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Relationship between Sediment Supply and Transport Processes in Miyagawa Dam Catchment

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Synopsis

Because sediment supply affects sediment yield, knowledge of the relationship between sediment supply and transport are needed to estimate catchment-scale sediment yield. This study investigates timing and volume of sediment supply and transport based on aerial photo interpretation and volume of sediment deposits behind the dam in Miyagawa Dam catchment. We discuss the factors that affect the relationship between sediment supply and transport processes. Timing of sediment transport around the dam lake corresponds to large rainfall-runoff events. Sediment supply affects sediment yields for more than several years; this influence depends on the position of landslide/debris flow deposits in the catchment.

Keywords: sediment supply, sediment transport, dam deposits, Miyagawa Dam, channel deposits

1. Introduction

Because sediment supply processes affect sediment yield (Walling and Webb, 1982; Asselman, 1999), a unified sediment supply/transport model is needed to develop better mitigative measures for preventing sediment disasters. The relationship between sediment supply and transport (sediment yield) has been discussed in sediment budget studies. Slaymaker (2003) reviewed many sediment budget studies and noted that both temporal and spatial factors characterize sediment budgets. Factors inherent in sediment budgets (e.g., sediment delivery ratio and types of sediment movement processes) are relatively clear for smaller catchments if only chronic sediment supply processes (e.g., surface erosion and gully erosion) dominate (Kasai et al., 2001). In larger catchments, various sediment supply processes operate on hillslopes, as well as many sediment transport processes (including episodic landslides and debris flows). Sediment supply from hillslope to the channel affects the timing and volume of sediment yield at the catchment on outlet. However, only long term studies have been conducted in larger catchment because of the lack of short term data to estimate catchment scale sediment yields (Benda and Dunne, 1997a; Benda and Dunne, 1997b).

Volume of dam deposits behind almost all of big dams is measured every year in Japan, and these large catchment scale sediment yields are available. Miyazaki and Onishi (1996) investigated timing of sediment supply and transport by analyzing the volume of dam deposits and rainfall. Hiramatsu et al. (2002) evaluated influence of forest management on the volume of dam deposits. However, sediment storage on hillslopes and in channels, which contributes to the time lag between sediment supply and transport (Benda, 1990; Nakamura et al. 1995; May and Gresswell, 2003), was not investigated.

The overall aim of this study is to clarify the relationship between sediment supply and transport processes at the large catchment scale in Miyagawa Dam catchment, central Japan. The specific objectives of this study are: (1) to investigate sediment supply and transport in the catchment using aerial photos and sediment deposition at the dam; (2) to clarify the temporal and volume relationships between sediment supply and transport processes; and (3) to identify processes that influence the sediment supply/transport relationship.

2. Study area

Miyagawa Dam catchment, upstream of Miyagawa Dam, is located in southern Mie Prefecture, central Japan (Fig. 1). Miyagawa Dam (completed in May 1957; capacity of water is 70,500,000 m^3) is a concrete gravity dam designed for power generation, flood control and water supply. Catchment area above the dam is 125.6 km^2 and channel length is 26 km. The lowest point of the catchment is the Miyagawa Dam (270 m a.s.l.; northeast location) and the highest point is the peak of Mt. Hidegatake (1695 m a.s.l) at southwest end of the catchment. The Miyagawa Dam catchment is suitable for investigation of sediment movement because little human activity has occurred within the area, except for timber harvesting.

The main geologic unit is Chichibu Paleozoic strata comprised of sandstone and clay slate. Most of the catchment is characterized by steep, sub-vertical slopes; typical gradients of hillslopes are 30˚–50˚.

Miyagawa Dam catchment is known for high annual rainfall, ranging 1600–4500 mm 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 (from June to July) and in the autumn typhoon season (from late August to early October). Sediment supply processes are active because of high precipitation and sometimes cause sediment disaster around the catchment. From September 28 to 29, 2004, Typhoon Meari (T0421) brought heavy rainfall (maximum rainfall per hour was 139 mm at Kuzu rainfall station, about 1.5 km southeast of Miyagawa Dam); six people were killed (one person missing) by landslides in the area (Hayashi et al., 2004; Kondo et al., 2004). Winter snowfall occurs at high elevation sites in the catchment, but precipitation from December to February is only about 7 % of total annual precipitation.

