Linkage of sediment supply and transport processes in Miyagawa Dam catchment, Japan

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Abstract

Linkages between sediment supply by episodic geomorphic processes, obtained from aerial photographs and field surveys, and sediment transport, estimated from changes in sediment deposition behind a large dam, were investigated in the Miyagawa Dam catchment, central Japan. A total of 6667 landslides were confirmed in the period from 1965 to 2000 based on seven temporal pairs of aerial photographs. Both the occurrence of landslides and discharge into the dam lake affect sediment yield, indicating that fluvial systems in Miyagawa Dam catchment are supply-limited with respect to sediment. Sediment yields are not only affected by the initial failed volume of landslides but also the mobility of landslides and debris flows. In Miyagawa Dam catchment, percentages of landslides reaching channels varied from 56% in 1997–2000 to 75% in 1976-1981, and were correlated with maximum hourly rainfall. In addition, the mobility of debris flows was higher during periods with high maximum instantaneous discharge compared to lower discharge, suggesting that the water content both in initially failed materials and transported sediment controlled their mobility. Topography also affected the mobility of landslides/debris flows. For catchments >0.1 km^2, the percentage of channel network length impacted by debris flows decreased with increasing catchment area due to reduced channel gradient. Thus, both the magnitude of rainfall-runoff events and catchment topography affect how landslide sediment contributes to sediment yield at the large catchment scale.

Index terms: Hydrology (1800), Catchment (1804), Debris flow and landslides (1810), Hillslope geomorphology (1826); and Sediment transport (1862).

Key words: landslide, debris flow, sediment budget, dam deposits, forest roads, and hillslope-channel linkages

1. Introduction

Because sediment supply processes affect sediment yield [*Walling and Webb*, 1982; *Asselman*, 1999, *Gomi et al.*, 2004], a unified sediment supply/transport model is needed to develop better measures for mitigating sediment disasters and assessing downstream impacts. A thorough understanding of sediment transport from the hillslope to downstream is required to develop such a unified model. However, linkages between sediment supply and transport processes are poorly understood, especially in moderate to larger-sized catchments. As a result, prior studies typically have not supported the development of temporally and spatially continuous sediment transport models at the larger catchment scale.

The relationship between sediment supply and transport (i.e., sediment yield) has been investigated using sediment budgets. *Slaymaker* [2003] reviewed sediment budget studies and noted that these are characterized by both temporal and spatial factors. In smaller catchments (e.g., catchment areas < 100 km^2), the frequency of episodic processes (e.g., landslides and debris flows) is limited, and occurrence of one episodic process event in the catchment greatly affects sediment yield [*Gomi et al*., 2004]. In larger catchments, long-term studies have been conducted because of the lack of short-term (yearly) sediment yield data [*Benda and Dunne*, 1997a, b]. The influence of sediment supply from episodic processes on short-term sediment yield (i.e., shorter than annual sediment yield) was assessed in larger catchments in Taiwan and New Zealand [*Trustrum et al.*, 1999; *Hovius et al.*, 2000; *Dadson*, 2003]. These studies revealed that size of rainfall-runoff events and the occurrence of landslides affect sediment yields. However, types of processes that entrain sediment from hillslopes into fluvial channel networks and factors that affect these entrained materials (e.g., channel gradient, catchment area, rainfall characteristics) are still unclear. Thus, transfer of sediment via episodic processes from hillslopes to channels needs to be better

articulated to more accurately estimate sediment yield from frequent and distributed mass wasting events in larger catchments [*Benda and Dunne*, 1997a].

In Japan, sediment deposition behind certain large dams has been measured annually since the 1930's [*Miyazaki and Onishi*, 1996; *Hiramatsu et al.*, 2002]. Such long-term annual sedimentation records are unique and represent some of the most useful global data to assess temporal trends in total sediment yields from larger catchments. *Miyazaki and Onishi* [1996] examined the timing of sediment supply and transport by comparing annual rainfall data with changes in the volume of dam deposits. *Hiramatsu et al.* [2002] evaluated the influence of forest management on the volume of dam deposits; however, processes linking sediment supply and transport were not discussed. Methods for clarifying linkages between sediment supply and transport include theoretical/physical methods (models) and statistical/stochastic methods. In larger catchments, factors that affect sediment yield (e.g., supply of sediment from various geomorphic features, volume of channel deposits, channel topography, water discharge, sediment storage features) have not been investigated in most tributaries because of large time and labor requirements. Thus, it is very difficult to apply theoretical/physical methods to larger catchments (compared to statistical/ stochastic analysis) due to the lack of distributed input data, even though such models may effectively predict episodic processes in small catchments [*Takahashi*, 1991; *Wu and Sidle*, 1995; *Chen and Lee*, 2000; *Revellino et al.*, 2004].

The overall aim of this study is to clarify the linkages between sediment supply and transport processes in larger catchments based on investigations in Miyagawa Dam catchment, central Japan. Specific objectives include: (*i*) to examine the relationship between sediment supply (especially by episodic processes) and sediment yield in the entire catchment using geomorphic data derived from aerial photographs and sediment deposition surveys behind the dam; (*ii*) to assess the ratio of landslide sediment transfer to streams (relative to landslide volume) as well as

the mobility of the sediment in channels as debris flows using statistical analysis based on Geographic Information Systems (GIS), digital elevation models (DEM), and field survey data; and (*iii*) to clarify factors that affect sediment supply-transport linkages based on temporal changes in mobility of landslides and debris flows.

2. Study area

Miyagawa Dam catchment (125.6 km^2) is located in southern Mie Prefecture, central Japan, upstream of the concrete gravity Miyagawa Dam (completed in May 1957; water holding capacity = 70,500,000 m^3) designed for hydropower generation, flood control and water supply (Figure 1). Average inflow and outflow of the lake in the period from 1957 to 2003 was 17.0 and 14.0 m^3/s, respectively. Differences between inflow and outflow include both water supply and evaporation from the surface of the lake. The area of Miyagawa Dam lake is 2.0 km^2 and average depth of the lake is 35 m. Main channel length in the catchment is 26 km; lowest elevation is at the dam (270 m a.s.l.) in the northeast portion of the catchment; the highest elevation is the peak of Mount Hidegatake (1695 m a.s.l.) in the southwest end of the catchment. Other than timber harvesting, which has occurred in 19% of the catchment in the period from 1965 to 1996 [*Hiramatsu et al.*, 2002], almost no anthropogenic disturbances have occurred. Because we focus on transport processes of landslide sediment and not on initial failure conditions that would be affected by root strength decay, timber harvesting may not strongly influence our analysis. Thus, the Miyagawa Dam catchment is suitable for investigation of sediment movement. The main geologic unit is the Chichibu Paleozoic strata comprised of sandstone and slate. Most of the catchment is characterized by very steep slopes; slopes with gradients of 30˚– 40˚ and 40˚–50˚ comprise 38% and 30%, respectively, of the entire catchment. Brown forest soil covers most of the catchment; soil depth is

shallow (typically < 1 m). Planted conifer forests composed of mainly sugi and hinoki occupy about 35% of the catchment [*Hiramatsu et al.*, 2002]; natural and secondary forests including broad-leaved deciduous and conifer forests occupy the remainder of the catchment.

The Miyagawa Dam catchment receives abundant rainfall, ranging from 1600 to 4500 mm annually in the period from 1957 to 2003 (average 3300 mm). Heavy rainfall events (i.e., total rainfall > 100 mm) occur during the Baiu rainy season (June and July) and in the autumn typhoon season (late August to early October). Active sediment supply processes are associated with high precipitation; landslides and debris flows often occur throughout the catchment [*Hiramatsu et al.*, 2002]. From September 28 to 29, 2004, Typhoon Meari (T0421) delivered epic rainfall to the area; maximum hourly rainfall was 139 mm at Kuzu rainfall station, about 1.5 km southeast of Miyagawa Dam and total rainfall was 1046 mm at Miyama town, about 6 km south of the catchment. Six people were killed (one person missing) by landslides in the sparsely populated area [*Hayashi et al*., 2004; *Kondo et al.*, 2004]. Winter snowfall occurs at higher elevations within the catchment from December to February, but precipitation in this period is only about 7% of total annual precipitation. Furthermore, annual maximum depth of snow cover is less than 10 cm (average from 1971 to 2000). Thus, snowmelt is typically not a significant landslide-triggering mechanism in this area.

