Responses of bed load yields from a forested headwater catchment in the eastern Tanzawa Mountains, Japan

Marino Hiraoka1, Takashi Gomi1, Tomoki Oda2, Tomohiro Egusa2 and Yoshimi Uchiyama3

1Graduate School of Agriculture, Tokyo University of Agriculture and Technology, Japan
2Graduate School of Agricultural and Life Sciences, The University of Tokyo, Japan
3Natural Environment Conservation Center, Kanagawa Prefecture, Japan

Abstract:

We investigated bed load yields from a headwater catchment (7.0 ha) in the eastern Tanzawa Mountains in Kanagawa Prefecture, Japan from 2009–2014 using measurements from a weir pond in the catchment. Precipitation and stream discharge were continuously monitored at 10-min intervals. The mean (± standard deviation) volume of transported bed load was 0.019 ± 0.040 m³/ha/day (0.023 ± 0.049 t/ha/day by yield) and zero bed load events were observed during the monitoring period. The particle size of the bed load sediment tended to be small compared to that of sediment in the stream bed. Bed load yields in summer–autumn were 5.7-fold those during winter–spring. A significant correlation was detected between bed load yield and peak discharge (p < 0.05). Variations in the availability of sediment induced discontinuous sediment transport during major precipitation events. These intermittent responses of the bed load yield were associated with the available sediment and transport capacity in the stream channel. Our findings help for clarifying sediment flux in a headwater channel based on its potential storage and yields.

KEYWORDS bed load transport; headwater catchment; intermittent response

INTRODUCTION

Headwater streams are the origin of river networks and are important sources of sediment and water for downstream systems (Sidle et al., 2000; Gomi et al., 2002; Benda et al., 2004). Yields of bed load and suspended sediment from headwaters are important indicators of downstream sedimentation in rivers (Lisle, 1989; Benda and Dunne, 1997). Bed load yields typically contribute 40–70% of the total sediment load in a headwater stream (Gomi et al., 2004). Therefore, the accurate estimation of bed load yields from headwater streams provides key information for effective watershed management.

The dynamics of the bed load sediment in steep headwater channels (> 2% channel gradient proposed by Grant et al., 1990) can differ from those of downstream channels. High-energy gradients can initiate intense sediment transport (Lisle, 1987; Yager et al., 2007), while the availability of roughness elements from channel steps and large boulders reduces the probability of bed load entrainment (Church, 2002). Larger particles create consistently turbulent flow and their interlocking structures also alter the stability of channels (Church et al., 1991). Hence, once the in-channel structure such as a step-pool is rearranged, relatively large particles can be mobilized (Turowski et al., 2009). Moreover, sediment supplies from hillslopes are also closely linked to the sediment transport within channels (Gomi et al., 2004). Such responses of sediment yields can be complex in channel reaches with the coexistence of colluvial and fluvial processes (Gomi and Sidle, 2003; Hattanji et al., 2006; Imaizumi and Sidle, 2012).

Various hydrological processes govern bed load yields in a headwater stream. The frequency of storm events influences the timing and magnitude of runoff water and the resulting bed load transport from headwaters to downstream reaches (Dunne, 1991). The transport distances of sediment depend on the channel gradient, valley configuration, and formation of channel roughness (Benda and Cundy, 1990). The availability of sediment within channels can also alter the relative concentrations of sediment in a given discharge volume (Theule et al., 2012). Seasonal changes and/or sequences of floods are also important indicators for the bed load response (Gomi and Sidle, 2003; Turowski et al., 2009).