3. Methodology

3.1 Aerial photo analysis

Monochrome aerial photos taken during five years

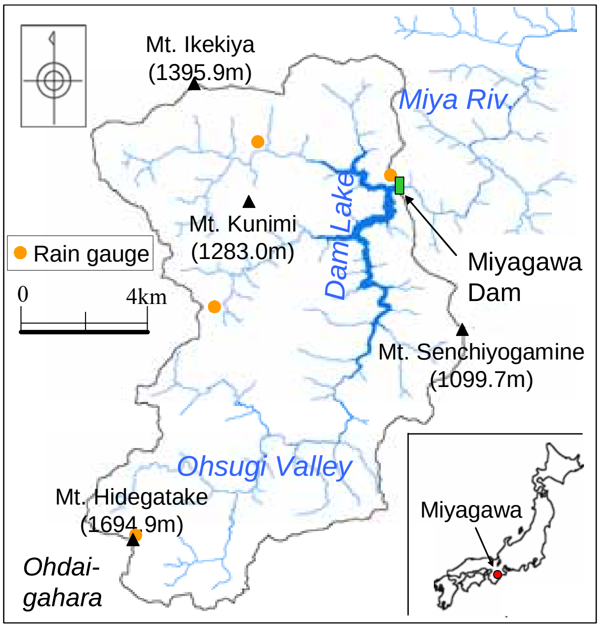


Fig. 1 Map of Miyagawa Dam catchment

(1982, 1986–87, 1992, 1996–1987, 2001) were used to investigate the location and area of landslides and debris flows in the catchment. Landslides and debris flows are confirmed by stereograph and mapped on 1: 5000 forest management maps. Most of aerial photos were taken in March (before the Baiu season), thus almost all of the landslides and debris flows confirmed by aerial photo up through autumn of the previous year. New occurrences of landslides and debris flows in each period (1982–86, 1987–1991, 1992–1996, 1997–2000) were confirmed by comparing former and later aerial photos. Brardinoni and Church (2004) noted a underestimation of landslides < 4000 m^3 in forested terrain in British Columbia based on assessment of 1 : 12,000 to 1 : 15,000 aerial photos. Landslides and debris flows mapped on the Miyagawa forest management map include the initiation zone, transport zone and deposition zone. Individual zones are not distinguished in this study because the main subject of aerial photo analysis is not to identify local erosion and deposition, but to clarify sediment flux within catchment.

3.2 Dam deposits

Changes in volume of channel deposits were estimated by fixed cross section surveys on the dam lake from 1957 to 2003. Field investigations indicated that the turbidity of stream water draining into the lake was low shortly after heavy rainfall. Thus, the amount of washload transported downstream without deposition in the dam lake should be small compared to the total volume of sediment transported. Therefore, we treat deposition behind the dam as sediment yield.

3.3 Rainfall

A rain gauge was installed near Miyagawa Dam in 1957, and three gauges were later installed to identify the distribution of rainfall which could be affected by elevation and spatial factors (Fig. 1). Comparison of rainfall data recorded at the four sites showed that no clear relationship exists between elevation and rainfall amount. Thus, the Thiessen method was used to estimate rainfall within the entire catchment.

3.4 Discharge into the dam lake

Changes in water level of the Miyagawa Dam lake have been measured every 10 min since the completion of the Miyagawa Dam. Instantaneous discharge (m^3/s) is derived from changes in volume of accumulated water in the lake, which are estimated from changes in water levels and lake topography. 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.

3.5 Field survey

Hillslope and fluvial processes (and attributes) that influence the relationship between sediment supply and transport were checked by field surveys. Storage on hillslopes and in channels may affect the relationship between sediment supply and transport (Benda, 1990; Nakamura et al. 1995; May and Gresswell, 2003); however, the ratio of storage and newly produced sediment cannot be identified from aerial photos. Thus, volume and position of landslide/debris flow deposits at the foot of hillslope were measured.

3.6 GIS and topography analysis

Mapped landslides/debris flows were scanned and analyzed their position and area using Arc GIS software. Channel topography was also investigated using Arc GIS and the TIN model constructed from a 50 m grid DEM. In this study, we define the term “channel” as the place where sediments and water accumulate, confirmed by a line which crosses slope contours at an angle < 90° continuously on the 1:_5000 forest management map. According to this definition, zero order basins are also included as channels.

