,000 m^3/yr. These values are termed Group P2 in Figure 3f and 3h. The remaining data values in 2006, 2008, 2012, and 2013, when Q_{max} was not so high and *Sf* was around 5,000 m^3/yr, were termed Group P3.

The rules for whether cD_{60} or $cP_{<100\text{mm}}$ assumed a positive or negative value were different between groups P1, P2, and P3. In Group P1, most cD_{60} were positive and $cP_{<100\text{mm}}$ were negative. That is, the bed materials became coarser over time (Figure 4). In Group P2, on the other hand, the bed materials became finer over time (Figure 4). Lastly, P3 exhibited an entirely different trend of having positive values for both cD_{60} and $cP_{<100\text{mm}}$ (Figure 4).

Inter-annual comparison of flow and tractive force with algal biomass

Algal biomass values were typically lower than 100 mg/m^2 at all stations in all years, except at St2 and St3 in 2008, which had algal biomass higher than 200 mg/m^2 (Figure 5). Among the MD_{cri}-classified groups (G1 & G2), algal biomass was lower in G2 than in G1 (ANOVA $p < 0.01$; Figure 6a). However, among the *Mdf*-classified groups (R1 and R2), there was no difference in algal biomass (ANOVA $p = 0.11$; Figure 6b). A significant difference was, however, seen between G1R1, G2R1, and G2R2 (ANOVA $p < 0.05$; Figure 6c). Algal biomass was higher in G1R1 than in G2R2 (Tukey's HSD $p < 0.016$; Figure 6c),