Four moderately large earthquakes (M = 5.5 – 6.0) occurred within 100 km of the Miyagawa dam catchment after completion of the dam (Table 1). Earthquakes in 1960 and 2000 were closer to the catchment and slightly larger compared to others, indicating the potential for seismically-triggered landslides to affect sediment supply.

3. Methodology

3.1 Aerial photograph analysis

Seven temporal pairs of aerial photographs (1965, 1970, 1976, 1982, 1986–1987, 1992, 1996–1997, 2001) were used to determine the location and area of landslides and debris flows by stereoscopic assessment (Table 2). Confirmed landslides and debris flows were mapped on 1:5000 forest management maps (Figures 2a and 2b). Most of the aerial photographs were taken in March (before the Baiu season), thus almost all of the mass movements confirmed by aerial photograph stereographs likely occurred prior to December of the previous year. New occurrences of mass movements for each period (1965–1969, 1970–1975, 1976–1981, 1982–86, 1987–1991, 1992–1996, 1997–2000) were confirmed by comparing earlier and later aerial photographs. Mapped mass movements were divided into slope and channel components. All mass movements on hillslopes were designated as landslides and all in-channel mass movements were designated as debris flows. Based on our definition, landslides represent sediment supply processes from hillslopes and debris flows are sediment transport processes in steep channels. Even though other definitions exist to distinguish landslides and debris flows [e.g., *Coussot and Meunier*, 1996, *Hungr*, 2005], the definition adopted in this study appears best for distinguishing between sediment supply and transport using aerial photographs. Our definition ignores the travel distance of landslides and debris flows; therefore movements that travel short distances along channels (20–30 m in length) are also classified as debris flows in spite of their limited mobility. In this study, we define "channels" as geomorphic features where sediment and water accumulate, confirmed by a line that continuously crosses slope contours at an angle less than 90 degrees on the 1:5000 forest management maps (Figure 2b). Hollows by definition are not channelized [e.g., *Tsukamoto and Ohta*, 1988]. Channels and hollows are distinguished by their surrounding contours; hillslope contours along both sides of channels are nearly parallel to the channel, while hillslope contours are more oblique to the bottoms of hollows.

3.2 Dam deposits

Sediment deposition behind large dams is measured annually in Japan, with changes in the volume of dam deposits estimated by surveying cross-sections; at Miyagawa Dam lake, twenty-eight fixed cross-sections were surveyed from 1957 to present (Figure 1). Some of survey transects are located near large tributaries; thus, the volume of deltas developing at the confluence with the dam lake is also included in the volume of dam deposits. Surveys were conducted in the period from October to March when sediment inputs are small. Topography of the lake bed (below water) was measured by echo sounding, while other topographic features were measured by surveys using transit compasses or total stations. To quantify changes in the volume of deposits behind Miyagawa Dam, we compared cross-sections in the interval from 1957 to 2003. Increases in the volume of dam deposits are used to estimate sediment yield from the entire catchment. The dam lake has never been flushed of sediment or dredged since completion of the dam.

3.3 Rainfall

A rain gauge was installed near Miyagawa Dam in 1957; three additional gauges were later installed to compare the spatial distribution of rainfall (Figure 1). Comparison of rainfall data for four sites showed no clear relationship between elevation and rainfall amount. Thus, a Thiessen polygon approach [*Thiessen*, 1911] was used to estimate rainfall within the entire catchment. Daily rainfall data from 1957 to 2000 and hourly rainfall data from 1989 to 2000 are available in this area. Because no strategy was adopted to correct for non-vertical rainfall, rainfall intensity may include some error during intense rainfall with high winds.

3.4 Discharge into the dam lake

Changes in water level of Miyagawa Dam lake have been measured every 10 min since the completion of the dam. Instantaneous discharge (m^3/s) was derived from changes in lake volume for the last one minute of each interval; volume changes are estimated from fluctuations in water levels and lake topography. Water level is measured by both floating-type and pressure differential water level sensors. Winds that may affect the accuracy of water level observations were not considered in calculations of discharge. In 2003, maximum wind velocity exceeded 5 m/s for 34 days but wind velocities > 10 m/s were not observed at Kii-Nagashima observation site, about 8.5 km from the Miyagawa Dam catchment. Wind is generally moderate in this area except during typhoons.

There is a possibility that deposition of sediment within the 1-yr interval between topographic measurements may introduce some error related to discharge calculations; however, the maximum annual volume of newly accumulated dam deposits during the study period is only about 0.5% of the total water holding capacity. Thus, changes in lake bed topography may not introduce much error in discharge calculations. Evaporation from the lake surface is not considered for estimation of inflow. Because higher flows are observed on rainy days, the greater discharge errors introduced by ignoring evaporation on sunny days may not significantly affect sediment transport. Daily discharge can be calculated from average instantaneous discharge during any given day multiplied by time, while yearly discharge is discharge per day summed for the year. Given this method of calculation, large errors may be expected for individual instantaneous discharge values, including effects of daily changes in temperature, diurnal lake circulation, and strong winds. Such instantaneous discharge errors would diminish greatly by daily averaging (or longer), although the averaged discharge records will underestimate peak flows.

3.5 Field survey

Volumes of 51 landslide scars (excluding volumes of deposits) were measured to develop a volume-area relationship of landslides in the catchment. The range of the landslide size measured by field surveys (from 10 m^2 to 3000 m^2) covers most of the landslides confirmed on aerial photographs; this relationship was used to estimate landslide volume from landslide area derived from aerial photographs. Landslide volumes were estimated from widths measured at 2–10 transects, horizontal distances between adjacent transects, and depth of side walls along transects. Soil depth at the head scar was also used to estimate volume around the head scar. Small landslide dimensions were measured with a tape and stadia rod; larger landslides were measured by a laser instrument (precision of 0.1 m for both). Two types of bare areas were noted on aerial photographs on the downslope side of roads: (1) bare areas with uneven surfaces and (2) bare areas with flatter surfaces. Uneven bare sites usually can be identified on aerial photographs in the next photograph period, while flat bare areas typically cannot be found on the next sequence of aerial photographs because of recovery of vegetation. The uneven bare sites proved to be landslides, whereas flat bare areas were newly placed fill slopes on the downslope side of mountain roads. Based on field inspections of newly constructed roads in the catchment as well as our knowledge of mountain road construction practices in Japan, we believe that stable fill slopes (i.e., flat bare areas with no landslides) do not supply significant sediment to the Miyagawa channel network. In contrast, bare areas along the upslope side of roads (always cutslopes) and bare areas with uneven surfaces along the downslope side of the road may supply larger amounts of sediment. Therefore, we need to estimate sediment supply from these landslides. Landslide volume in each period is defined as the total of new landslide volume plus the increase in volume of older landslides (i.e., which grew in size from the last photoperiod).

Hillslope and fluvial processes (and attributes) that influence the relationship between sediment supply and transport were examined by field surveys. Storage on hillslopes and in

channels affects the relationship between sediment supply and transport [*Megahan et al.*, 1978; *Benda*, 1990; *Nakamura et al.*, 1995]. The ratio of storage to newly produced sediment cannot be assessed from aerial photographs; thus, volumes and positions of landslide deposits at the foot of hillslopes were measured.

3.6 GIS and topographic analysis

Topographic maps on which landslides/debris flows have been mapped were scanned and their location and areas were analyzed using Arc GIS software. Channel topography was also examined by Arc GIS using a 10 × 10 m grid DEM constructed from a 1:25,000 topographic map prepared by Hokkaido-chizu Corporation (Figure 2c). Because this DEM was based on 10 m contours of the topographic map, maximum elevation error is theoretically 10 m. However, terrain between contours was interpolated using the cubic Hermite function that nicely reproduces steep terrain [*Ardiansyah* and *Yokoyama*, 2002]; thus, it is expected that elevation errors are much less than 10 m.

Catchment area above channel grid cells was also assessed using Arc GIS (Figure 2c). The procedure for calculating catchment area involves two steps. First, the slope direction of all grid cells in the catchment was investigated using a DEM. Flow directions (both surface and subsurface runoff) were assumed to correspond to these slope directions. Secondly, cells without inflow grid cells were assumed to have catchment area of 100 m^2; catchment areas of other cells correspond to the number of upstream cells multiplied by the area of each cell (100 m^2) plus the area of the investigated cell itself (100 m^2).

