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SEDIMENT BUDGET AND POTENTIAL SEDIMENT YIELD DUE TO SHALLOW LANDSLIDES IN THE UPPER BASIN OF THE OI RIVER

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ABSTRACT
An understanding of the sediment delivery for a catchment scale is required to develop strategies to mitigate sediment disasters in harmony with the catchment environment. I analyzed the sediment budgets of the upper basin of the Oi River using sedimentation data of reservoirs and estimated the potential sediment yield as a first step to understanding the sediment delivery system for the catchment scale. The average annual sediment yield in the upper basin of the Oi River (upper basin of IK dam, 459 km^2) was 2,380,000 m^3, close to the sediment of deposits in the three H1, H2 and IK reservoirs. Only 7 percent (170, 000 m^3) runs off from the IK dam. A 5200 m^3/ km^2/year of the specific sediment yield indicates that the upper basin of the Oi River has one of the highest rates of sediment production in Japan. A sediment budget analysis that includes the ratio of bed material load to wash load in the sedimentation data for reservoirs suggests that fine material loads, such as a wash load and some part of a suspended load, would be considerably higher than the ratio we assume in the upper stream of the basin. An analysis of potential sediment yield based on a zero order basin indicates that the potential sediment yield may be 32,920,000 m^3 (36,200,000 tons) in the upper basin of the H2 dam basin and that on average, sediment of 5 percent of the potential sediment yield may run off at the H2 reservoir annually. The sediment yield in the upper basin of the H2 dam caused by the 1982 event can be estimated to be 10,150,000 m^3 (15,220,000 tons), which is almost half of the potential sediment yield. This may suggest that the method based on an analysis of a zero order basin is valid for estimating the potential sediment yield. The results of this study may have important implications for catchment scale strategies to mitigate sediment disasters in harmony with the environment.
KEYWORDS: catchment scale, sediment budget, potential sediment yield, zero order basin, fine material load

INTRODUCTION

An understanding of sediment delivery for the catchment scale from the headwater to the river mouth is needed for Japan to develop successful strategies to mitigate sediment disasters in harmony with conservation and recovery and restoration of the catchment environment. Studies of sediment budgets that analyzed sediment routing as a system controlled by linkages between erosion from source areas, sediment storage, and sediment transport revealed that storage processes in the sediment delivery system are important along with the production processes in upstream sediment sources (Dietrich and Dunne, 1978; Trimble, 1981; Meade, 1982). Japanese studies of small mountain streams revealed pulses of rapid aggradation followed by degradation in successive floods and discussed the importance of storage processes (Araya, 1971; Nakamura, 1986; Maita, 1988; Nakamura and Maita, 1995). However, these studies focused primarily on the behavior of the bed load, while attention to fine material loads, such as a wash load and some part of a suspended load, was not sufficient in the

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sediment budget approaches. Fine material loads in sediment also play an important role in responses of the ecosystem structure and function as links with environmental issues in catchments as well as bed loads.

In this study, I discuss sediment budgets as a first step to understanding the sediment delivery system for a catchment scale, taking both bed material loads and wash loads into consideration. I utilized sedimentation data of reservoirs for estimating sediment budgets and Tsukamoto's method (1998) for estimating potential sediment yields due to shallow landslides.

STUDY SITE

The Oi River flows from Mt. Ainotake (3189m) into the Pacific Ocean, covering a distance of 180 km and draining a basin area of 1300 km^2 in Shizuoka Prefecture in Central Japan. The study site is the upper basin of 460 km^2 (Fig. 1). The basin of the study site receives an average annual precipitation of about 3000 mm. The basin is largely underlain by shale and sandstone of the Mesozoic Cretaceous Assemblage. The rock unit has been deformed by numerous fractures and share zones due to the basin's location within the high uplift zone of the Japanese Southern Alps. Rock deformation has resulted in incompetent beds. This, coupled with the high rainfall and steep terrain, contribute to the high erodibility of this catchment.

