Changing suspended sediment dynamics due to extreme flood events in a small pluvial-nival system in northern Japan

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Abstract Suspended sediment concentration (SSC) has been monitored in a small, steep and forested pluvial-nival system from 2001 to 2007. The hydrological regime is characterized by rain-on-snow and snowmelt, in addition to high intensity summer rains that normally produce the maximum annual flood. Turbidity and stage were logged every 5–10 minutes, with flood stage activating a pump sampler for determining SSC by filtration. Total suspended sediment yield was estimated by the SSC-turbidity relationship, if possible, or by separate discharge-rating curves (SSC-Q) on rising and falling limbs. Shifts in the SSC-Q rating curves were detected after three extreme flood events occurred during 2004 and 2005, causing a period of channel instability. Channel aggradation and bank erosion appear to have been caused by chronic supply of sediment where re-activated landslides feed directly into the channel, and subsequently by a large pulse of sediment entering the channel as a meander cut-off was formed.

Key words suspended sediment concentration; suspended sediment yield; turbidity; sediment-rating curves; sediment supply; channel instability; Japan

INTRODUCTION

The dynamics of suspended sediment transport in small headwater basins play an important role in determining the sediment budgets of large continental-scale river basins. Steep slopes, high precipitation intensities, snowmelt and/or glacier melt, and the frequent occurrence of mass wasting processes such as landslides lead to a very complex pattern of sediment supply to, and movement through, stream channel systems in these headwater source areas. There may also be further impacts on the system related to land-use change such as deforestation, or climate change, that leads to changes in the seasonal snowpack accumulation or rainfall intensities.

The purpose of this study is to evaluate the characteristics of suspended sediment concentration and yield at the event scale, as well as seasonal patterns and variation over a period of years for a small humid headwater basin. Such work has previously been undertaken in various environments worldwide, including the southwest of England (Walling, 1977), the Italian Dolomites (Lenzi & Marchi, 2000; Lenzi *et al.*, 2003), the Italian Apennines (Pavanelli & Pagliarani, 2002), the Spanish Basque Country (Zabaleta *et al.*, 2007), the semi-arid northern Negev of Israel (Alexandrov *et al.*, 2007), the Nepal Middle Hills (Brasington & Richards, 2000), the Lake Tahoe region of Nevada (Langlois *et al.*, 2005), the Waipaoa River Basin of North Island in New Zealand (Hicks *et al.*, 2000), and the Upper Niger river basin (Picouet *et al.*, 2001), to mention only a selection. A major focus of research has been the investigation of variability in the relationship between sediment concentration and water discharge, namely hysteretic patterns, which have been used to explain the variability of sediment sources from one flood to another (Klein, 1984; Williams, 1989; Jansson, 2002; Seeger *et al.*, 2004). In an attempt to better predict the continuous variability of suspended sediment concentration during a flood event, and in turn the total sediment yield, a second major focus of research has been the development and application of turbidity monitoring (Walling, 1977; Gippel, 1995; Lewis, 1996; Wass & Leeks, 1999; Pfannkuche & Schmidt, 2003; Orwin & Smart, 2005). However, difficulties remain in obtaining reliable turbidity data during extreme flood events in mountain rivers.

This paper presents results from seven years of monitoring work in a small headwater basin that combines a distinct snowmelt season with a summer rainy season (pluvial-nival system). The occurrence of three extreme floods within the space of about a year led to a period of channel aggradation and subsequent degradation, and allowed the examination of changes in sediment-rating curves as the channel adjusted to the movement of a large pulse of sediment through the channel system. We also discuss issues related to the accuracy of suspended sediment rating curves in small mountain basins with flashy hydrographs, and look at scaling issues and the difficulties in extending the results from small-headwater scales to continental scales.

STUDY LOCATION AND METHODS

Stream gauging and suspended sediment monitoring were undertaken at Takiya River between 2001 and 2007 (Fig. 1). The hydrological regime is a hybrid pluvial-nival type which experiences flood events due to rain-on-snow and snowmelt from winter through spring, and high intensity summer rains that normally produce the maximum annual flood. Summer floods are flashy, with increases in stage of up to 1 m recorded over 10 minutes, due to steep mountain slopes and rainfall intensities exceeding 50 mm/h. Mean monthly air temperature ranges from 0.2°C in January to 25.2°C in August, and mean monthly precipitation ranges from 167 mm in May to 332 mm in December (Miomote Dam, elevation 130 m, Fig. 1). Mountain snowpack, present from November to May, contributes to the high mean annual runoff of about 3000 mm. A full description of the physical and hydrological characteristics of the basin is given in Whitaker *et al.* (2008).