Despite the unique spatial and temporal variations in bed load sediment transport, the responses of bed load yields to hydrological processes in steep headwater channels has not been extensively studied through field observations (Rickenmann, 1997; Whiting et al., 1999). Moreover, the application of theoretical sediment transport equations to headwater streams is difficult because of the turbulent flow created by variations in velocity, channel geometry, roughness, and sediment supply (Yager et al., 2007; Chiari and Rickenmann, 2011). The transition of colluvial and fluvial processes in channel reaches also makes it difficult to examine the timing of sediment yields (Hattanji et al., 2006). Understanding these responses of bed load sediment is important to elucidate material dynamics in channel networks from headwaters to downstream reaches. This study investigated the responses of bed load yields from a steep headwater stream based on five years of monitoring and evaluated how bed load yields vary with respect to their hydrological responses.

METHODOLOGY

We monitored bed load yields in a headwater catchment located in the Oborawara Monitoring Watershed (35°28’N,
139°12′E) in the eastern part of the Tanzawa Mountains, Kanagawa Prefecture, Japan (Figure 1). The studied headwater lies in the upper portion of the Sagami River system. The mean temperature and annual precipitation are 12°C and 3000 mm, respectively (Oda et al., 2013), and 41–66% of all precipitation falls from June–October. Snow often falls from the end of January to early March, and can accumulate on hillslopes, usually for a maximum of one week. The catchment is underlain by uniform Cenozoic sedimentary rocks. The stream consists of second-order channels, and the drainage area is 7.0 ha. The mean slope gradient of the catchment is 36°, and steep hillslopes (> 40°) are distributed along the stream (Gomi et al., 2013). The total perennial stream length and mean gradient of the stream bed are 627 m and 0.52 m/m, respectively. The channel topography consists of boulders, steps, pools, and cascades. Two sediment check dams are located within 50 m from the outlet of the basin (gaging station). The dominant forest vegetation of the upper and lower parts of the catchment is coniferous trees (Cryptomeria japonica and Chamaecyparis obtusa) aged 20–30 years, and deciduous broadleaf trees (Cercidiphyllum japonicum and Aesculus turbinata). Six moderately large earthquakes ($M_\text{J}$ = 6.5–8.2) occurred within 50 km of the Tanzawa Mountains on 1923, 1924, and 1930. The epicenter of the main shock of the earthquakes in 1923 and 1924 were near to the catchment and slightly larger ($M_\text{J}$ = 7.9–8.2 and 7.3) compared to others. Many landslides and debris flows occurred due not only to these earthquakes but also heavy rainfall after the earthquakes (Inoue and Kasahara, 2009) and affected approximately 20% of the entire Tanzawa Mountains (Inoue, 2001).

Sediment deposition, stream discharge, and precipitation were monitored from June 2009–November 2014. A 90° V-notch weir was installed in the spring of 2009 to measure discharge and sediment yield in the stream (Oda et al., 2013). Water levels were monitored every 10 min using a pressure transducer connected to a data logger. The discharge was estimated from an empirical formula for the relationship between water level and discharge. Precipitation was also monitored at 10-min intervals with a 0.5-mm tipping-bucket rain gauge at an open canopy area on the ridge of the catchment (Figure 1).

We estimated sediment yield based on periodic measurements of sediment captured by a weir pond (Figure 1). The dimensions of the weir pond were 6.7 m in width, 11.0 m in length, and 2.6 m in depth. Because the lowest part of the V-notch was located approximately 1.5 m from the bottom of the weir pond, the pond had sufficient capacity to capture all bed load sediment. Benchmarks were set at 1-m intervals in a longitudinal direction at either end of the weir pond to create survey transect lines. Along each transect line, we measured the depth of sediment at 1-m intervals in a lateral direction using an engineering level. We then calculated the volume of transported sediment in a given period from the difference in the volume of measured sediment between each measurement and the previous one. We measured the depth of sediment mainly after large rainfall events and early spring. Once a year, we removed all deposited sediment from the weir pond and reset our measurements. We assumed that the weir pond could capture most of the sediment greater than moderate sand-size fractions (> 2 mm in diameter), whereas finer sediments smaller than 2 mm could be transported as suspended matter during major storm events (Gomi and Sidle, 2003). Thus, we considered particles > 2 mm to be bed load sediment. For selected periods, sediment samples were collected to measure the density ($t/m^3$) and particle size distribution (% by weight) of the bed load sediment. To estimate the bulk density of bed load, we dried the collected sediment samples at 80°C for 24 hours and then measured the amount and weighed the volume. To estimate the particle size distribution of bed load materials in the channel, three dimensional measurements of 100 particles were taken every 30 cm along a 30-m channel segment in June 2014 which is before the beginning of the main rainy season in Japan. During the observation period, we did not confirm large bank failures in our study catchment. Therefore, we assumed the size distribution of bed-sediment can be representative in our study catchment. We classified particles as very fine pebbles (2–4 mm), fine pebbles (4–8 mm), medium pebbles (8–16 mm), coarse pebbles (16–32 mm), very coarse pebbles (32–64 mm), small cobbles (64–128 mm), large cobbles (128–256 mm), small boulders (256–512 mm), and medium boulders (512–1024 mm), based on the system established by Friedman and Sanders (1978).