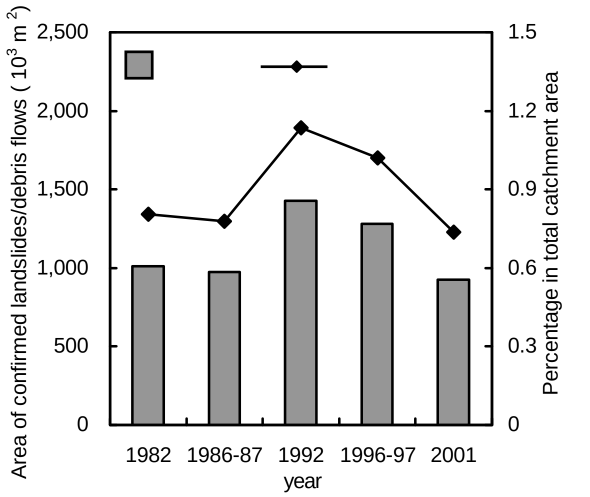


Fig. 2 Area of confirmed landslides and debris flows

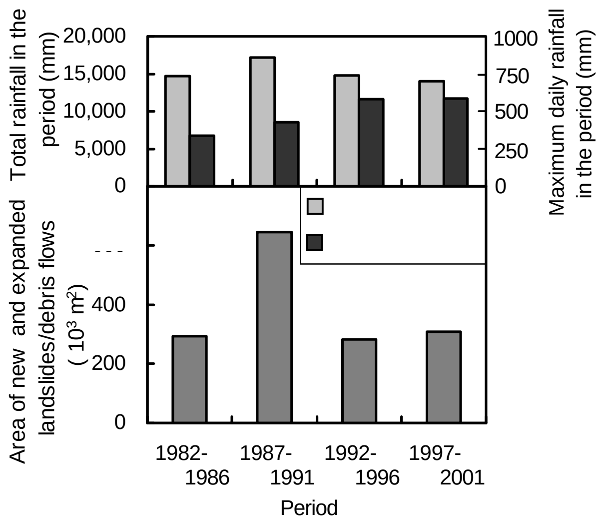


Fig. 3 Area of new and expanded landslides/debris flows

4. Results

4.1 Sediment supply processes

The areas of landslides and debris flows confirmed from aerial photos occupy 0.7 – 1.2 % of the total Miyagawa Dam catchment (Fig. 2). An increase in area of landslides and debris flows area can be seen in 1992; the area of new and expanded landslides/debris flows during 1987–1991 is high compared to the periods (Fig. 3). Initiation of landslide/debris flows might be affected by total rainfall in the period rather than maximum daily rainfall; however, influence of rainfall factors on landslide/debris flow area is not clear (Fig. 3). Hiramatsu et al. (2002) and Numamoto et al. (2004) noted that clear cutting induced many landslides and debris flows in the Miyagawa Dam catchment, thus, both rainfall factors and forest management may contribute to these mass

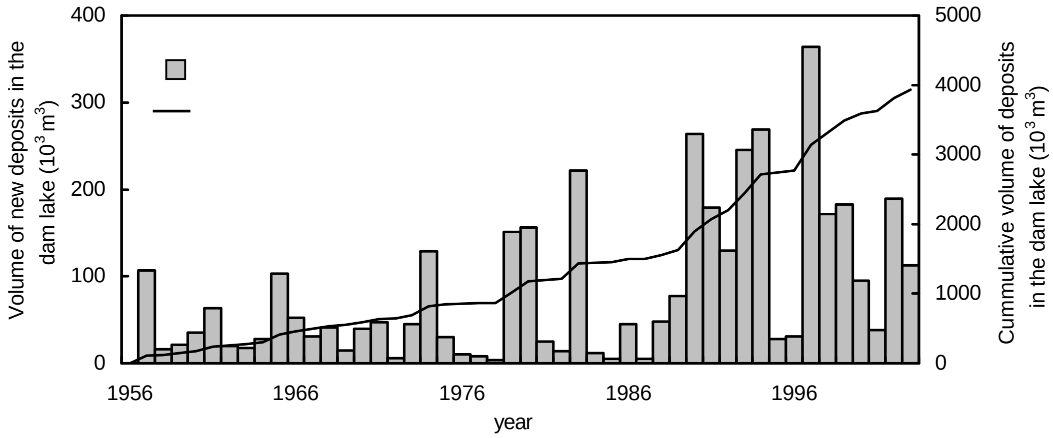


Fig. 4 Changes in volume of dam deposits

wasting processes.