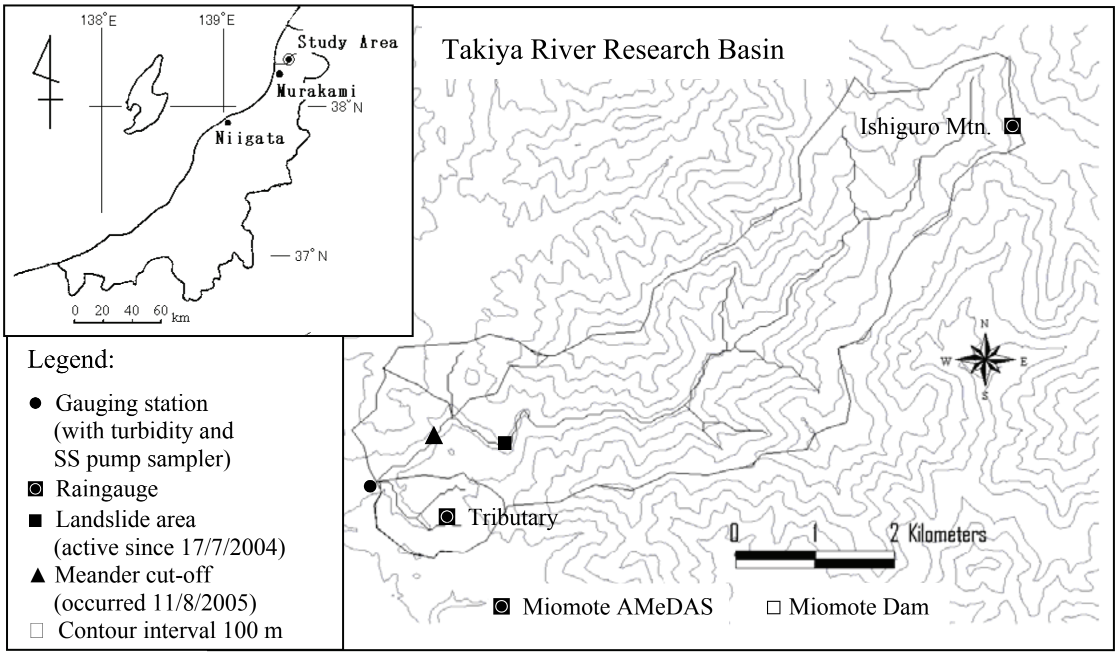

Fig. 1 Takiya River located in northern Niigata Prefecture on the Sea of Japan coast (area 19.45 km^2, elevation 40–950 m).

At the gauging station, main stem channel length is 11.5 km, channel width is 12 m, channel slope is 1.0%, and channel morphology is riffle-pool with predominantly gravels to boulders and areas of exposed bedrock (D_{50} of 75 mm in 2000). The geology of the basin is complex and heavily faulted, dominated by sandstone and conglomerate, dark grey mudstone and hard shale in the upper basin, and with a mixture of slate and sandstone, granite, and rhyoritic pyroclastic rocks in the lower basin. The main stem of Takiya River often runs over bedrock, and the basin topography is steep, especially in the central part of the basin where the majority of slopes are greater than 30°, limiting soil development. Landslide and avalanche activity are high. Vegetation consists of mixed deciduous forest and shrubs (beech, oak and maple) in the middle and upper elevations, with locally managed cedar stands in the lower elevations. Between 30 and 40 years ago some of the upper elevation beech forest was harvested and replanted with cedar, but the upper basin is now protected national forest.

Turbidity (OBS-3) was logged every 5 minutes, and the stage measurement interval was 10 minutes. Flood stage activated a pump sampler (Sigma 900), which took 24 samples over a 24-hour period at increasing time intervals (from 5 minutes to 4 hours). During 2001–2004, before channel aggradation occurred, the sampler was activated at a stage of 0.55 m (4.5 m^3/s) that approximately coincided with the initiation of bed load movement. Turbidity sensor, pressure transducer and pump sampler intake were all fixed about 15 cm above the streambed and close to the stream bank next to the staff gauge. Discharge measurements were made frequently to establish the stage-rating curve, and depth-integrated grab samples were taken across the full channel width to compare with the pumped samples. Flow conditions were extremely turbulent at the gauging station at flood stage and we found good agreement between pumped-sample SSC and depth-integrated grab sample SSC. However, during extreme floods we cannot assume the samples pumped close to the stream bank are representative of conditions in the centre of the channel where we might expect a higher proportion of sand particles in the suspended load.