4 Results and Discussion

4.1 Dam deposits

Cumulative volume of dam deposits increased progressively since the completion of Miyagawa Dam in 1956 (Figure 3). While volume of annual deposition fluctuates greatly from year to year, there is a long-term trend of increasing deposition with time; average rate of increases in dam deposits from 1956 to 2003 is 8.4 x 10^4 m^3/yr. This rate is higher in the latter portion of the study period; average rate from 1990 to 2003 is 16.4 x 10^4 m^3/yr.

On 22 March 2005, when the water level in the lake was low, samples of deposits were collected at three depths (0, 50 and 100 cm) at each of four sites to investigate grain size distribution (Figure 4). Almost all of sediments at sites A and D were < 1 mm (remote from larger tributaries), whereas layers of both fine and relatively coarse sediment occurred at sites B and C, which were near entry points of larger tributaries to the dam lake (Figure 1).

Grain size of the deposits around sites B and C should be affected by the water level of the dam lake; when water levels are low, channels extend into the middle of the lake, causing deposition of coarse sediment around junctions. Conversely, when the lake level is high, streams do not extend into the center of the dam lake and only finer washload is deposited in the lake. Hyperpycnal flows may also carry coarser material into middle of the lake.

Because the dam lake has never been flushed of sediment or dredged since completion of the dam, we assume that the volume of dam deposits is a good representation of total sediment yield, including wash load, suspended sediment, and bedload. Difference in density of sediments between dam deposits and hillslopes may affect the sediment budget analysis of the catchment. Density of reservoir deposits surveyed in other lakes is widely variable (450-1350 kg/m^3) and affected by grain size distribution of sediment and other factors [e.g., *Juracek*, 1997, *Verstraeten and Poesen*, 2001, *Tamene et al.*, 2006]. Density of dam deposits in the Miyagawa dam lake may also differ amongst measurement points because of differences in grain size (Figure 4). However, a

thorough investigation of the density of dam deposits for the entire dam lake is not realistic. Thus, we do not consider differences in density of dam deposits, although this may introduce some error in the sediment budget analysis.

4.2 Sediment supply and yield at the catchment scale

Based on aerial photograph analysis, a total of 6667 landslides were confirmed in the period from 1965 to 2000. Of these, 16% (1045 in total) were connected to channels and continued downstream as debris flows. Scales of aerial photographs differ slightly amongst photoperiods (Table 2), the precision of confirming smaller landslides differs amongst each period; the minimum landslide size that can be detected on aerial photographs in each period ranges from 15 m^2 to 40 m^2.

The field survey indicates that landslides unrelated to roads have a power law relationship of area and volume (Figure 5). The volumes of other landslides in the catchment were estimated by this power law relationship. However, landslides that initiated from roads exhibit different dimensions; cross-sections of road-related landslides are usually flat and depth is not related to size of landslides. Thus, volume of road-related landslides was estimated by multiplying the landslide area by the average depth of six surveyed landslides (1.43 m). *Bradinoni et al.* [2002] also noted that characteristics of road-related landslides differed from other landslides. Field surveys confirmed that some of landslides smaller than 40 m^2 were missed by aerial photograph analysis, while most of the landslides > 100 m^2 were confirmed by aerial photographs. Smaller landslides that were missed may introduce some error in the assessment of total landslide volume; however, such error may not affect trends of total landslide volume amongst individual periods. In the Miyagawa Dam catchment, elongated landslides are typical; triangular or tear-drop shaped landslides are few. Based on the field survey, the sliding surfaces of elongated landslides (i.e.,

widths < 10 m) are usually on bedrock. In the Miyagawa Dam catchment, steep slopes with shallow soils typically cause evacuation of all soil layers. In contrast, larger and wider landslides usually occur as failures within bedrock.

Changes in landslide volumes, estimated from aerial photographs and the field survey, are presented for the periods corresponding to intervals between aerial photographs (Figure 6a). The percentage of the landslide volume initiating from roads was much higher in the earlier years (1965–1975, 27%) compared to later years (1976–2000, 7%). The density of landslides is extremely high along newly constructed roads. Furthermore, changes in sediment volume of road-related landslides correspond to changes in length of newly constructed roads (Figure 6a). Thus, extensive road construction from 1965 to 1975 contributed to the large number of road-related landslides.

Landslide volume was typically greater than incremental increases in dam deposit volume up until 1992, and was exceptionally high from 1987 to 1991 (Figure 6a). These volume estimates include deposition of sediment upstream of the lake, because the increase in sediment storage in the catchment should equal the difference between total sediment supply (derived from the sum of episodic and chronic processes) and sediment yield (increases in dam deposits) as calculated from the sediment budget. After 1992, increases in dam deposits exceed landslide volume (Figure 6a).

Because the photoperiods are not uniform in length, landslide rates are calculated from landslide volume divided by photoperiod length (yr) and catchment area (Figure 6b). The relationship between landslide rate and rainfall is not very clear (compare Figure 6b and Table 3). For example, during the period with the highest landslide rate (1987-1991) none of rainfall attributes were exceptionally high compared to other periods. Such relationships may be affected by timber harvesting; *Hiramatsu et al*. [2002] and *Numamoto et al.* [2004] examined empirical relations between forest harvesting and landslide initiation in the Miyagawa catchment which

suggested that clearcutting enhanced sediment supply from hillslopes. An examination of aerial photographs for the period from 1965 to 1996 revealed an increase in landslides within clearcuts where trees were not replanted [*Hiramatsu et al*., 2002]. However, because the largest percentage of the catchment area that was clearcut during any photoperiod was only about 6% (from 1965 to 1969), and this percentage declined with time (to 1.6% in the 1992 to 1996 period), it appears that harvest-related landslides did not significantly affect the linkage between sediment supply and transport in the entire catchment.

In the period from 1997 to 2000, two earthquakes occurred near the study area (M 5.6 and 5.7, Table 1). Maximum hourly rainfall during this period is the minimum for the entire study period (Table 3), however, total volume of landslides is larger compared to the periods from 1982 to 1986 and from 1992 to 1996 (Figure 6a). Thus, there is a possibility that these two earthquakes contributed to the landslides. Although the largest earthquake (M 6.0) in the period from 1957 to 2001 occurred in 1960 (Table 1), the total landslide volume in the period from 1965-1969 (first period analyzed) is not notably high.

The greater estimated landslide volumes compared to increases in dam deposits prior to 1992 include deposition of sediment upstream of the lake, because the increase in sediment storage in the catchment should equal the difference between total sediment supply (derived from the sum of episodic and chronic processes) and sediment yield (increases in dam deposits) as calculated from the sediment budget. After completion of the dam, the rising water in the lake causes deposition on topset beds [*Kostic and Parker*, 2003]. This, in turn, may have suppressed sediment fluxes into the dam lake before 1991. The relatively greater reservoir deposition after 1992 (Figure 6a) is possibly due to degradation of topset beds or related to chronic processes (e.g., surface erosion, gully erosion and bank erosion) and small landslides which cannot be easily detected on aerial photographs [*Brardinoni and Church*, 2004]. The highest period of landslide inputs (1987 to 1991)

may have increased sediment supply to the dam lake after 1991.

4.3 Characteristics of sediment yield

Sediment transport by fluvial mechanisms has been described based on hydraulic equations derived from flume experiments [e.g., *Lane and Kalinske*, 1941; *Meyer-Peter and Müller*, 1948; *Bagnold*, 1956], indicating that sediment yields in transport-limited (energy-limited) catchments can be easily explained by hydraulics. However, hydraulic factors cannot accurately explain sediment yield in supply-limited catchments where sediment supply from hillslopes affects sediment yield. Thus, comparison of hydraulic factors and sediment yield can be one method to classify catchments into supply-limited and transport-limited systems, and can be used to investigate the influence of sediment supply on sediment yield. Annual increases in dam deposits were compared against various measures of discharge (Figures 7a, 7b, and 7c). Because increases in dam deposits were smaller than total landslide volume prior to 1992 and larger after 1992 (Figure 6a), the two periods were considered separately. For years prior to 1992, all discharge factors are poorly related to increases in dam deposits; after 1992 these factors generally exhibit much stronger relationships with increases in dam deposits. The change in discharge-yield scaling within the same dynamic range indicates a change in the sediment transfer in rivers. Instantaneous discharge has strongest relationship with increases in dam deposits of all discharge factors (Figures 7a, 7b, and 7c), indicating that short-term peak flows affect annual sediment yield in the Miyagawa dam catchment. Annual increases in dam deposits were also compared against various rainfall attributes (Figures 7d, 7e, 7f, and 7g); some of these were more highly correlated than discharge – dam deposit relations.