4.2 Sediment transport processes

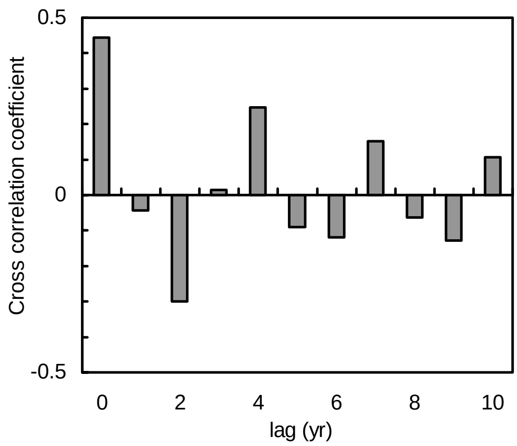
Cumulative volume of dam deposits increased gradually since the completion of Miyagawa Dam in 1956 (Fig. 4). Volume of new deposits fluctuate from year to year; however, the long-term trend exhibits an increase with time, particularly after 1990. This trend may be affected by the activity of sediment supply, because increases in sediment yield start correspond to the period when sediment supply is high (1987–1991; Fig. 3).

Factors that affect the timing of sediment transport were investigated by cross correlation analysis (Table 1). The yearly volume of new dam deposits was used as a lagged variable, whereas the three discharge parameters (maximum instantaneous discharge, maximum daily discharge, and yearly discharge) and the three rainfall parameters (maximum daily rainfall, yearly rainfall, and maximum total rainfall) are used as fixed variables. All of the cross correlation functions were calculated by subtracting the 5-yr moving average from annual parameter volume, with the annual value "centered" in the 5 yr moving average interval to remove the effect of the active sediment supply in 1987–91. Maximum instantaneous discharge yields the highest cross correlation coefficient of these six discharge/rainfall parameters. Maximum daily rainfall was the most highly correlated rainfall parameter. The highest cross correlation coefficient between the new dam deposit volume and maximum instantaneous discharge occurred for a lag of 0 yr; this correlation rapidly declines for a lag of 1 yr (Fig. 5a). These characteristics are also seen in the cross correlation function between the dam deposit volume and maximum daily rainfall (Fig. 5b). Thus, it appears that sediment reaches the lake within the same year after large rainfall-runoff events, and the effects of such large events do not continue substantially into the next year. Miyazaki and Onishi (1996) also investigated the relation between rainfall factors and dam deposit volume more than 15 dam lakes in Japan; in most of these catchments, maximum daily rainfall was strongly correlated with sediment volume behind the dams. Because channel gradients near the dam lakes are usually gentle (< 5˚) (e.g., Miyagawa Dam: about 3˚), fluvial processes, which can be explained by hydraulic conditions, dominate sediment transport near the Dam lake. Thus, the timing of sediment transport can correspond to high instantaneous discharge and/or high short-term rainfall intensity, which is closely related to instantaneous discharge.

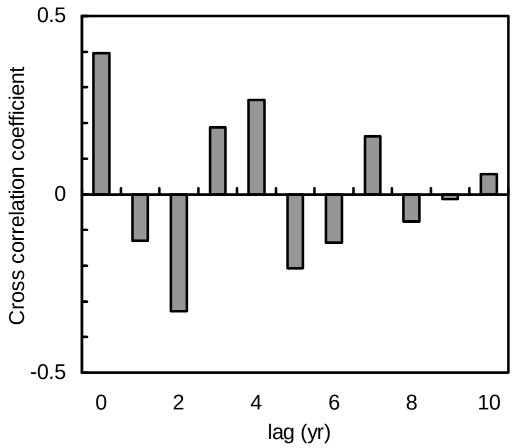
Table 1 Maximum cross correlation coefficient between volume of new dam deposits and discharge/rainfall parameters

Fixed variable	Maximum cross-correlation coefficient
Discharge	
Maximum instantaneous discharge (m^3/s)	0.44
Maximum daily discharge(m^3/day)	0.39
Yearly discharge (m^3/yr)	0.24
Rainfall	
Maximum daily rainfall(mm/day)	0.40
Yearly rainfall (mm/yr)	0.25
Maximum total rainfall (mm)	0.20

*Volume of new dam deposits are used as lagged variable



(a) Cross correlation function between volume of new dam deposits and maximum instantaneous discharge



(b) Cross correlation function between volume of new dam deposits and maximum daily rainfall