RESULTS

The annual precipitation during the monitoring period ranged from 2355 mm in 2013 to 2757 mm in 2010 (Figure 2). The mean annual runoff ranged from 1778–2110 mm (also see Oda et al., 2013). Monthly precipitation and discharge were greatest during September to October, with the exception of 2012 (when they were greatest during June to July), and lowest from January to February. The mean maximum daily precipitation with standard deviation was 143.7 ± 69.0 mm/day (Table I). The total discharge for specific monitoring periods ranged from 18.3–1390.1 mm. The mean discharge was 9.0 ± 12.7 mm/day. Minimum and maximum daily discharges were 1.6 ± 1.6 mm/day and 83.9 ± 90.3 mm/day, respectively. Large peak discharges (> 200 mm/day) occurred on October 19, 2011 (223 mm/day), June 1, 2012 (314 mm/day), and June 11, 2014 (272 mm/day). The recurrence interval of maximum daily precipitation was estimated

Figure 1. Study area and location of the sediment basin, weir, and weather station
as ~5.0 years based on a 30-year record of 24-hour precipitation collected at the Automated Meteorological Data Acquisition System (AMeDAS) in Tanzawako (Figure 1).

We sampled bed load 23 times during the entire period (Figure 2, Table I). On average, bed load events occurred two or three times per year. During some events, the estimated bed load was 0 m$^3$ because no detectable changes occurred in our periodic surveys. Significantly large bed load yields were observed on November 24, 2010 (0.172 m$^3$/ha/day), July 3, 2012 (0.064 m$^3$/ha/day), and October 24, 2013 (0.086 m$^3$/ha/day). Mean (± standard deviation) of bed load transport in the period of summer–autumn (0.023 ± 0.044 m$^3$/ha/day) was 5.7 times greater than during winter–spring (0.004 ± 0.008 m$^3$/ha/day). Using a bulk density of 1.23 t/m$^3$, the estimated annual bed load yield ranged from 2.7–34.0 t/yr. Bed load yield positively increased with the increases in peak discharge ($r_1 = 0.63, p < 0.01$), peak precipitation ($r_1 = 0.47, p < 0.05$), and total discharge ($r_1 = 0.44, p < 0.05$) except for total precipitation in the study catchment (Figure 3). A significant correlation was found between bed load yield and peak discharge for bed load events only ($r_2 = 0.55, p < 0.05$).

More than 50% of the bed load sediment by weight was composed of sediment with particle sizes ranging from 2–10 mm in diameter (Figure 4). The mean (± standard deviation) diameter of the bed surface materials was 82 ± 107 mm, and the dominant step-forming materials in the stream bed were comprised of particles larger than 200 mm.