Simple correlation analyses cannot simultaneously consider the influence of high-frequency,

low-magnitude events and low-frequency, high-magnitude events. Both may generate large amounts of sediment [*Trustrum et al*., 1999]. Consequently, the following equation is proposed:

$$Q_s = a\,Q^{\,b} \qquad (1)$$

where Q_s is the total load transport rate, Q is the discharge (any discharge unit can be used for Q_s and Q), and a and b are empirical constants. This transport equation is based on power law relationships between suspended sediment rates and discharge [*Mizuyama*, 1980; *Sidle and Campbell*, 1985, *Ferguson*, 1986; *Asselman*, 1999; *Hicks et al.*, 2000; *Chikita et al.*, 2002; *Richards and Moore*, 2003] as well as bedload transport rates and discharge [*Sidle*, 1988; *D'Agostino and Lenzi*, 1999; *Emmett and Wolman*, 2001; *Ryan et al.*, 2002] that are observed in many regions. Daily values of Q_s were obtained by using daily discharge (Q, instantaneous discharge averaged for one day) and various combinations of a and b in equation (1); these values were summed for each year to yield annual values of Q_s. Then these annual Q_s values were compared against sediment data from dam surveys. The values of constants a and b that yield the minimum error between estimated Q_s and the sediment data from surveys (based on an iterative selection procedure) are then considered representative values for the Miyagawa Dam catchment (Figure 8). This procedure enables us to analyze annual sediment records using daily discharge values for the entire year without averaging the discharge data, and we can consider both high and moderate events. Empirical constants in equation (1) were $a = 2.5 \times 10^{-3}$ and $b = 0.80$, for 1957 to 1991, and $a = 2.0 \times 10^{-11}$, $b = 2.0$, for 1992 to 2000 (Figure 8). The exponent (b) for 1992 to 2000 is higher compared to that for 1957 to 1991, indicating that sediment yield responds more strongly to increasing discharge in 1992-2000 compared to 1957-1991.

To evaluate the precision of equation (1) in the two periods, sediment yields estimated by each

equation were compared with increases in dam deposits for the respective period (Figure 9). The relationship between estimated sediment yield and increases in dam deposits was very poor up through 1991 (Figure 9, R^2: -0.005, p-value: 0.37). In contrast, equation (1) roughly estimates sediment yield after 1992 (R^2: 0.59, p-value: 0.01). Estimated sediment yields are generally less than increases in dam deposits in the years with intense rainfall events (hourly rainfall > 50 mm/h), whereas equation (1) overestimates sediment yield in the years without intense rainfall events (Figure 9). Additionally, some rainfall attributes have stronger relationships with reservoir deposition compared to discharge factors (Figures 7d, 7e, 7f, 7g). Thus, both transport capacity of sediment in streams and sediment supply from hillslopes affect sediment yield. Because rainfall factors are not strongly related to landslide volume (compare Figure 6a and Table 3) hydrologic conditions in hillslopes and headwaters together with landslide volume may affect sediment yields. To confirm role of these other factors on sediment yields, we need to clarify processes in headwaters.

4.4 Linkage of sediment supply and transport

While some landslide sediment is directly transported into the fluvial channel network, other landslide sediment terminates on hillslopes, at hillslope-channel junctions, or in steep channels. Not only initial volume of landslides needs to be considered, but also mobility of landslide/debris flow sediments to clarify links between sediment supply and transport. Three important factors may represent the mobility of landslide/debris flow sediments: (*i*) mobility of landslide sediment on hillslopes, (*ii*) behavior of sediments at hillslope-channel junctions, and (*iii*) types of sediment transport in channels (i.e., suspended sediment, bedload, debris flows). To quantify the influence of these factors, characteristics of landslides and debris flows confirmed from aerial photographs are examined using GIS and DEM.

4.4.1 Mobility of landslides on hillslopes

Portions of landslide sediment that directly reach channels may be immediately entrained as bedload or debris flows, while deposits on hillslopes may reside for long periods before reaching the channel because of the relatively slow rate of hillslope transport processes (e.g., soil creep, ravel, remobilization of landslide sediment) [*Megahan et al.*, 1978; *Benda*, 1990; *Sidle and Ochiai*, 2006]. Therefore, the position of landslide deposits is an important factor linking sediment supply to transport. Two types of landslides are categorized depending on where they terminate: (1) landslides terminating in a channel (type A, Figure 10a), and (2) landslides terminating on the hillslope (type B, Figure 10b). The former supplies large volumes of sediment directly into channels and immediately affects sediment yield, while the immediate effect of the latter landslides on sediment yield is only through suspended load and wash load entrained by overland flow during severe storms. *Gomi et al.* [2004] distinguished between landslides that reach channels and those that diffusely deposit sediment at the foot of hillslopes. The impact on sediment yield is very different for these two types of landslides. However, low order channels in the Miyagawa dam catchment are usually covered by forests, and it is difficult to confirm on aerial photograph stereographs whether landslides actually reached channels or not. Therefore, both types of landslides are defined as type A landslides here.

The percentage of total new landslide volume that is comprised of type A landslides is examined for each period after 1976 when the influence of road construction on landslide occurrence was small. Landslides that join with other landslides are not considered as new landslides because of unclear terminuses. The percentages of type A landslides were 75, 70, 68, 71, and 56% in 1976–1981, 1982–1986, 1987–1991, 1992–1996, and 1997–2000, respectively (average 68%). To ascertain the percentage of type A landslide deposits on hillslopes and in

channels, volumes of 30 representative landslide scars and their hillslope deposits were measured by field surveys. On average, only 5% of this sediment was deposited on hillslopes (mainly on the foot of hillslopes) and no clear relationship between landslide length and percentage of deposited sediment was found. The reminder of the sediment (95% of total landslide sediment) reached the channels. Because 68% of the landslide volume was classified as type A landslides and 32% was classified as type B landslides (average from 1976 to 2000), an estimated 35% [(68% x 5%) + 32%] of the total landslide volume deposited on hillslopes in the catchment.

The percentage of type A landslides may be affected by maximum hourly rainfall in each period (Table 3); the percentage of type A landslides is highest in the period from 1976 to 1981 when the maximum hourly rainfall was largest (> 80 mm/h), while the percentage was lowest in the period from 1997 to 2000 when the maximum hourly rainfall was smallest (53 mm/h). Conversely, the percentage of type B landslides appears to be inversely related to rainfall intensity. High rainfall intensity causes high water content in soils, not only initially in failed material, but also soil that is eroded downslope. Because landslides with high water contents have greater mobility compared to dry landslides [*Legros*, 2002], landslides that occur during intense storms tend to travel longer distances and reach channels more frequently. Forest management may also influence the percentages of type B landslides that occurred in each period in the Miyagawa Dam catchment, because large standing trees and fallen logs block sediment in old-growth forests, whereas such roughness factors are typically less in clearcuts [*Johnson et al.*, 2000].

The average percentage of type A landslides in the Miyagawa dam catchment (68%) is similar to such landslides in the gentler Tutira and Waipaoa catchments of North Island, New Zealand, underlain by sandstone and mudstone [*Page et al.*, 1994; *Reid and Page*, 2003]. The amount of landslide sediment storage in hillslopes of the Miyagawa dam catchment (35%) is within the range reported in the Clearwater National Forest in Idaho, USA (23%) [*Megahan et al.*, 1978], however,

it is lower than estimated hillslope storage in most other landslide-affected catchments, e.g. 57% in Waipaoa catchment in New Zealand [*Dymond et al.*, 1999], 42% in Saru River, Japan [*Nakamura et al.*, 1995], and 40% in Queen Charlotte Islands in British Columbia, Canada [*Roberts and Church*, 1986]. The uniformly steep topography in the Miyagawa Dam catchment likely promotes efficient delivery of landslide sediment to channels. Slope gradients from the head crop of landslides to channels are generally > 35° based on field surveys of the 30 type A landslides; this gradient is almost the same or larger than the angle of repose of talus cones in the area.