Fig. 5 Cross correlation function

The relationship between maximum instantaneous discharge, which had the highest cross-correlation coefficient, and volume of new dam deposits is different for each assessment period (Fig. 6). The volume of dam deposits in from 1987 to 1991 is higher than the preceding period (1982–86); this trend corresponds to the activity of sediment supply (Fig. 3), implying that sediment supply from landslides and debris flows affects sediment yields within a few years. Activity of sediment supply in the period from 1992 to 1996 is almost same as that of 1987 to 1991; however, the volume of new dam sediments is still high. Thus, the effect of sediment supply on sediment yield may be sustained for more than several years. Contributions of chronic sediment supply processes (e.g. surface erosion, bank erosion) might be small compared to episodic sediment supply processes (e.g. landslide and debris flow) in the Miyagawa Dam catchment, because large differences in new dam deposit volumes are evident for different periods determined by the frequency of aerial photos.

4.3 Position of landslide/debris flow deposits

A portion of the landslide/debris flow sediments are transported directly into the channel, while the other portion of the sediments accumulate on hillslopes and in channels (Photo 1). Thus, the position of landslide/debris flow deposits must be considered when discussing the relationship between sediment supply and transport because position can influence on the future movement of these deposits (Benda, 1990).

Landslides and debris flows can be classified by the position of its deposits as shown in Fig. 7: (1) all sediment deposits on the hillslope (Type-1); (2) some portion of sediment reaches the channel while the other portion remains on the hillslope (Type-2, Photo 1); and (3) almost all sediment reaches the channel (Type-3). The terminus of new landslides/debris flows that occurred between 1982 and 1986 were investigated using GIS software. This period was selected because it is prior to the rapid increase of unstable sediment produced by landslides and debris flows during 1987 to 1991. The area of landslides/debris flows was used as an index of sediment volume. Based on these aerial estimates, about 15% of landslides and debris flows deposited completely on hillslopes (Type-1); the other 75% reached the channels (Type-2 and Type-3). We could not distinguish

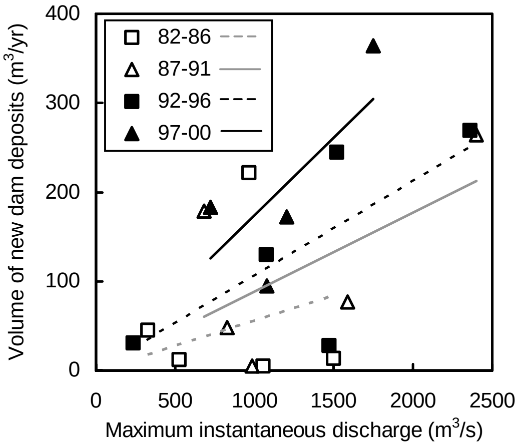


Fig. 6 Comparison of maximum instantaneous discharge and volume of new dam deposits

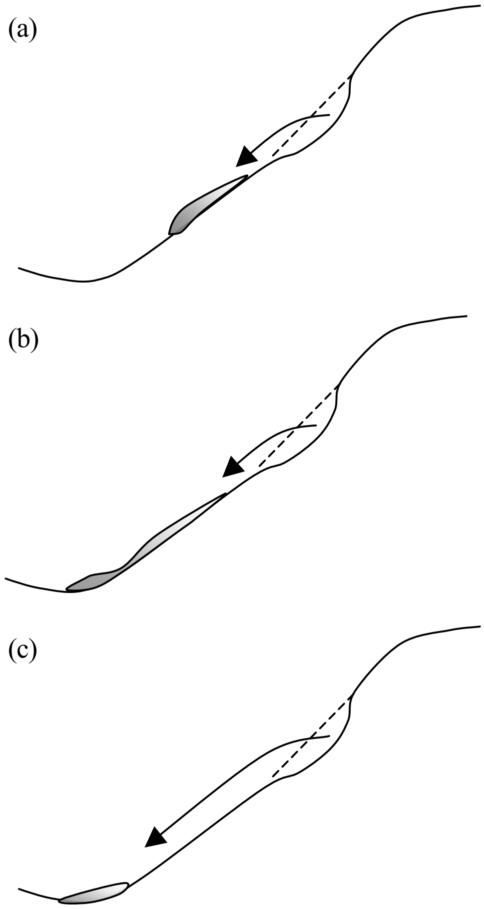
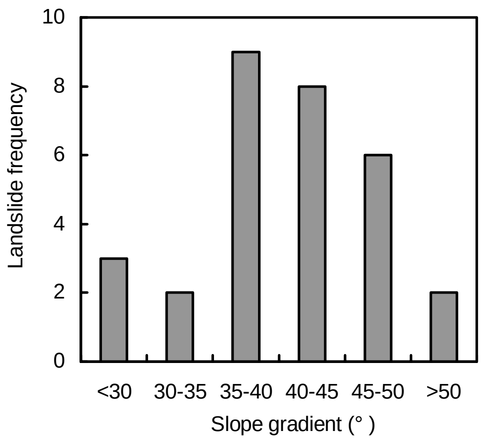