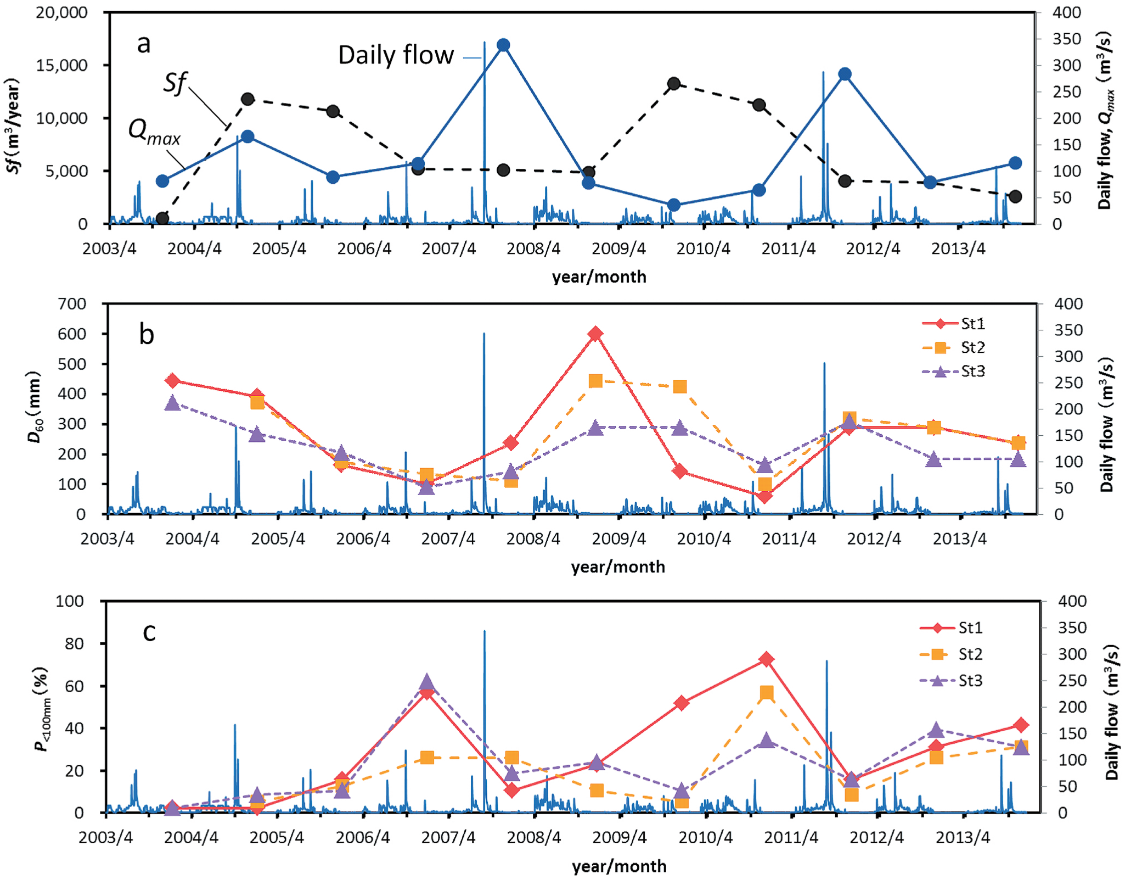

Figure 2. Annual changes of: (a) Q_{max} and *Sf*; (b) D_{60}; and (c) $P_{<100mm}$ relative to daily flow for sampling Stations 1–3

and higher in G1R1 than in G2R1 (Tukey's HSD $0.016 < p < 0.05$; Figure 6c). The dominant algal species did not change significantly between locations or years, even in 2008, when algal biomass was extremely high.

DISCUSSION

Annual changes of bed material composition after sediment replenishment

The characteristics of Group P1 indicate that when Q_{max} was very high, the bed material size became coarser than in the previous year (Figure 4). This phenomenon was likely caused by fine bed materials and replenished sediment being swept away by heavy flooding, which was the case in 2007 and 2011. The characteristics of Group P2 indicate that when *Sf* exceeded 10,000 m³/yr, the bed material became finer than in the previous year (Figure 4). In this group, most replenished sediment flowed out of the replenished site during the rainy season. This indicates that if there is a certain extent of discharge and a large amount of replenished sediment placed in the rainy season, sediment from the replenished site will be transported downstream, contributing to finer bed material in the downstream reaches. However, if the flow is very low, the sediment will not be transported as far from the sediment replenishment site. This scenario was observed in 2009, when Q_{max} was at its lowest (27 m³/s; Figure 2), and sediment only reached the sample station nearest the sediment replenishment site (i.e. St1).

The characteristics of Group P3 were complex because D_{60} was coarser than in the previous year, while $P_{<100mm}$ was finer (Figure 4). These observations suggest that at the Group P3 points, there was a large proportion of particles smaller than 100 mm in size and only a very small proportion of midsized particles (100–200 mm) in the riverbed. In this scenario, because flow was low and the riverbeds less disturbed, it is possible that only the fine fraction of the replenished materials reached the downstream areas (Figure 4c). In contrast, D_{60} was finer in Group P2, despite the low flow (Figure 4). In this case, it is possible that the greater volume of replenished sediment may have promoted the movement of the midsized particles. This is likely because a high volume of fine particles results in greater porosity in the materials, and thus more air gaps in the sediment (Parker *et al.*, 1982). These fine particles and air gaps act as lubricant, reducing the friction between moving particles. A high volume of this low-friction sediment could easily transport midsized materials downstream and replace them with finer ones.

The effects of sediment replenishment on the size distribution and attached algae of riverbed material

As indicated by the significant difference in algal biomass between Groups G1 and G2 (Figure 6a), algal growth may be restricted on moving materials that are larger than