RESULTS AND DISCUSSION

During 2001–2007, there were three extreme flood events with peak discharges estimated at 80–100 m^3/s and precipitation exceeding 200 mm/day and 50 mm/h (Table 1). The first event occurred on 17 July 2004 and the subsequent events occurred on 27 June and 11 August 2005, separated by a period of only six weeks. The first event re-activated a landslide area located 2.2 km upstream of the stream gauge (Fig. 1), leading to a chronic supply of sediment directly into the channel, and ultimately to channel aggradation, bank erosion, and the development of a meander cut-off that occurred 0.7 km upstream (Fig. 1) during the third large flood on 11 August 2005. At the gauging station the streambed showed noticeable accumulations of fine gravel after the first large flood of 17 July 2004, although it was not until the third large flood on 11 August 2005 that a shift in the stage-rating curve occurred due to channel aggradation and changes in the size distribution of the streambed. Between August 2005 and June 2007, a period of channel instability persisted with at least six shifts detected in the stage-rating curve and aggradation reaching 50 cm at the gauging station. During this period it was more difficult to estimate discharge accurately due to the frequent shifts in the rating curve, and also there were problems with burial of the sampler intake and turbidity sensor as the large pulse of accumulated sediment moved downstream. Currently the channel cross-section is relatively stable again with a net aggradation of about 10 cm over pre-2005 levels.

During 2002, both suspended sediment samples and turbidity data were obtained for several large floods, including a rain-on-snow event on 17 April and two rainstorms over 10–11 July (Table 1). We found that power regression relationships gave the best fit between SSC and turbidity, with variations in the slope and intercept from one flood to another (Fig. 2(a)) that are likely caused by variability in the size-distribution of the suspended sediments. Analysing the relationship between SSC and turbidity over the long-term, we see an increase in scatter and a shift in the relationship for the data after 17 July 2004 (Fig. 2(b)). We attribute this to an increase in the number and type of sediment sources due to landslide activity and channel instability after the 17 July 2004 flood. In particular, the landslide area became a major source of silt and clay-sized particles. Generally, we found that turbidity-rating curves showed a higher degree of fit compared to discharge-rating curves, due to the fact that SSC is controlled by a number of sediment supply factors that are not always closely linked to discharge. However, problems related to woody debris accumulation around the turbidity sensor, or burial of the sensor under sediment deposits, meant that the turbidity record was very intermittent. We therefore often had to resort to a discharge-rating curve for the estimation of suspended sediment yield for flood events (Table 1). As sediment samples were not obtained for the 17 July 2004 and 11 August 2005 flood events, the SSC-Q rating curve obtained for the 27 June 2005 flood was applied to all three extreme floods.

Table 1 Estimation of 24-hour period suspended sediment yield for selected events, including the three largest floods on record, using event-specific SSC-T or SSC-Q rating curves.

Date	Max. stage (m)	Max. discharge (m^3/s)	Daily precip. (mm)	Max. precip. (mm/h)	Daily SS yield (t/km^2)	Estimation method
17/4/2002	1.03	18.2	35	9	12.2 (7.7)[4]	SSC–T[1]
10/7/2002	1.14	22.7	117	27	9.5 (8.4)	SSC–T[1]
11/7/2002	1.09	20.8	45	20	7.6 (13.2)	SSC–T[1]
24/8/2003	1.00	17.3	66	16	7.8 (3.9)	SSC–T[2]
17/7/2004	2.30	99.3	191	46	1365 (1401)	SSC–Q[3]
27/6/2005	2.15	85.8	227	34	474 (635)	SSC–Q
11/8/2005	2.59	79.8	224	51	1212 (1664)	SSC–Q[3]
29/6/2007	1.73	59.1	138	30	52.2 (338)	SSC–Q

[1] Turbidity rating curves shown in Fig. 2(a).
[2] SS samples not obtained: surrogate SSC-T rating curve used from 21/8/2003 flood.
[3] SS samples not obtained: surrogate SSC-Q rating curve used from 27/6/2005 flood.
[4] All values in parenthesis are estimates using the long-term SSC-Q rating curves given in Fig. 3(a) and (b), with full results in Table 2.