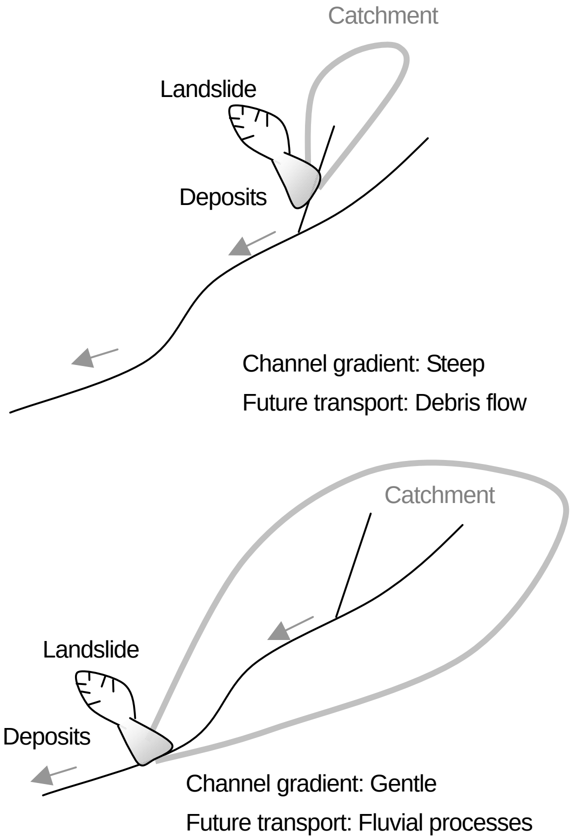
Fig. 7 Position of landslide/debris flow deposits. (a) Hillslope, (b) Hillslope and Channel, and (c) Channel.

Photo 1 Landslide scar and deposits at the foot of a hillslope; overall, 17% of the total sediment deposits accumulated at the foot of hillslope.

between Type-2 and Type-3 deposition based on aerial photo analysis. Thus, volumes of landslide/debris flow scars and hillslope deposits were measured by field survey and the percentage of hillslope deposits of the total sediment produced was calculated. An average of about 5 % of total landslide/debris flow sediment remained on the hillslope in the 30 failures that were classified as Type-2 and Type-3; >90% of landslide/debris flow sediment was transported directly into the stream. Thus, about 20% of total landslide/debris flow sediment deposited on the hillslope and about 80% reached the channel in the Miyagawa Dam catchment. This percentage is lower than other catchments, e.g. 40% in Saru River, Japan (Nakamura et al., 1995). The steep topography in Miyagawa Dam catchment could reduce the amount of sediment deposited on the hillslope; slope gradients from the headcrop of landslides/debris flows to the channel are generally >35˚ based on field surveys conducted in the 30 Type-2 and Type-3 landslides/debris flows (Fig. 8). The relationship between erosion and deposition caused by landslides and slope gradient in coastal Alaska was examined; slopes whose gradients exceeded 35˚ were considered erosion zones for all forest types (Johnson et al. 2000). This gradient is almost the same or greater than the internal friction angle of the soils; thus, most of the sediments in the Miyagawa Dam catchment are entrained and transported into the channel.

4.4 Channel gradient of landslide/debris flow deposits





Processes which transport landslide/debris flow deposits depend on the channel gradient near the deposits. Debris flows entrain deposits in steep channels, while fluvial processes entrain sediments in gentle channel (Fig. 9). Benda (1990) indicated that the drainage area above deposits influences the longevity of debris flow 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.