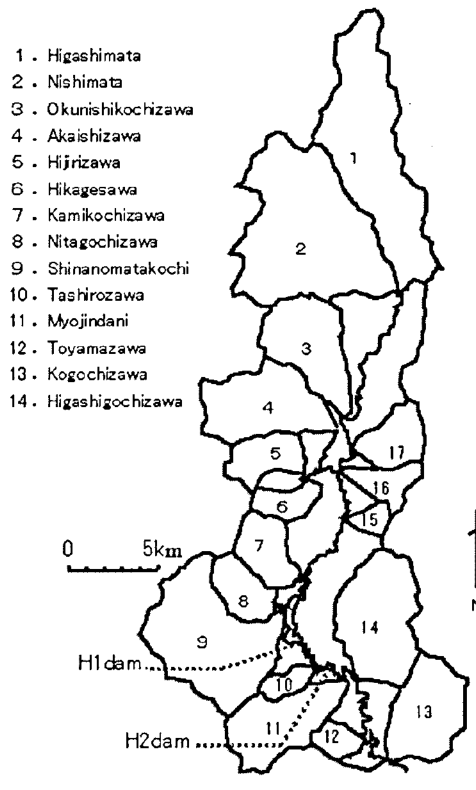

Fig. 1 Location map showing the upper basin of the Oi River

SEDIMENT BUDGET IN THE UPPER BASIN OF THE OI RIVER

Sediment Budget Equation

The sediment budget of a basin that has a reservoir is generally expressed as equation (1) in a given period (Kira, 1978).

$$V_{LS}+V_{SE}+V_{BE}-(V_{DS}+V_{DB}+V_{DD})=V_T \quad \cdots\cdots(1)$$

Where V_{LS}, V_{SE}, and V_{BE} are the volumes of sediment yields due to slope failure, surface erosion, and bank erosion. V_{DS}, V_{DB}, and V_{DD} are the volumes of storage sediment in the hillslope, riverbed, and reservoir. V_T is the volume of total sediment runoff, consisting of bed material load and wash load.

We can estimate the V_T at the dam site using the equation "$Q_S = \alpha Q^{n+1}$" or the sediment trap efficiency of the reservoir because the V_T at the dam site mostly consists of wash load. Here, Q_S is the volume of wash load, Q is the discharge, α is a constant, and n nearly equals 1 (Kitukawa, 1985).

The sediment volume flowing into the reservoir, which is expressed as $(V_{LS}+V_{SE}+V_{BE}-(V_{DS}+V_{DB}))$, can be estimated using $(V_{DD}+V_T)$ because $(V_{LS}+V_{SE}+V_{BE}-(V_{DS}+V_{DB}))$ equals $(V_{DD}+V_T)$. Moreover, V_{DD} and V_T can be estimated using reservoir sedimentation data and the estimation of wash load, respectively.

Sediment Budgets in the Upper River Oi

H1, H2,and IK dams are located in the upper basin of the Oi river; H1dam connects directly to H2 dam without a river channel (Fig. 2, Table 1). Sediment budgets in the upper Oi River can be estimated if V_{DD} and V_T can be obtained in equation (1). V_{DD} can be estimated using data from the sedimentation of each reservoir, and V_T can be estimated using the sediment trap efficiency (E_T) calculated by equation (2) that was proposed by Kira (1978) based on an analysis of 50 Japanese reservoirs.

$$E_T = 0.96^{0.25^{\log C/I}} \quad \text{——} \quad (2)$$

Where C is the water storage volume of the reservoir (m^3) and I is the annual water inflow into the reservoir (m^3).

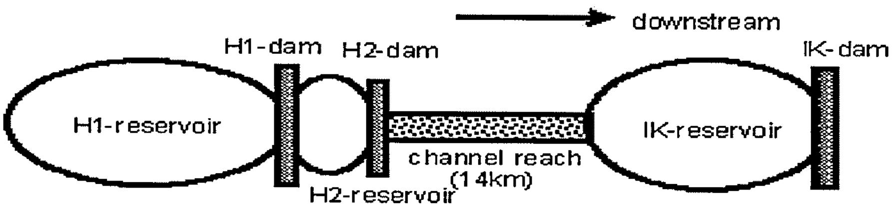

Fig. 2 Location of each dam in the upper basin of Oi River

Table 1 Area of the dam basin and initial water storage volume of the reservoir

Dam	Basin area(km^2)	*Direct basin area (km^2)	Initial volume(m^3)	Built year
H1dam	318.0		107,400,000	1961
H2dam	329.2	11.2	11,400,000	1961
Ikdam	459.3	130.1	150,000,000	1957