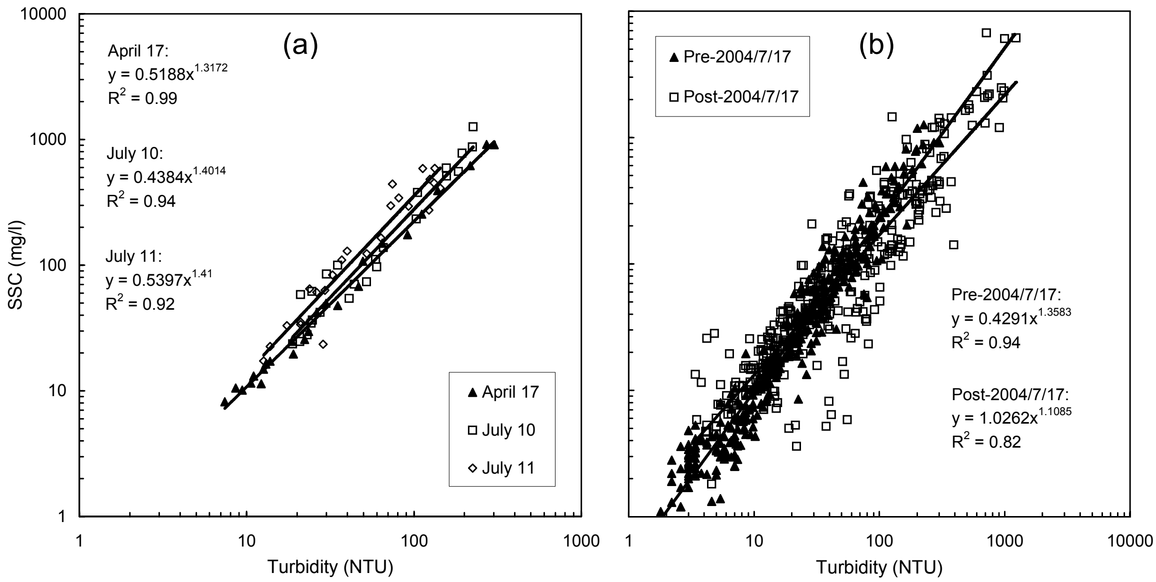

Fig. 2 Relationship between suspended sediment concentration and turbidity for: (a) major floods in 2002, and (b) pre/post-17 July 2004 flood event (y-axis same).

Also shown in Table 1, in parenthesis, are the estimates obtained by applying the long-term SSC-Q rating curves, using separate regressions for the rising and falling limbs of the hydrograph for the periods before and after the first extreme flood on 17 July 2004. In attempting to estimate the sediment yield for an un-sampled flood event, we do not know whether a single-event surrogate SSC-Q rating curve or a long-term SSC-Q rating curve is more appropriate. We might expect a surrogate SSC-Q rating curve for a similar magnitude flood occurring close in time to give the best estimate (if one exists), but our data showed high variability in the rating curve between even similar floods. For the three extreme floods, the long-term SSC-Q rating curve estimates range from 3 to 37% greater than the single-event SSC-Q estimates showing a high degree of uncertainty. However, both estimation methods do show the dominance of the extreme flood events, with suspended sediment yields 1–2 orders of magnitude greater than those floods sampled in 2002–2003 (Table 1).

In Fig. 3 we present the results of analysing the long-term trends in the relationship between SSC and discharge, and also the multiplicative model of suspended sediment load (SSL) on