About 15% of Type-2 and Type-3 landslides/debris flows deposited in channels with gradient < 10˚ (Fig. 10). Deposits in this zone are likely later entrained by fluvial processes because of large drainage areas and gentle channel gradients. About 45% of Type-2 and Type-3 landslides/debris flows terminated in channels steeper than 25. Many debris flows initiate in such reaches (VanDine 1985; Pareschi et al. 2002), and role of debris flows on the transport of these deposits might be high. About 30% of the landslide/debris flow sediments deposit in channels > 30˚ (corresponding to

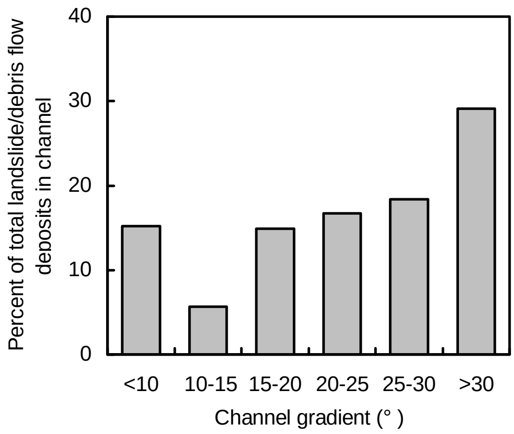


Fig. 10 Channel gradient of landslide/debris flow deposits

zero-order basins in Miyagawa Dam catchment based on field surveys). Surface flow might not occur in these channels because debris flows can run down in unsaturated conditions (Imaizumi et. al, 2005); thus, fluvial processes in such conditions would be insignificant.

5. Discussion

Sediment supply from landslides and debris flows affects sediment yield and the influence continues for more than several years in Miyagawa Dam catchment. This indicates that a large portion of the sediments produced from landslides and debris flows are stored temporally in the catchment as hillslope and channel deposits. Location of sediment deposits (both on the hillslope and in the channel) affects sediment mobility, specifically, the timing and amount of sediment distributed downstream.

Landslide deposits on hillslope can be entrained into channel by surface erosion and soil creep; however, these processes (especially creep) are slow. Thus, the timing landslide deposition on hillslopes may lag sediment transport. The mobilization of sediment deposits to channels depends on channel gradient; the frequency of sediment transport in steep channels is low because of the long intervals between debris flows (Benda and Dunne, 1997; May and Gresswell, 2003), whereas sediment can be entrained frequently by fluvial processes in gentle channels.

The position of deposits varies from catchment to catchment depending on hillslope and channel topography. Only a small portion of landslide/debris flow sediments (≈ 20%) deposit on hillslopes in Miyagawa Dam catchment because of steep slopes. About 45% of the total channel deposits produced from landslide/debris flows are in debris flow initiation zones (>25˚); there may be a significant lag time between sediment supply and transport in the Miyagawa Dam catchment for such deposits. About 15% of total channel deposits are in gentle channels. Even though armoring of the channel can effectively decrease sediment mobility, sediment can be entrained during stormflows and rapidly be transported downstream.

6. Conclusion

Although a clear relationship between sediment supply and transport processes at the large-catchment scale is necessary to develop a unified sediment supply/transport unified model, field data concerning this relationship are scarce. The following conclusions are obtained based on aerial photo assessments, sediment deposits above the dam, and field investigation in the Miyagawa Dam catchment, central Japan:

(1) Timing of sediment transport near Miyagawa Dam lake corresponds to large rainfall-runoff events because sediment transport processes near the lake are fluvial processes that can be explained by hydraulic factors.

(2) Sediment yield from entire catchment is affected by occurrence of landslides and debris flows in steep areas of the catchment. Occurrence of landslides/debris flows begin to affect catchment sediment yield quite rapidly, and the influence is sustained for more than several years.

(3) The position of landslide/debris deposits plays an important role on the relationship of sediment supply and transport. Sediments delivered into gentle channels are easily transported downstream during high discharge events, whereas the mobility of sediment delivered into debris flow sites (primarily zero-order basins), is not high because debris flows occur infrequently at such sites.

(4) Of the landslide/debris flow sediments that were initially classified as being deposited in channels, about 30% of the deposits terminated in steep channels (> 30˚) where fluvial processes are minimal. Furthermore, about 20% of sediments are deposited in channel reaches where they may later move as debris flows (gradients of 25–30˚). Because mobility of deposits in such debris flow channels is not high, these deposits create long-term sediment supplies that influence later sediment yields.

Thus, the position of deposits and frequency of sediment transport processes (especially debris flows) should be considered when developing a unified sediment supply and transport model.