Table I. Observation results for precipitation, discharge, and bed load transport

| Observation period | Period | Total precipitation (mm/period) | Peak precipitation (mm/day) | Total discharge (mm/period) | Mean discharge (mm/day) | Minimum discharge (mm/day) | Peak discharge (mm/day) | Amount of bed load yield (m$^3$/period)(m$^3$/ha/day)(t/ha/day) |
|--------------------|--------|---------------------------------|-----------------------------|-----------------------------|-------------------------|---------------------------|------------------------|---------------------------------------------------------------|
| 1 1 Jun., 2009     | 4 Aug., 2009 | 521.5                           | 118.0                       | 243.3                       | 3.8                     | 1.4                       | 15.9                   | 0.40 0.0009 0.0011                                          |
| 2 4 Aug., 2009     | 24 Aug., 2009 | 144.2                           | 127.2                       | 112.0                       | 5.6                     | 1.9                       | 34.4                   | 2.11 0.0151 0.0186                                          |
| 3 24 Aug., 2009    | 22 Oct., 2009 | 429.7                           | 123.2                       | 203.6                       | 3.5                     | 0.9                       | 64.5                   | 0.24 0.0006 0.0007                                          |
| 4 22 Oct., 2009    | 24 Jun., 2010 | 1735.8                          | 104.3                       | 1037.7                      | 4.2                     | 0.6                       | 37.5                   | 0.34 0.0002 0.0002                                          |
| 5 24 Jun., 2010    | 21 Sep., 2010 | 727.7                           | 134.3                       | 302.8                       | 3.4                     | 0.9                       | 20.7                   | 0 0 0                                                        |
| 6 21 Sep., 2010    | 8 Nov., 2010  | 819.2                           | 170.1                       | 595.7                       | 12.4                    | 2.1                       | 75.5                   | 0.43 0.0013 0.0016                                          |
| 7 8 Nov., 2010     | 24 Nov., 2010 | 59.9                            | 28.1                        | 40.0                        | 2.5                     | 1.6                       | 5.1                    | 19.26 0.1720 0.2115                                          |
| 8 24 Nov., 2010    | 1 Aug., 2011  | 1611.6                          | 196.0                       | 987.3                       | 3.9                     | 0.7                       | 71.7                   | 1.74 0.0010 0.0012                                          |
| 9 1 Aug., 2011     | 19 Oct., 2011 | 1237.9                          | 273.2                       | 844.7                       | 11.0                    | 1.6                       | 222.9                  | 15.91 0.0316 0.0388                                          |
| 10 19 Oct., 2011   | 1 Jan., 2012  | 1747.1                          | 255.0                       | 1390.1                      | 6.2                     | 0.7                       | 314.3                  | 27.49 0.0174 0.0214                                          |
| 11 1 Jan., 2012    | 19 Jun., 2012 | 110.6                           | 27.0                        | 49.5                        | 2.7                     | 1.7                       | 5.2                    | 0 0 0                                                        |
| 12 19 Jun., 2012   | 3 Jul., 2012  | 295.9                           | 129.7                       | 237.9                       | 17.1                    | 4.1                       | 58.6                   | 6.24 0.0637 0.0783                                          |
| 13 3 Jul., 2012    | 20 Aug., 2012 | 325.1                           | 126.9                       | 271.7                       | 5.7                     | 1.2                       | 104.5                  | 0 0 0                                                        |
| 14 20 Aug., 2012   | 12 Apr., 2013 | 1385.0                          | 155.0                       | 841.8                       | 3.6                     | 1.2                       | 76.6                   | 2.26 0.0014 0.0017                                          |
| 15 12 Apr., 2013   | 1 Jul., 2013  | 530.7                           | 137.9                       | 306.1                       | 3.8                     | 1.0                       | 42.4                   | 0 0 0                                                        |
| 16 1 Jul., 2013    | 28 Aug., 2013 | 236.2                           | 73.0                        | 140.0                       | 2.4                     | 1.4                       | 4.9                    | 0 0 0                                                        |
| 17 28 Aug., 2013   | 11 Sep., 2013 | 97.0                            | 54.3                        | 18.3                        | 1.3                     | 0.0                       | 3.8                    | 0 0 0                                                        |
| 18 11 Sep., 2013   | 24 Oct., 2013 | 873.6                           | 208.6                       | 619.9                       | 14.4                    | 1.5                       | 188.4                  | 25.90 0.0860 0.1058                                          |
| 19 24 Oct., 2013   | 31 Oct., 2013 | 163.0                           | 78.0                        | 143.8                       | 20.5                    | 8.2                       | 62.3                   | 0.23 0.0046 0.0057                                          |
| 20 31 Oct., 2013   | 4 Jun., 2014  | 904.9                           | 133.0                       | 762.8                       | 3.5                     | 0.8                       | 24.5                   | 0 0 0                                                        |
| 21 4 Jun., 2014    | 11 Jun., 2014 | 434.0                           | 234.5                       | 437.2                       | 62.5                    | 0.9                       | 271.8                  | 0.67 0.0136 0.0168                                          |
| 22 11 Jun., 2014   | 26 Aug., 2014 | 458.0                           | 120.0                       | 331.4                       | 4.4                     | 1.7                       | 30.0                   | 0.62 0.0012 0.0014                                          |
| 23 26 Aug., 2014   | 5 Nov., 2014  | 804.5                           | 188.5                       | 644.1                       | 9.1                     | 0.7                       | 194.0                  | 8.18 0.0165 0.0202                                          |
diameter of the mobilized particles lay roughly within the range of the 10 to 30% diameter of the channel bed substrate.