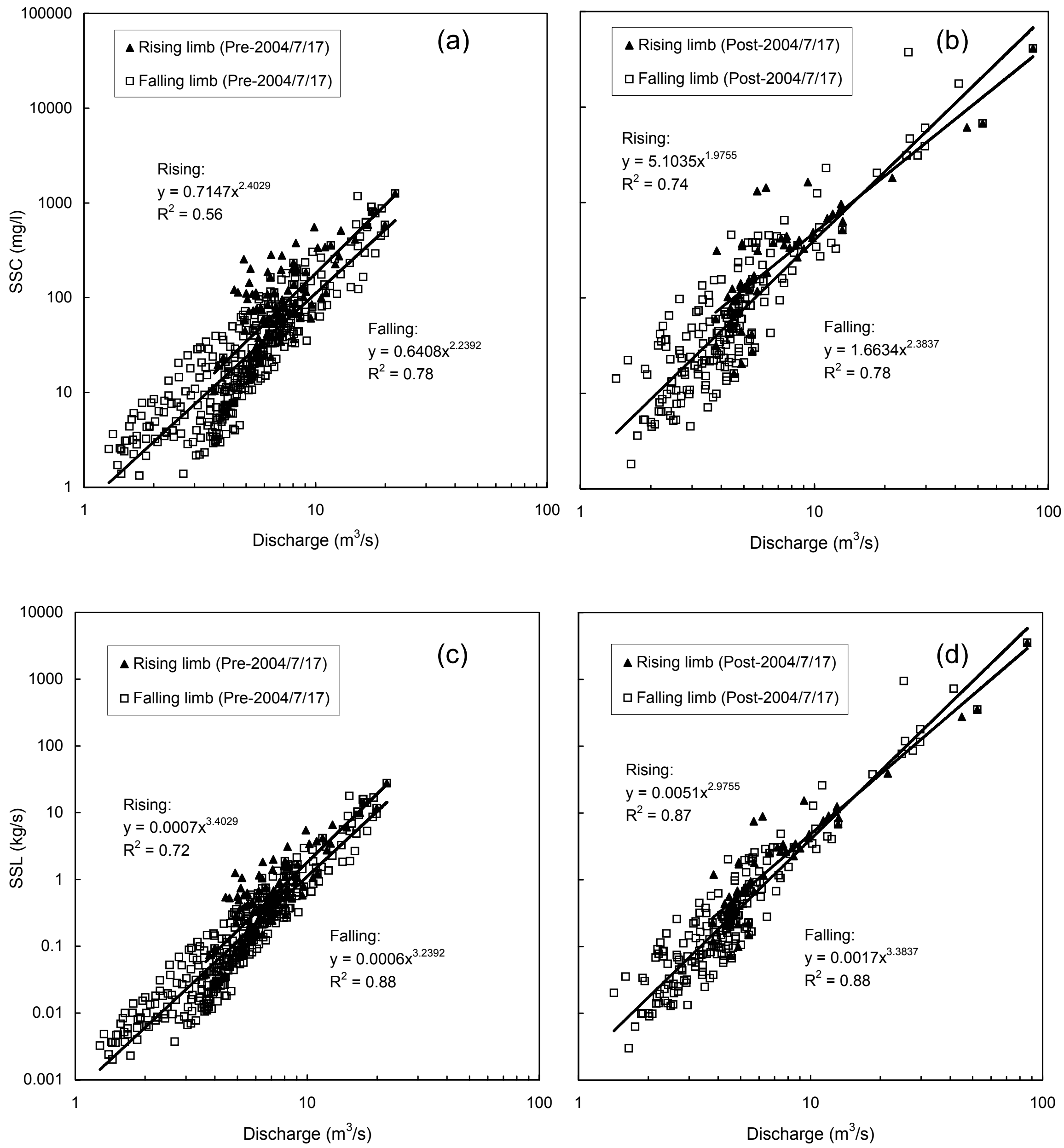

Fig. 3 Rising and falling limb suspended sediment rating curves for: concentration, (a) and (b), and load, (c) and (d), for pre/post-17 July 2004 flood event (y-axis same for L and R panels).

discharge. In this analysis, the post-17 July 2004 data does not include the period of greatest channel instability from August 2005 to June 2007, when there were problems in obtaining sediment samples and the wide range in scatter in the data precluded any meaningful regression analysis. In the pre-17 July 2004 data we see that the slope of the relationship is slightly steeper for samples taken on the rising limb of the flood hydrograph, and a typical clockwise hysteresis pattern is observed where SSC is higher on the rising limb for a given discharge amount due to sediment flushing. In the post-17 July 2004 data we see a different pattern emerges with a cross-over of the rising and falling limb curves giving an "8"-shaped hysteresis. This pattern may be explained by the greater volume of easily entrained sediment stored in the channel post-17 July 2004, and the release of sediment into the channel from bank erosion and landslides near the time of peak flows. Even though the period of greatest channel instability is not included, we see much higher levels of SSC in the post17 July 2004 data for comparable discharges (up to 1 order of magnitude).