4.4.2 Processes at hillslope-channel junctions

Hillslope-channel junctions of type A landslides indicate locations where landslides supply sediment to channels. Catchment area above deposits, obtained from 10 × 10 m grids on GIS (example illustrated in Figure 2c), and channel gradient at the hillslope-channel junction of type A landslides that occurred from 1982 to 1986 (minimum landslide volume in the 36 yr period) and from 1987 to 1991 (maximum landslide volume) are compared to clarify characteristics of sediment movement related to these junction characteristics (Figure 11a). The channel gradient, obtained from 10 × 10 m grids, decreases with increasing catchment area (Figure 11a). This is affected by channel topography in the catchment; channels in headwaters (small catchment areas) are steeper than downstream channels with larger catchment areas. Channel gradient of 10 × 10 m grids fluctuates from cell to cell, while catchment area changes gradually along the channel. Channel gradient of 10 × 10 m grids might be highly affected by local channel components (i.e., water falls or cascades), as well as calculation errors resulting from the use of 10 × 10 m grids. Because not only local channel gradient, but also average gradient along the channel may define the mode of sediment transport, it is difficult to use a specific index of channel gradient derived from 10 × 10 m grids to represent the sediment transport system. Hereafter, we use catchment area,

which is a more continuous function for describing the channel network compared to local channel gradients, as an index of sediment transport in the channel.

The increases in cumulative percentage of new type A landslide volume with increases in catchment area (above their respective hillslope-channel junctions) are similar for the 1982 to 1986 and 1987 to 1992 periods (Figure 11b). Landslide volumes increase rapidly around 1 km^2 in the 1982 to 1986 period because of hillslope excavation activities in the catchment related to a large water conveyance system for power generation; this disturbance caused many large landslides within a relatively small area. This finding implies that the distribution of hillslope-channel junctions where landslide sediment accumulates and occasionally moves downstream is only affected by the topography of the catchment with little difference occurring among periods.

Type A landslides can be classified into two categories based on linkages between sediment supply and transport: landslides whose sediment is transported onward through the channel system as debris flows (Figure 10c, type A1) and landslides whose sediment terminates at hillslope-channel junctions (Figure 10d, type A2). The percentage of type A landslide volume comprised of type A1 landslides is 24% and 29% for 1982–1986 and 1987–1992, respectively; the remainder of the landslides terminated at hillslope-channel junctions (type A2). These percentages might be affected by catchment area above the junctions (Figure 12). About 40 to 50% of type A landslides are sub-classified as type A1 landslides for catchment areas < 0.02 km^2. The percentage of landslide volume transported downstream decreases rapidly for catchment areas > 0.02 km^2, and almost all of landslide sediment terminates at junctions with catchment areas > 1 km^2.

The transport processes of landslide sediment delivered to channels (type A landslides) differ amongst individual channels because of in-channel conditions. In steep headwater channels, debris flows may be the predominant process entraining sediments, while fluvial processes entrain sediments in channels of gentler gradient with larger contributing catchment area [*Gomi et al.*,

2002]. Furthermore, *Benda* [1990] indicates that the drainage area above deposits influences the longevity of the deposits; deposits below small drainage areas remain in the channel for a long time, while deposits below large drainage areas (>20 km^2) are eroded by fluvial processes within several years. Therefore, the time lag between sediment supply and transport might be affected by topographic conditions at hillslope-channel junctions where landslide sediments are delivered to the channel (Figures 11a and 11b). The observed decreases in type A1 landslides with increasing catchment area (>1 ha) illustrate the increasing disconnectedness between sediment supply and transport processes in progressively larger catchments (Figure 12).

4.4.3 Debris flow behavior

To clarify changes in debris flow contributions to total sediment transport with increasing catchment area, the percentage of new debris flow runout cells related to total channel cells was assessed (Figure 13a). Cells whose catchment areas are < 0.005 km^2 were not assessed because some of the 10 × 10 m grids on lower portions of long hillslopes also have upslope areas in the range of 0.001–0.005 km^2 based on GIS, thus creating problems for estimating total channel length in this size category. For each period, the percentage of new debris flow runout cells increases with catchment area for catchments up to 0.02 km^2; peaks appear in the range of 0.02–0.1 km^2 (Figure 13a), the approximate size of larger first- to second-order basins in Miyagawa Dam catchment based on topographic maps. For catchment areas up to 0.1 km^2, larger channels have many debris flow sources and receive debris flows from their tributaries, thus increasing the percentage of total channel length impacted by debris flows. Similar relationships were also found by *Benda and Dunne* [1997a] and *May and Gresswell* [2004]. The percentage of total channel length that experiences debris flows decreases with increasing upstream area above the maximum value noted at 0.02-0.1 km^2, and debris flows did not progress into channel

segments with upstream areas >1-5 km^2 (Figure 13a). About 58% of all debris flows in Miyagawa terminated at channel junctions. No debris flows directly entered the dam lake due to the gentler channel gradients near the lake; fluvial processes, such as bedload and suspended sediment transport, are the primary processes immediately adjacent to the lake.

For catchment areas < 0.01 km^2, the ratio of the percentage of debris flow-impacted channels between any two periods roughly corresponds to the ratio of landslide volume between these same periods (Figure 6a). For example, the percentage of new debris flow runout cells in 1992-1996 is similar to 1982-1986 and 1997-2000 for catchment areas < 0.01 km^2; landslide volumes in these periods are also similar. However, the percentage of new debris flow runout cells in 1992-1996 are higher compared to 1982-1986 and 1997-2000 for catchment areas 0.02-0.05 km^2 (Figure 13a). Thus, changes in the percentage of new debris flow runout cells are not only related to landslide volume and area-slope relationships, but also to other factors.

Log-log plots of catchment area and channel gradient have been used to determine predominant sediment transport processes in channels [e.g., *Stock and Dietrich*, 2003]. In the Miyagawa Dam catchment, a power function based on catchments > 1 km^2 can be applied to catchment sizes in the range from 0.1 to 1 km^2 where both debris flows and fluvial processes occur (Figure 13b). However, this relationship breaks down around 0.1 km^2, where the percentage of debris flow-affected channel length is maximum (Figure 13a).

To quantify mobility of debris flows and clarify factors affecting these mass movements, the proportion of debris flows that progressed through successive 10 x 10 m grid cells in a range of catchment areas (M_i for category i) is calculated as:

$$M_i = (D_i - T_i) / D_i \qquad (2)$$

where D_i is the number of debris flow cells (10 × 10 m) in category i, and T_i is number of debris flow cells that terminate in category i. The M_i ratio decreases with increasing catchment area

(Figure 14). Cells whose catchment areas are < 0.005 km^2 were not assessed because of difficulties in confirming channel cells. Because catchment area is related to channel gradient, decreases in M_i are affected by channel gradient [e.g., *Pierson*, 1980; *Benda and Cundy*, 1990, *Fannin and Wise*, 2001]. A more detailed analysis of these trends reveals that M_i decreases gradually for catchment areas < 0.1 km^2 and differences amongst various time periods are not significant (Figure 14). This catchment size corresponds to the area in Figure 13b below which the area – slope relationship for fluvial channels cannot be applied. However, changes in M_i for larger catchments (>0.1 km^2) differ amongst periods; M_i decreases rapidly with increases in catchment area from 0.1 to 1 km^2 during the periods of 1976–1981, 1982–1986, and 1997–2000, while M_i decreases with increases in catchment area from 1 to 10 km^2 in the period from 1987 to 1991. Maximum instantaneous discharge has the strongest relationship with periodic differences in debris flow mobility (compare Figure 14 and Table 1); mobility of debris flows in larger catchments is relatively high during periods with high maximum instantaneous discharge, while mobility of debris flows is low in periods with lower maximum instantaneous discharge.

Mobility of debris flows in Miyagawa is strongly affected by high flows and precipitation; earthquakes may exert a much smaller influence. Even though differences exist between instantaneous discharge from the dam lake and discharge in the tributaries, it appears that instantaneous discharge alters debris flow contributions to the overall sediment transport process (Figure 14 and Table 1). Because the physical mechanics of debris flows, which determine their mobility, are expressed by the concentration of solids within the debris flow mass [*Takahashi*, 1991; *Iverson*, 1997], the amount of water in and around the debris flow path may also affect mobility. Triggering mechanics of landslides may also influence debris flow mobility; landslides triggered by earthquakes in Taiwan remained in the upper catchment compared to landslides triggered by heavy rainfall, which were mobilized downstream [*Dadson et al.,* 2003]. In the

Miyagawa Dam catchment, two earthquakes in 1999 (M = 5.6) and 2000 (M = 5.7) may have contributed to landslide initiation in the 1997-2000 period. Because of the low mobility of debris flows during this period (Figure 14), different landslide triggering processes (i.e., rainfall versus earthquakes) may strongly affect debris flow mobility.