DISCUSSION

Bed load yields and materials in a headwater catchment

The annual bed load yields in our study catchment (0.3–5.6 t/ha/yr) fell within the ranges reported in previous studies. Grant and Wolff (1991) reported average bed load yields during pre- and post-timber harvesting periods in Oregon, USA of 0.03–5.60 t/ha/yr. Alvera and García-Ruiz (2000) reported bed load yields in a high mountain catchment in the Central Spain Pyrenees ranging from 0–0.76 t/ha/yr. Nishimune et al. (2003) reported bed load yields after a forest fire in Hiroshima, Japan with ranges from 0.01–0.18 t/ha/yr.

By comparing headwater and downstream, our estimated bed load yields in headwaters were one or two orders of magnitude lower than those estimated from sedimentation at a reservoir dam (Ministry of Land, Infrastructure, Transport and Tourism, Kanto Regional Development Bureau, 2011). These differences were likely associated with inclusion of other sediment sources downstream (Green et al., 2013). The number of sediment sources related to landslides and debris-flow sources increases with increasing drainage area (Benda and Dunne, 1997). Moreover, legacies of sediment supplies by the past landslide can still be prolonged in sediment yields downstream (Page et al., 1994), while current sediment storage in channels are more responsible in a headwater channel. Indeed, numerous landslides occurred by earthquakes (MJ > 6.5) in the period from 1923 to 1924 in a watershed located adjacent to our study areas (Inoue and Kasahara, 2009). Such sediment is still stored on hillslopes and in channels and possibly has been propagated to a downstream reservoir (Koi et al., 2008). In addition, the proportion of suspended sediment to total sediment load is highly variable and its contribution becomes greater in sediment yields downstream (Lenzi and Marchi, 2000), which we did not consider in this study.

The bed load sediment was significantly finer than the channel bed surface material (Figure 4). Finer particles < 2.0 mm actively participated in transport, while particles > 10.0 mm remained inactive. Church et al. (1991) found that bed load particle sizes were significantly finer than channel bed material in a gravel bed stream. Consequently, selective transport of fine materials dominates in steep headwater channels (Ashworth and Ferguson, 1989). Therefore, the finer component of sediment in the channel can be transported in the stream and the rest of the particles remain in the channels for much longer periods with a transition of colluvial to fluvial processes (Gomi and Sidle, 2003).