We used the long-term SSC-Q rating curves given in Fig. 3(a) and (b) to estimate the monthly and annual suspended sediment yield for Takiya River (Table 2). By using separate regressions for the rising and falling limbs of the hydrograph, we could simulate, to a certain degree, the hysteresis patterns commonly found in the relationship between SSC and discharge. However, we acknowledge that many of the flood events, including two of the three largest floods, could not be sampled to confirm the nature of the SSC-Q relationship at peak flows, and so there is considerable uncertainty in the estimates provided in Table 2. There is uncertainty not only in characterizing the SSC-Q relationship, but also in extrapolating the stage–discharge relationship to peak flows that could not be measured by wading, and also in identifying the exact timing of shifts in the stage–discharge relationship during peak flows. An alternative method of estimating the suspended sediment yield uses the multiplicative model of suspended sediment load (SSL) on discharge (Fig. 3(c) and (d)), which places more weight on the higher values of SSC and discharge in fitting the regression model, and therefore could be argued to be the better approach in flashy streams where suspended sediment yields are dominated by a short period around the peak flow. However, this paper only presents those results obtained by applying standard SSC-Q rating curves. Because rating curves estimate the peak SSC to occur with peak discharge, sediment yields estimated by this method are very much influenced by uncertainties in the estimation of peak discharges.

Table 2 Monthly suspended sediment yield and summary characteristics for the Takiya River estimated using rising/falling limb SSC-Q rating curves for pre/post-17 July 2004 flood event (see Fig. 3(a) and (b)).

Yield (t/km^2)	2001	2002	2003	2004	2005	2006	2007
Jan.	0	7	0	0	0	0	1
Feb.	0	0	0	11	0	17	2
Mar.	3	20	1	2	13	14	78
Apr.	16	18	49	15	53	63	59
May	0	16	5	31	5	88	1
June	33	0	1	3	640	0	403
July	1	84	8	1 454	2	352	78
Aug.	1	3	6	39	1 694	0	64
Sep.	4	0	0	1	0	0	0
Oct.	2	21	0	0	26	36	0
Nov.	3	10	1	1	4	24	3
Dec.	0	1	10	4	0	24	6
Annual	63	180	82	1 562	2 437	618	694
Max. Daily	14	54	24	1 217	1 664	329	335
Max. Daily / Annual (%)	23	30	29	78	68	53	48
Max. SSC (mg/L)	1 400	2 320	1 710	47 300	55 200	16 700	26 100
Max. Q (m^3/s)	23	29	25	99	86	49	59

Every year the highest suspended sediment yields occur in the summer season from June to August, with the exception of 2003 which had a particularly weak rainy-season (Table 2). The snowmelt season is generally of secondary importance to the annual sediment yield, with a peak occurring during March to May. In 2004 and 2006 there were small peaks in the sediment yield during February due to rain-on-snow events, although we can see these are still two orders of magnitude smaller than the largest summer monthly sediment yields (17 *vs* 1700 t/km^2). In 2004 and 2005, estimated peak SSC reaches values of about 50 g/L, and even in 2007 remain about an order of magnitude greater than values during the period 2001–2003. The flashy nature of summer floods is apparent by the fact that 68–78% of the annual suspended sediment yield occurs within one day for the years 2004 and 2005. Channel instability is a key factor contributing to the high sediment yields through much of the spring and autumn of 2006, in addition to a July rainstorm. The estimated maximum annual suspended sediment yield shown in Table 2 (2437 t/km^2) is five