Acknowledgements

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山地流域における土砂生産と土砂流出の量的・時間的な関係

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要旨

本研究では、三重県宮川ダム流域において、空中写真判読、ダム堆砂量の解析、現地調査等を行い、土砂生産と土砂流出の量的・時間的な関係、およびその関係に影響を及ぼす要因を検討した。ダム湖周辺における土砂流出のタイミングは大きな降雨流出イベントのあった年と一致する。また、土砂生産の影響は土砂流出に数年以上継続する。これらの特性は、崩壊・土石流による堆積土砂の堆積位置に影響を受けていると考えられる。

キーワード：土砂生産、土砂流出、ダム堆砂、宮川ダム、渓床堆積物

山地流域における土砂生産と土砂流出の量的・時間的な関係

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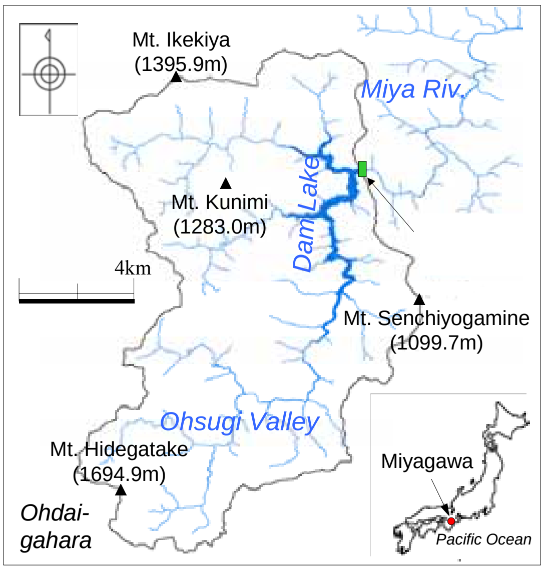
１．はじめに

山地で生産された土砂は土石流として人的被害を与えるほか，浮遊砂・掃流砂として流下し，ダム湖の貯水容量の減少など経済的被害を与える可能性がある。これらの被害の抑制には，砂防構造物等での流出土砂量の調整に加え，森林整備等による生産土砂量の抑制が必要である。山腹で生産された土砂が一時的に谷底に貯留した後に下流へ流下を開始するように，土砂生産と土砂流出の間には量的・時間的な関係が存在する。しかしながらこの関係は未解明の部分が多く，従来土砂生産と土砂流出は個別に研究されていた。そこで本研究は，実際の山地で両者の間に存在する時間的・量的な関係を明らかにするため，三重県南部の宮川ダム流域において現地調査・空中写真判読等を行った。

２．研究対象地および研究方法

本研究対象地の宮川ダム流域は大台ケ原山系日出ヶ岳から宮川ダムまでの流域面積 125.6 km²，流路長約 26 km である（図－1）。年降水量 1600 mm～4500 mm の多雨地域であり，地質は秩父古生層の粘板岩および砂岩が大部分を占めている。

宮川ダムでは毎年，ダム湖の堆砂量が測量されており，これから流域からの流出土砂量を推定した。また，流域内での崩壊・土石流の発生による土砂生産状況把握するため，最近約 20 年間の白黒空中写真（1982，1986-87，1992，1996-97，2001 年）を判読した。これらのデータおよび降雨データを対比させることにより，土砂生産と土砂流出の間に存在する関係を検討した。



図－1　宮川ダム流域

３．結果および考察

ダム堆砂の増加量と降雨因子・流量因子の相互相関関数を調べたところ，ダム堆砂量の増加量と最も相関の高いものは年間最大流量（瞬時値）であった。また，相関係数が最大となるタイムラグは 0 年であった。このことから，ダム湖周辺での土砂流出現象は大きな降雨・流出イベントのある年に活発であるといえる。その理由として，ダム湖周辺での土砂の移動形態は主に掃流砂・浮遊砂であり，これらの流出は水理条件で説明することが可能であることから，流量によって流砂量が決定されることが考えられる。また，空中写真判読結果とダム堆砂量の変化を対比させた結果，流域内での多数の崩壊・土石流の発生がみられるとそれに伴い流砂量が増加すること，さらには流砂量の増加は数年以上持続することが明らかになった。これらの結果から，流域内での土砂生産が流砂量へ影響していること，さらには生産された土砂のすべてがすぐに下流へ流下するわけではなく，流域内に一時的に貯留した後に流下する土砂が存在することがわかる。宮川ダム流域では，河川で堆積する崩壊･土石流土砂のうちの約 45%が土石流の発生する可能性がある急勾配区間（河床勾配 25˚以上）に堆積する。土石流は頻度の低い土砂移動現象であるため，ここでの堆積は土砂生産と土砂流出の間に時間的なラグを生じさせる原因のひとつであると考えられる。