Channel junctions and gradients strongly influence the depositional processes of debris flows in Miyagawa. Similarly, *Benda and Cundy* [1990] noted that channel junctions affected deposition of debris flows. Junctions where channel gradient decreases rapidly, particularly promote the termination of debris flows. Additionally, gentle tributary channel gradients around the dam lake (≈ 3 degrees) impede the mobility of debris flows as observed in other studies [*VanDine*, 1984, *Benda and Cundy*, 1990].

Results from Miyagawa which show that debris flows terminate in channels whose catchment areas are >1-5 km^2 (Figure 13a) are comparable to findings from mountainous regions of Taiwan where most episodic sediment processes are generated by large earthquakes and typhoons [*Dadson et al*., 2004]. Because the percentage of new debris flow runout cells is related to the frequency of debris flows, our results imply that the influence of debris flows on total sediment transported in channels decreases with increasing catchment area. Area-slope relationships for fluvial channels have been shown to exhibit a break at the lowermost point of debris flow termination [*Stock and Dietrich*, 2003]. Because channel gradient and catchment area are the primary factors controlling discharge and shear stress of the stream, changes in the area – slope relationship around 0.1 km^2 imply a shift in sediment transport from debris flows to fluvial processes in the catchment.

Two processes appear to control the connectivity and yield of sediment in Miyagawa catchment. Firstly, we showed that debris flows can progress long distances in channels with large contributing catchments during major runoff events (Figure 14, Table 1). Secondly, in the channel

continuum, source areas of bedload and suspended sediment expand during heavy rainfall events because surface runoff extends into wider floodplains [*Sidle et al.*, 2000; *Gomi et al.*, 2002]. As a result of these two processes, sediment delivery ratio in the catchment network may increase during large rainfall-runoff events, causing sediment supply to be more tightly linked to sediment yield. An example from Lake Tutira catchment in New Zealand also shows how rainfall-runoff magnitude strongly affects the connectivity of sediment sources to fluvial channels; sediment delivery during a single major cyclone (total rainfall 753 mm) was higher than the average sediment delivery ratio for the previous 114 years (0.56 and 0.43, respectively) [*Page et al.*, 2004].

5. Summary and Conclusions

In the Miyagawa Dam catchment, not only discharge in the channels, but also rainfall attributes that trigger episodic processes and control water content in the landslide/debris flow mass affect sediment yield (Figures 7 and 9). These characteristics were also noted in areas with steep topography and active sediment supplies in Taiwan [*Hovius et al.*, 2000]. Thus, sediment supply into fluvial channels must be considered when estimating sediment yield. To clarify linkages between sediment supply and transport, we focused on landslide volume and three other factors that affect mobility of landslide/debris flow sediments: mobility of landslide sediment on hillslopes, behavior of sediment at hillslope-channel junctions, and frequency (and mobility) of debris flows. Landslide volume has the largest influence on sediment yield; landslide volume changes by more than 2-fold between successive photoperiods (Figure 6). The volume of landslide sediment entrained within channels is determined not only by landslide volume, but also by the mobility of landslide sediment. The percentage of landslides reaching channels varies from 56% in 1997–2000 to a maximum of 75% in 1976-1981, correlating with maximum hourly rainfall. Because landslide

volume varied much more than landslide delivery, the influence of landslide mobility on sediment yield is not as large as that of landslide volume.

Conditions at hillslope-channel junctions control the volume of landslide sediment that continues to be transported downstream; a large portion of the landslide sediment reaching channels terminates at hillslope-channel junctions in Miyagawa Dam catchment (76 and 71% in the periods 1982 to 1986 and 1987 to 1992, respectively). The percentage of landslide sediment terminating at hillslope-channel junctions is affected by the catchment area above the junctions; larger areas promote significantly less sediment movement downstream via debris flows compared to smaller areas (Figure 12). Catchment area is negatively correlated with channel gradient (Figure 11a); thus, mobility of debris flows diminishes with increasing catchment area because of gentler channel gradients.

Because the percentage of channels affected by episodic processes is small (maximum in 1975–2000 was 4.1% for catchments 0.05–0.1 km^2), the impact of such processes on catchment storage may be smaller and more localized in larger catchments. Only episodic rainfall events, such as the 28-29 September 2004 typhoon in Miyagawa (total rainfall 1046 mm at Miyama town) can affect a larger percentage of sediment storage in the entire catchment (compared to data from 1976 to 2000). Thus, except for such epic rainfall events, the influence of sediment supply on sediment yield does not persist for a long time after the event, except for bed aggregation in fluvial channels. In contrast to the rather short-lived influence of sediment supply on sediment transport in larger catchments, changes in storage volume caused by episodic sediment inputs contribute to longer-term sediment yield in small catchments [*Benda and Dunne*, 1997a; *Bovis and Jakob*, 1999; *May and Gresswell*, 2003; *Gomi et al.*, 2004]. Thus, the influence of sediment supply on sediment yield is also affected by catchment size.

As demonstrated in this study, episodic processes must be considered for the prediction of

sediment yield, especially in supply-limited catchments. Knowledge obtained in this study is useful for estimating sediment supply into fluvial channels. By integrating landslide prediction models, sediment transport models, and knowledge such as that obtained in this study, sediment yields from mountainous catchments can be estimated more precisely.

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References

Asselman, N., E., M. (1999), Suspended sediment dynamics in a large drainage basin: the River Rhine, *Hydrol. Process.*, *13*, 1437–1450.

Ardiansyah, P. O. D, and Yokoyama R. (2002), DEM generation method from contour lines based on the steepest slope segment chain and a monotone interpolation function, *ISPRS J. Photogramm. Remote Sens.*, *57*, 86–101.

Bagnold, R. A. (1956), The flow of cohesionless grains in fluids. *Philos. Trans. R. Soc. London* A 249, 235–297.

Benda, L. (1990), The influence of debris flows on channels and valley floors in the Oregon coast range, U.S.A., *Earth Surf. Process. Landforms*, *15*, 457–466.

Benda, L. and Cundy T. W. (1990), Predicting deposition of debris flows in mountain channels, *Can. Geotech. J.*, *27*, 409–417.

Benda, L., and Dunne, T. (1997a), Stochastic forcing of sediment supply to channel networks from landsliding and debris flow, *Water Resour. Res.*, *33*, 2846–2863.

Benda, L., and Dunne, T. (1997b), Stochastic forcing of sediment routing and storage in channel networks, *Water Resour. Res.*, 33, 2865–2880.

Bovis, M. J., and Jakob, M. (1999), The roll of debris supply conditions in predicting debris flow activity, *Earth Surf. Process. Landforms*, *24*, 1039–1054.

Brardinoni, F., and Church, M. (2004), Representing the landslide magnitude-frequency relation: Capilano River Basin, British Columbia, *Earth Surf. Process. Landforms*, *29*, 115–124.

Brardinoni, F., Hassan, M. A., and Slaymaker H.O. (2002), Complex mass wasting response of drainage basins to forest management in coastal British Columbia, *Geomorphology*, *49*, 109–124.

Chen, H., and Lee, C. F. (2000), Numerical simulation of debris flows, *Can. Geotech. J.*, *37*, 146–160.

Chikita, K. A., Kemnitz, R., and Kumai, R. (2002), Characteristics of sediment discharge in the subarctic Yukon River, Alaska, *Catena*, *48*, 235–253.

Coussot, P., and Meunier, M. (1996), Recognition, classification and mechanical description of debris flows. *Earth Sci. Rev.*, *40*, 209–227.

D'Agostino, V., and Lenzi, M. A. (1999), Bedload transport in the instrumented catchment of the

Rio Cordon Part II: Analysis of the bedload rate, *Catena*, *36*, 191–204.

Dadson, S. J., Hovius, N., Chen, H., Dade, B., Lin, J. C., Hsu, M. L., Lin, C. W., Horng, M. J., Chen, T. C., Milliman, J., and Stark, C. P. (2004), Earthquake-triggered increase in sediment delivery from an active mountain belt, *Geology*, *32*, 733–736.

Dymond J. R., Jesen, R., and Lovell, R. (1999), Computer simulation of shallow landsliding in New Zealand hill country, *Int. J. Appl. Earth. Obs.*, *1*, 122-131.