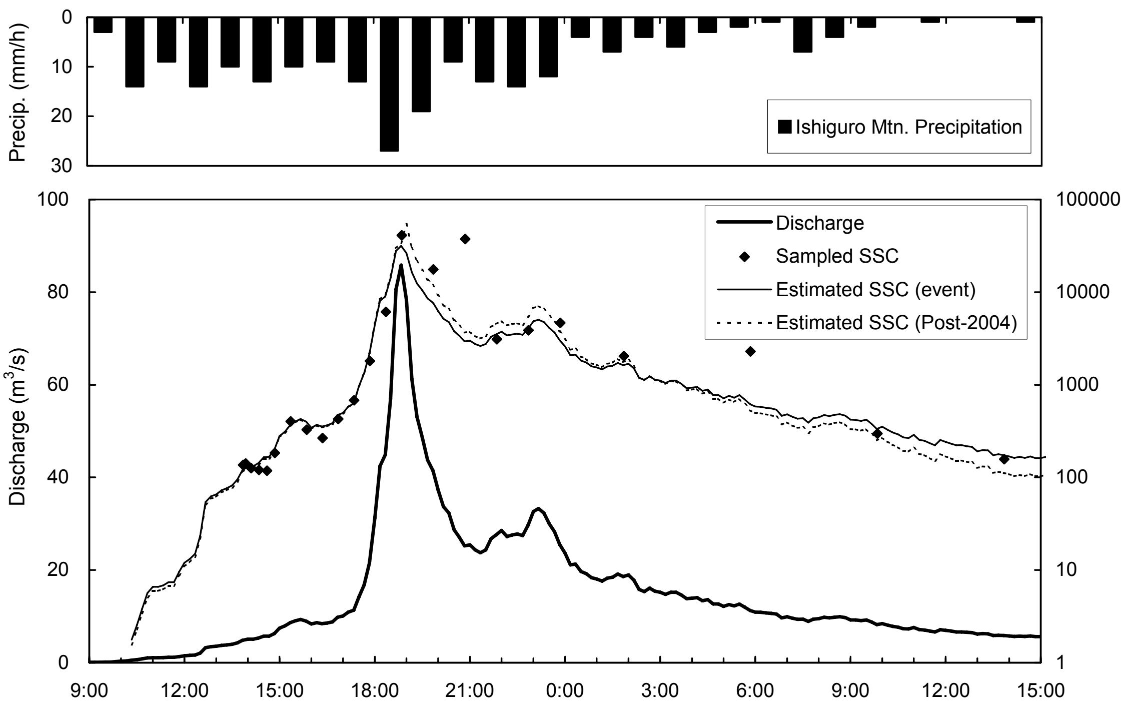

Fig. 4 Discharge hydrograph and precipitation for the second extreme flood, 27–28 June 2005, showing sampled SSC and continuous estimated SSC by two methods; single-event and post-2004 SSC-Q.

times greater than the maximum value for a small alpine basin in the Italian Dolomites (Lenzi *et al.*, 2003), although this value in no way approaches those extremes estimated for the Waipaoa River in New Zealand, where the long-term annual yield was estimated to be 11540 t/km^2 (Hicks *et al.*, 2000).

Figure 4 illustrates the case for the second extreme flood, 27–28 June 2005, which was the largest flood for which SSC samples were obtained. The maximum sampled SSC of 41 g/L at the peak of the flood was the maximum sampled value during 2001–2007, while 37 g/L was also sampled on the falling limb of the flood. These measured values are comparable to the maximum estimated values given in Table 2. Continuous SSC was estimated by using two different SSC-Q rating curve methods; the first based on samples obtained in the 27 June 2005 flood event only (single power function), and the second based on samples obtained over the long-term post-2004 (separate rising/falling limb power functions as given in Fig. 3(b)). Although both estimates are almost identical on the rising limb, there are significant differences on the falling limb, especially soon after the peak, so that the long-term SSC-Q rating curve estimate of event sediment yield is 34% greater than the single-event SSC-Q estimate (Table 1).

CONCLUSIONS

Although we encountered major difficulties in the estimation of flood event and long-term suspended sediment yields for a flashy pluvial-nival system in northern Japan, we have established that summer rainstorms are by far the most dominant runoff event in determining the total sediment budget. Up to 78% of the annual suspended sediment yield was estimated to have occurred in a single day during such storms. Furthermore, by examining the sediment yield over a period of years, we could establish that a cluster of three extreme floods caused channel aggradation and a period of continuing channel instability that has elevated the sediment yield values by an order of magnitude or greater.

Applying the results of this relatively small-scale headwater basin study to larger continental scales poses major difficulties. The sediment concentrations and yields, and the sediment-rating curves obtained, are all specific to the scale of the investigation and the particular hydrogeomorphic processes operating in the basin. But such individual field investigations are the building blocks of larger scale physical or conceptual models, and they are necessary for use in validating such models. Field observations at a range of scales are needed to improve process understanding (e.g. Sidle, 2006), allowing us to tackle scaling issues on a firmer footing.

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