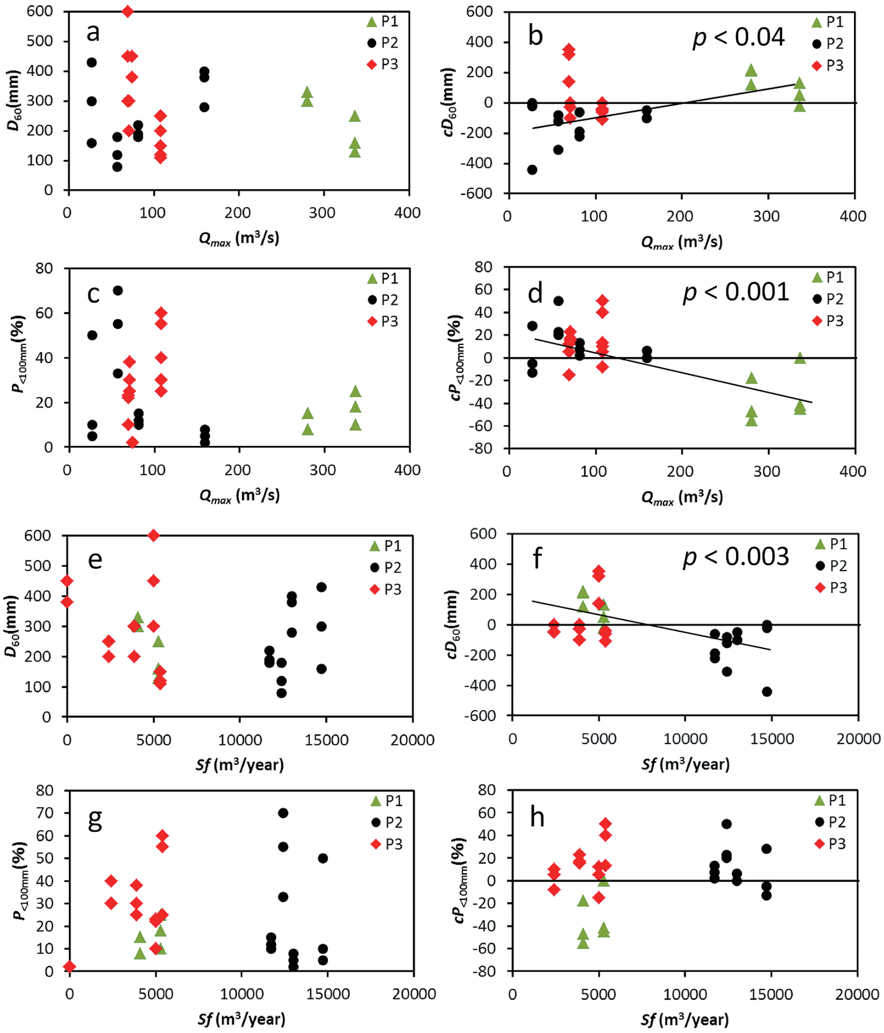

Figure 3. Relationships between the annual maximum daily flow (Q_{max}) and bed material characteristics: (a) representative size of bed material (D_{60} in mm); (b) change in D_{60} from the previous year (cD_{60}); (c) proportion of particles less than 100 mm in diameter ($P_{<100mm}$); and (d) change in $P_{<100mm}$ from the previous year ($cP_{<100mm}$). Additionally, relationships between the annual volume of sediment (Sf) and bed material characteristics: (e) D_{60}; (f) cD_{60}; (g) $P_{<100mm}$; and (h) $cP_{<100mm}$ (P1: values in 2007 and 2011, years when Q_{max} was very high (at its highest and second highest) and $P_{<100mm}$ exhibited a sudden decrease; P2: values in 2004, 2005, 2009, and 2010, years when Sf was very high (over 10,000 m^3/yr); and P3: values in 2006, 2008, 2012, and 2013, years when Q_{max} was not as high and Sf was around 5,000 m^3/yr)

2 mm in diameter. However, since there were no significant differences between Groups R1 and R2 (Figure 6b), algal biomass may not be restricted by the force of discharge alone.

D_{cri} appears to be a more effective criterion than flow or discharge for the evaluation of river bed disturbance. This is likely because D_{cri} is determined by the characteristics of both flow and size distribution of the bed material. D_{cri} is always high when the flow is high (as in G2R2), but when the flow is low, the magnitude of D_{cri} depends on the size distribution of the bed material. Because algal biomass was lower in G2R1 than in G1R1 (Tukey's HSD $0.016 < p < 0.05$; Figure 6c), even if flow is low, algal biomass may be restricted when the bed material is fine and the material is easily disturbed by the flow.