Emmett, W. W., and Wolman, M. G. (2001), Effective discharge and Gravel-bed rivers, *Earth Surf. Process. Landforms*, *26*, 1369–1380.

Fannin R. J., and Wise, M. P. (2001), An empirical-statistical model for debris flow travel distance, *Can. Geotech. J.*, *38*, 982–994.

Ferguson, R. I. (1986), River loads underestimated by rating curves, *Water Resour. Res.*, *22*, 74–76.

Gomi, T., Sidle, R. C., and Richardson, J. S. (2002), Understanding processes and downstream linkage of headwater system, *Bioscience*, *52*, 905–916.

Gomi, T., Sidle, R. C., and Swanson, D. N. (2004), Hydrogeomorphic linkages of sediment transport in headwater streams, Maybeso Experimental Forest, southwest Alaska, *Hydrol. Process.*, *18*, 667–683.

Kostic, S., and Parker G.. (2003), Progradational sand-mud deltas in lakes and reservoirs. Part 1. Theory and numerical modeling, *J. Hydraul. Res.*, *41*, 127-140.

Hayashi, S., Tsuchiya, S., Kondo, K., Shibano, H., Numamaoto S., Kosugi, K., Yamakoshi, T., and Ikeda, A. (2004), Sediment related disasters caused by typhoon Meari (T 0421) in Miyagawa village, Mie prefecture on September 29, 2004 (prompt report), *Journal of the Japan Society of Erosion Control Engineering*, 57(4), 48–55 (in Japanese with English abstract).

Hicks, D. M., Gomez, B., and Trustrum, N.A.(2000), Erosion thresholds and suspended sediment

yields, Waipaoa River basin, New Zealand, *Water Resour. Res.*, *36*, 1129–1142.

Hiramatsu, S., Kuroiwa, T., and Arasuna, T. (2002), Influence of changes of deforestation area and reforestation area on sediment yield, *Journal of the Japan Society of Erosion Control Engineering*, *55*(4), 3–11 (in Japanese with English abstract).

Hovius, N., Stark, C. P., Chu, H. T., and Lin, J. C. (2000), Supply and removal of sediment in a landslide-dominated mountain belt: Central Range, Taiwan, *J. Geol.*, *108*, 73–89.

Hunger, O. (2005), Classification and terminology, in *Debris-flow hazards and Related Phenomena*, Edited by Jakob, M. and Hunger, O., pp.9–23, Praxis Publishing Ltd, Chichester, UK.

Iverson, R. M. (1997), The physics of debris flows, *Rev. Geophys.*, *35*, 245–296.

Johnson, A. C., Swanson, D. N., and McGee, K. E. (2000), Landslide initiation, runout, and deposition within clear cuts and old-growth forests of Alaska, *J. Am. Water Resour. Assoc.*, *36*, 17–30.

Juracek, K. E. (1997), Analysis of bottom sediment to estimate nonpoint-source phosphorus loads for 1981-96 in Hillsdale Lake, Northeast Kansas, U.S. Geological Survey Water-Resources Investigations Report, wrir.97-4235.

Kondo, K., Hayashi, S., and Numamoto, S. (2004), Disasters due to slope failures caused by Typhoon Meari (T0421) in Miyagawa Village, Mieprefecrure in 2004, *J. Jpn. Landslide. Soc.*, *41* (4), 97–101 (in Japanese).

Lane, E. W., Kalinske, A. A. (1941), Engineering calculations of suspended sediments, *Trans. AGU*, *22*, 605–607.

Legros, F. (2002), The mobility of long-runout landslides, *Eng. Geol.*, *63*, 301–331.

May, C. L., and Gresswell, R. E. (2003), Processses and rates of sediment and wood accumulation in head water streams of the Oregon coast range, U.S.A., *Earth Surf. Process. Landforms*, 28,

409–424.

May, C. L., and Gresswell, R. E. (2004), Spatial and temporal patterns of debris-flow deposition in the Oregon Coast Range, USA, *Geomorphology*, *57*, 135–149.

Meyer-Peter, E., and Müller, R. (1948), Formulas for bedload transport, in *Proc. 2nd Meeting Intl. Ass. Hyd. Structures Res.*, Stockholm, Sweden, Appendix 2, 39–64.

Mizuyama, T. (1980), Measurement of Wash load in Mountain River, *Civil Engineering Journal*, *22*(5), 46–51 (in Japanese).

Miyazaki, Y., and Onishi, S. (1996), Study on the relation between the sediment and the rainfall, *J. Japan Soc. Civil Engineers*, *533*, 41–50 (in Japanese with English abstract).

Nakamura, F., Maita, H., and Araya, T. (1995), Sediment routing analyses based on chronological changes in hillslope and riverbed morphologies, *Earth Surf. Process. Landforms*, *20*, 333–336.

Numamoto, S., Kondo, K., Hayashi, S., and Kitagawa, M. (2004), Factors of devastation on forest slope caused by clear-cutting in upper Miyagawa-Dam watershed, *Chubu Forestry Research*, *53*, 273–276 (in Japanese).

Page, M. J., Trustrum, N. A., Brackley, H. L., Baisden, W. T., (2004) Erosion-related soil carbon fluxes in a pastoral steepland catchment, New Zealand, *Agric., Ecosyst. Environ.*, 103, 561–579.

Page, M. J., Trustrum, N. A., and Dymond, J.R., (1994), Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology*, *9*, 169-188.

Pierson, T. (1980), Erosion and deposition by debris flows at Mt. Thomas, North Canterbury, New Zealand. *Earth Surf. Process.*, *5*, 227–247.

Reid, L. M., and Page, M. J. (2003), Magnitude and frequency of landsliding in a large New Zealand catchment. *Geomorphology*, *49*, 71–88.

Revellino, P., Hungr, O., Guadagno, F. M., and Evans, S. G., (2004), Velocity and runout simulation of destructive debris flows and debris avalanches in pyroclastic deposits, Campania region, Italy. *Environ. Geol.*, *45*, 295–311.

Richards, G., and Moore, R. D. (2003), Suspended sediment dynamics in a steep, glacier-fed mountain stream, Place Creek, Canada, *Hydrol. Process.*, *17*, 1733–1753.

Roberts, R. G. (1986), The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia, *Can. J. For. Res.*, *16*, 1092–1106.

Ryan, S. E., Porth, L. S., and Troendle, C. A. (2002), Defining phases of bedload transport using piecewise regression, *Earth Surf. Process. Landforms*, *27*, 971–990.

Sidle, R. C. (1988), Bed load transport regime of a small forest stream, *Water Resour. Res.*, *24*, 207–218.

Sidle, R. C. and Campbell A. J. (1985), Patterns of suspended sediment transport in a coastal Alaska stream, *Water Resour. Bull.*, *21*, 909–917.

Sidle, R. C. and Ochiai, H. (2006), *Landslides: Processes, Prediction, and Land Use*, Am. Geophys. Union Water Resour. Mono. 18, Am. Geophys. Union, Washington, DC, 312 p.

Sidle, R. C., Tsuboyama, T., Noguchi, S., Hosoda, I., Fujieda, M, and Shimizu, T. (2000), Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm, *Hydrol. Process.*, *14*, 369–385.

Slaymaker, O. (2003), The sediment budget as conceptual framework and management tool, *Hydrobiologia*, *494*, 71–82.

Stock, J., and Dietrich, W. E. (2003), Valley incision by debris flows: evidence of a topographic signature, *Water Resour. Res.*, *39*, 1089, doi:10.1029/2001WR001057.

Thiessen, A.H. (1911) Precipitation averages for large areas, *Monthly Weather Review*, *39*, 1082–1084.

Takahashi, T. (1991), *Debris flow*, IAHR Monograph. A.A. Balkema, Rotterdam.

Tamene, L., Park, S. J., Dikau, R., and Vlek, P. L. G. (2006), Reservoir siltation in the semi-arid highlands of northern Ethiopia: sediment yield-catchment area relationship and a semi-quantitative approach for predicting sediment yield, *Earth Surf. Process. Landforms*, *31*, 1364-1383.

Tsukamoto, Y. and Ohta, T. (1988), Runoff processes on a steep forested slope, *J. Hydrol.*, *102*, 165–178.