Responses of bed load yields

We found that bed load was transported during two to three storms in a year (Figure 2, Table I). These findings are consistent with those of previous studies. For example, bed load entraining discharge occurred a minimum of two to three times during the storm season in a low gradient, second-order stream in southeast Alaska (Sidle, 1988). When monitoring headwater hollows, Hattanji et al. (2006) observed only a few occurrences in a year of bed load movement when the critical discharge was exceeded in headmost colluvial valleys. Gomi and Sidle (2003) observed more bed load events in steep headwater streams, which were associated with consistent sediment supplies from hillslopes.

Our findings reveal a significant relationship between the bed load yield and peak discharge for bed load events (Figure 3). Such a relationship between bed load yields and peak discharge agreed with some previous studies in steep (> 14% mean stream gradient) streams of forested catchments (Lisle, 1989; Rickenmann, 1997). This indicates that transport capacity of sediment in streams can affect bed load yield (Imaizumi and Sidle, 2007). Hence, we also had periods of zero bed load yield, although sufficient runoff and transport
capacity was available. For example, on November 24, 2010, we observed 0.172 m³/ha/day bed load yield at 5.1 mm/day peak discharge, however there were no bed load yields in a similar peak discharge (5.2 mm/day) on June 19, 2012. Such storm events with no bed load yield typically occurred after the occurrence of significant bed load yields (Figure 2). Discontinuous and intermittent bed load sediment movement with similar storm events is associated with a time lag if there is scouring and filling of substrate sediment in channels (Imaizumi et al., 2009). Key control factors determining bed load movement include temporal fluctuation and spatial distribution of channel sediment storage (Benda and Dunne, 1997). Sediment availability in the channel before and after the largest events altered the relationships between bed load yields and peak discharge (Sidle, 1988; Gomi and Sidle, 2003). Reduced bed load transport due to the exhaustion of available sediment throughout a sequence of storm events has previously been observed in mountain streams (Nanson, 1974; Moog and Whiting, 1998). 

The availability of sediment in channels alters the responses of bed load yield during storm events. The amount of available sediment depends on the sediment supply from hillslopes or upstream reaches (Hassan and Church, 2001), sediment exhaustion through sequences of storm events (Moog and Whiting, 1998), and disruption of channel bed conditions during high flows (Adenlof and Wohl, 1994). In our study catchment, no landslides or large-scale bank failures occurred during the monitoring periods, and sediment supplies were associated with soil surface erosion by rain during the rainy season, and frost freezing and thawing from early winter through early spring (Hiraoka et al., 2013). Although the bare surface on hillslopes near the stream channels possibly produced sediment (Gomi et al., 2013), these sediments can be deposited in the adjacent channels and remain untransported. Furthermore, most of the sediment supplied from the hillslopes due to freezing and thawing was typically larger than 10 mm in diameter. Such sediment can also remain in stream channels until it is weathered to small particles. Moreover, bed load transport can be limited with selective transport of fine particles caused by sediment accumulation, because our study site was located in a transition area between colluvial and fluvial processes (Wohl, 2010). Thus, large particles supplied from the adjacent hillslopes accumulated in the channel until mass movement and/or large rain storms occurred (Imaizumi and Sidle, 2007). Therefore, the time lag in sediment movement due to filling and scouring of sediment is an important hydrogeomorphic process for understanding long-term bed load dynamics in headwater streams.

**CONCLUSION**

By monitoring bed load yields in a steep headwater stream, we revealed the intermittent responses of bed load transport. Hydrological processes, especially peak discharge, correspond to bed load yield. The availability of sediment in channels with respect to their transport capacity induced an intermittent response of sediment yield to stream discharge. This may be related to the time lag of scour and fill sequences of bed load transport. The dominant transported bed load was smaller (< 30% diameter in channel bed substrate) than the channel bed substrate in all streams because much of the larger substrate (> 200 mm) contributed to rather stable interlocked channel structures. Because of the selective transport of finer particles, larger particles supplied from the adjacent hillslopes accumulated in the channels until future mass movement occurred. It is important to integrate information about sediment movement in headwater streams into management and restoration schemes for watershed systems.

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