Algal biomass was extremely high in 2008. It is assumed that the degree of riverbed disturbance in the rainy season of that year must have been low, easing any restriction on algal growth. This is supported by the results of Group P3, which showed low values of Sf and Q_{max} in 2008. In the previous year (2007), heavy flooding removed most of the fine bed material, so that by 2008 only coarse, difficult to disturb bed materials remained. Interestingly, the flow conditions were similar in 2012, but high algal biomass was not observed. The average MD_{cri} in winter was higher in 2012 (11 mm) than in 2008 (< 1 mm). This evidence suggests that algal biomass is affected by the disturbance one month prior to measurement, rather than by the flow and bed material size distribution of the preceding rainy season. This may be because algal biomass grows quickly, requiring only one month to recover after detachment (Biggs *et al.*, 1999). Therefore, we conclude that a monthly disturbance metric is important in evaluating the effect of bed material disturbance on algal biomass.

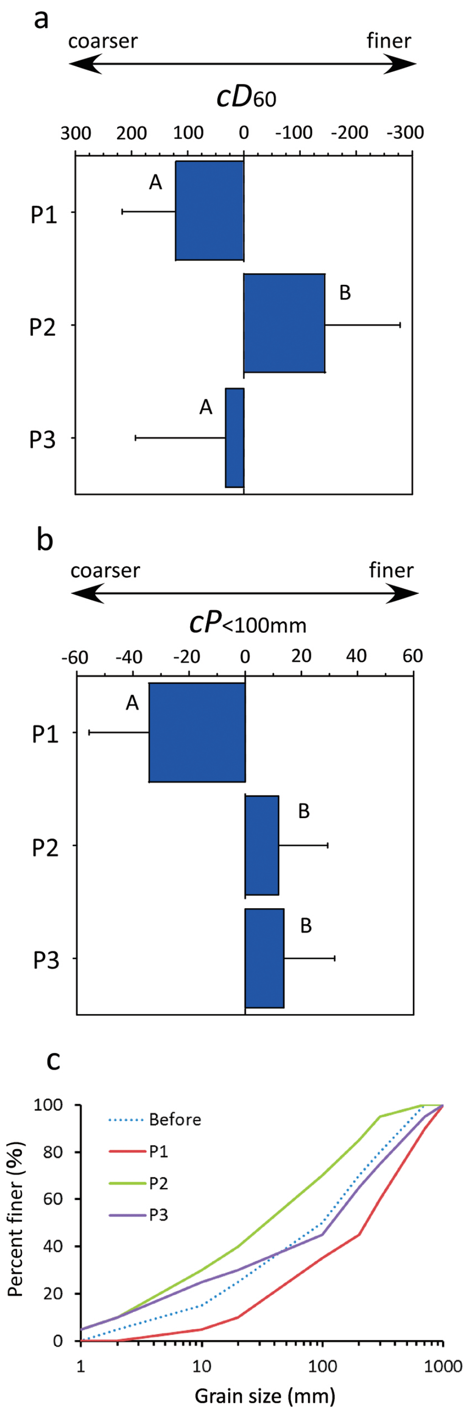

Figure 4. The average of: (a) cD_{60}; and (b) $cP_{<100\mathrm{mm}}$ values for Groups P1, P2, and P3 derived via One-way ANOVA and Tukey's HSD multiple comparisons test (Error bars signify value of the two standard deviations; P1, P2, and P3 signify same groups as in Figure 3). (c) The general particle size distribution curves of Groups P1, P2, and P3

ACKNOWLEDGMENTS

The data used in this study were supplied by the Ministry of Land, Infrastructure, Transport, and Tourism at the Kanto Regional Development Bureau, Futase Dam Management Office.