Trustrum, N. A., Gomez, B., Page, M. J., Reid, L. M., and Hicks, D. M. (1999), Sediment production, storage and output: The relative role of large magnitude events in steepland catchments, *Z. Geomorph. N. F.*, *115*, 71–86.

VanDine, D. F. (1984), Debris flows and debris flow torrents in the Southern Canadian Cordillera, *Can. Geotech. J.*, *22*, 44–62.

Verstraeten, G., and Poesen, J. (2001), Variability of dry sediment bulk density between and within retention ponds and its impact on the calculation of sediment yields, *Earth Surf. Process. Landforms*, *26*, 375–394.

Walling, D. E. and Webb, B. W. (1982), Sediment availability and the prediction of stormperiod sediment yields, in *Recent Developments in the Explanation and Prediction of erosion and Sediment Yield*, IAHS Publ. No. 137, pp. 327–337, International Assoc. Hydrol. Sci., Wallingford, UK.

Wu, W., and Sidle, R. C. (1995), A distributed slope stability model for steep forested basins, *Water Resour. Res.*, *31*, 2097–2110.

Table 1. Moderate to major earthquakes that occurred within 100 km of the Miyagawa Dam catchment during the period of aerial photograph investigation (1957-2001).

Date	Mw	Epicenter	Distance from the Miyagawa dam catchment (km)
26 December 1960	6.0	34˚8.6'N 136˚11.1'E	5
11 February 1984	5.5	34˚3.0'N 135˚43.1'E	40
21 August 1999	5.6	34˚1.8'N 135˚28.2'E	63
31 October 2000	5.7	34˚17.9'N 136˚19.2'E	11

Table 2. General information related to aerial photographs.

Year	Color	Scale
1965	Monochrome	1:20000
1970	Monochrome	1:20000
1976	Color	1:15000
1982	Monochrome	1:16000
1986–1987	Monochrome	1:16000
1992	Monochrome	1:16000
1996-1997	Monochrome	1:16000
2001	Monochrome	1:40000[a]

[a] Photographs enlarged 2x were used for investigations

Table 3. Rainfall and runoff factors in each photoperiod.

Period	Rainfall				Runoff		Averages of new dam deposits ($10^3 m^3/yr$)
	Total (mm)	Maximum hourly (mm/day)	Maximum daily (mm/day)	Maximum event [b] (mm)	Maximum instantaneous (m^3/s)	Maximum daily ($10^5 m^3/day$)	
1965-1969	17,262		631	1119	1550	853	48
1970-1975	21,538		503	1602	2100	670	50
1976-1981	19,185	>80 [a]	565	1594	2250	615	59
1982-1986	14,692	57 [a]	338	820	1500	551	60
1987-1991	17,196	76	429	1509	2401	698	115
1992-1996	14,763	65	580	1101	2357	747	141
1997-2000	14,041	53	586	1224	1749	804	204

[a] Hourly rainfall data in the catchment are available from 1989, and maximum hourly rainfall data from 1979-1988 were estimated from a rain gauge installed about 5 km south of the Miyagawa Dam

[b] Events are separated by at least a 1-day period of no rainfall before and after the maximum event

Figure captions

Figure 1. Map of Miyagawa dam catchment showing locations of sediment collection within the reservoir. Locations of annual survey transects for measurement of lake bottom topography that were used to calculate changes in volume of dam deposits are illustrated on the lake map.

Figure 2. An example of the methodology used for investigating landslide and debris flow runout based on aerial photo stereographs and GIS: (a) aerial photograph of a small catchment; (b) landslides and debris flows mapped on the topographic map (channels on the map are defined in the text); and (c) grids (10 × 10 m) of the area in Fig. 2a with channel cells and debris flow cells surrounded by thin black and black borders, respectively; cells that contain landslide sediments which run into channels are depicted as squares with bold black perimeters. Elongated landslides shown in the photograph are typical in this area compared to teardrop or triangle-shaped landslides that have been observed in other locations.

Figure 3. Changes in volume of dam deposits from 1956 to 2003.

Figure 4. Grain size distribution of dam deposits based on sediment samples collected at four sites (three depths – 0, 50, and 100 cm at each site) in the dam lake; see Figure 1 for locations.

Figure 5. Comparison of landslide areas and volumes measured in the field. The best fit power-law relationship and respective equation for landslides that were not affected by roads are also shown in the figure. In addition to the four road-related landslides shown here, depths of two additional road-related landslides were measured to obtain average depth values.

Figure 6. Volume and rate of landslides and new sediment deposits in the reservoir. (a) Volumes of new sediment deposits in the reservoir and landslide volumes in the seven photoperiod intervals from 1965 to 2000. Landslides initiating from forest roads are distinguished from other landslides in the catchment. Changes in length of newly constructed roads in each period are also depicted. (b) Changes in sediment delivery rate and landslide rate. Sediment delivery rate and landslide rate are calculated from increases in volume of dam deposits and landslide volume divided by catchment area.

Figure 7. Comparison of increases in dam deposits and discharge/rainfall factors. (a) Maximum instantaneous discharge; (b) maximum daily discharge; (c) yearly discharge; (d) maximum hourly rainfall; (e) maximum daily rainfall; (f) maximum event rainfall; and (g) annual rainfall were compared to increases in dam deposits. In each graph, data prior to 1992 (when increases in dam deposits were larger than total landslide volume) and after 1992 (when increases in dam deposits were smaller than total landslide volume) were segregated. Best fit lines, expressed as y = Ax + B, along with values of slope (A) and intercept (B) constants, squared multiple correlation coefficients adjusted for the degrees of freedom (R^2), and P-values for the linear expression are shown.

Figure 8. Total of annual squared error between sediment yield Q_s estimated by equation (1) and increases in dam deposits Q_s' (= Σ (Q_s - Q_s')^2) for various combinations of constants *a* and *b* in equation (1). Periods prior to 1992 (when increases in dam deposits were larger than total landslide volume) and after 1992 (when increases in dam deposits were smaller than total landslide volume) were segregated. Minimum squared errors were $10^{11.15}$ ($a = 2.5 \times 10^{-3}$, $b = 0.80$)

for 1957 to 1991, and $10^{10.55}$ ($a = 2.0 \times 10^{-11}$, $b = 2.0$) for 1992 to 2000.

Figure 9. Comparison of sediment yields estimated by equation (1) and increases in dam deposits. Plots prior to 1992 (when increases in dam deposits were larger than total landslide volume) and after 1992 (when increases in dam deposits were smaller than total landslide volume) are segregated. Correlation lines for the two periods are also illustrated in the figure.

Figure 10. Classification of landslides on the basis of position and mobility of sediments: (a) landslide reaching a channel (type A); (b) landslide terminating on hillslope (type B); (c) landslide whose sediment moves downstream as a debris flow (type A1); and (d) landslide whose sediment immediately stops in the channel (type A2). Types A1 and A2 are subclasses of type A landslides based on mobility of sediments in the channel.

Figure 11. Characteristics of type A landslide sediment movement related to channel junctions: (a) comparison of catchment area at the hillslope-channel junction (above landslide deposits obtained from 10 x 10 m GIS grids) and channel gradient; catchment area is group into 5 categories: 0.0001-0.001 km^2; 0.001-0.01 km^2; 0.01-0.1 km^2; 0.1-1.0 km^2; and 1.0-10 km^2; and (b) cumulative percentage in volume of landslides with increasing catchment area above the junction where landslide sediment passes or stops.

Figure 12. The percentage of volume of type A landslides that travel down the channel below hillslope-channel junctions for the following upslope catchment areas: 0-0.005, 0.005-0.01, 0.01-0.02, 0.02-0.05, 0.05-0.1, 0.1-0.5, 0.5-1, 1-5, and 5-10 km^2. Catchment area values for each category indicate the middle range of that category.

Figure 13. (a) Percentage of the total channel length impacted by debris flows for various categories of catchment area: 0.005-0.01, 0.01-0.02, 0.02-0.05, 0.05-0.1, 0.1-0.5, 0.5-1, 1-5, and 5-10 km^2. (b) Comparison of slope (S) and area (A) in the Miyagawa Dam catchment. Plots are mean channel slope (= tan S'; S' is slope gradient in degrees) for entire channels (including channels with and without debris flows). The solid line is a power function ($S = 0.30A^{0.22}$, $R^2 = 0.98$) that was fitted to data with $A > 1$ km^2.

Figure 14. Changes in mobility of debris flows (M) with increasing catchment area.