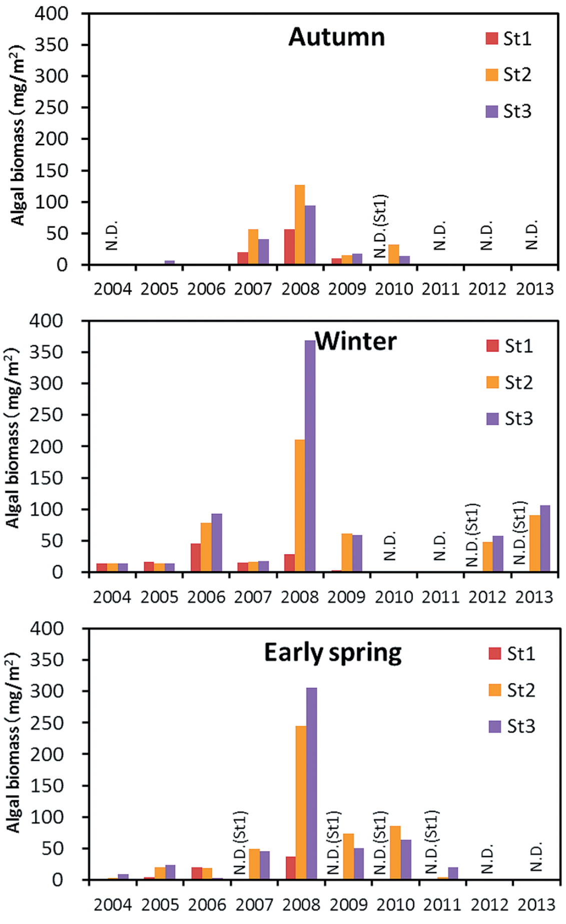

Figure 5. Algal biomass measured from 2004 to 2013 in autumn, winter, and early spring (N.D. signifies there no data was measured)

SUPPLEMENTS

Figure S1. The relationships between resources and disturbances related to attached algal biomass in streams and rivers

Figure S2. Annual schedule of sediment addition and field monitoring (in Japan, flooding usually occurs in the rainy season, and not in the dry season. Sediment addition or monitoring was carried out once during each period indicated by the arrows. Algal biomass was measured one to three times per year.)

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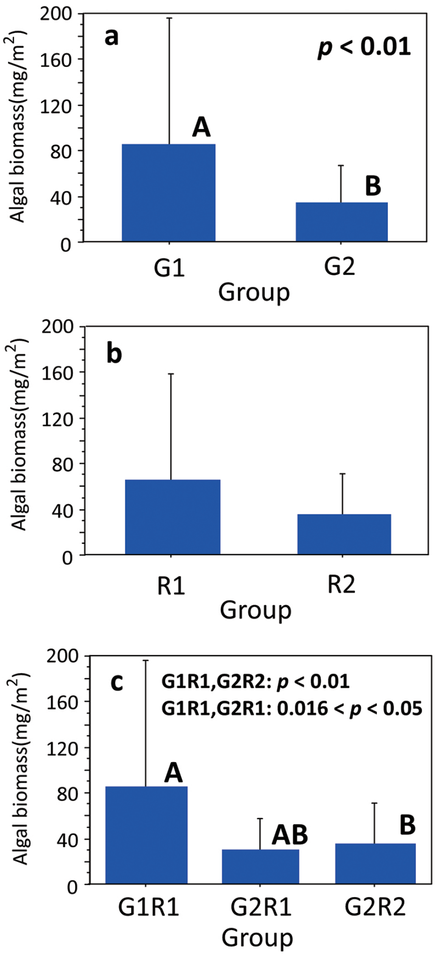

Figure 6. Comparison of algal biomass measurements in Groups: (a) G1 and G2; (b) R1 and R2; and (c) G1R1, G2R1, and G2R2, derived via One-way ANOVA and Tukey's HSD multiple comparisons test (Error bars signify values of the two standard deviations)

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