* (area of object dam basin - area of its just upper dam basin)

I_{H1}, I_{H2}, and I_{IK} in Table 2 represent the volume of sediment inflow into H1, H2, and IK reservoirs. V_{DH1}, V_{DH2}, and V_{DIK} represent the volume of sediment storage in H1, H2, and IK reservoirs, and O_{H1}, O_{H2}, and O_{IK} represent the volume of sediment runoff from H1, H2, and IK dams. The years 1973, 1976 ,and 1978 are excluded from the calculation of sediment budgets because the volumes of their annual depositions are negative; there are substantially negative values for 1976 in particular for reasons not presently known. The sediment yield from the direct basin for H2 dam is ignored because its area is small (11km^2) and it had no significant landslides that produced much sediment. Hence the volume of sediment runoff from H1 dam (O_{H1}) is given as the volume of sediment inflow into H2 reservoir (I_{H2}).

Table 2 Annual sediment budgets estimated in the upper basin of the Oi River.

year	I_{H1}	V_{DH1}	O_{H1}	V_{DH2}	O_{H2}	I_{IK}	V_{DIK}	O_{IK}
1967	878,224	777,210	101,014	17,606	83,408	515,900	453,265	62,635
1968	1,021,948	895,600	126,348	13,201	113,147	360,765	313,276	47,489
1969	1,354,226	1,168,798	185,428	63,911	121,517	1,232,848	1,051,205	181,643
1970	2,171,614	1,891,565	280,049	142,454	137,595	1,664,214	1,437,531	226,683
1971	547,899	475,644	72,255	13,598	58,657	4,424,927	3,790,237	634,690
1972	899,579	760,542	139,037	5,324	133,713	1,536,736	1,274,110	262,626
1973								
1974	639,556	547,902	91,654	11,242	80,412	532,798	447,491	85,307
1975	1,616,567	1,391,244	225,323	72,864	152,459	620,198	526,016	94,182
1976								
1977	374,808	326,740	48,068	33,296	14,772	1,704,137	1,471,926	232,211
1978								
1979	63,304	54,963	8,341	-47,032	55,373	372,203	320,514	51,689
1980	1,481,559	1,265,430	216,129	49,285	166,844	2,200,399	1,875,505	324,894
1981	763,227	657,587	105,640	25,264	80,376	150,243	129,014	21,229
1982	5,433,826	4,541,834	891,992	182,701	709,291	3,008,432	2,517,858	490,574
1983	3,926,580	3,180,545	746,035	46,667	699,368	2,737,355	2,228,034	509,321
1984	788,281	706,084	82,197	5,396	76,801	39,761	35,805	3,956
1985	1,575,490	1,301,121	274,369	-28,117	302,486	735,209	613,090	122,119
1986	883,669	761,206	122,463	113	122,350	11,509	9,989	1,520
1987	85,460	74,302	11,158	63,623	-52,465	30,271	26,471	3,800
1988	780,332	672,867	107,465	16,008	91,457	278,990	241,759	37,231
1989	625,362	519,488	105,874	26,544	79,330	174,234	145,241	28,993
1990	1,333,299	1,129,503	203,796	7,925	195,871	719,755	612,000	107,755
1991	760,778	625,000	135,778	101,000	34,778	1,254,399	1,038,000	216,399
mean	1,272,981	1,078,417	194,564	37,403	157,161	1,104,786	934,470	170,316

I_{H1} and I_{IK} show the volume of sediment inflow into H1, H2 and IK reservoirs respectively (unit: m^3)
V_{DH1}, V_{DH2} and V_{DIK} show the volume of sediment storage in H1, H2 and IK reservoirs respectively.
O_{H1}, O_{H2} and O_{IK} show sediment runoff from H1, H2 and IK dams respectively.

The reach between downstream from H2 dam and upstream from IK reservoir does not exhibit any remarkable aggradation or degradation tendencies. This suggests that it is in equilibrium from the long-term perspective. Therefore, the storage volume on the reach can be treated as zero in a calculation of the average sediment budget over the long term. However, it should be considered in a calculation of the short-term sediment budget. I treated it at this time as zero in the calculation of the annual sediment budget because there was no data regarding the storage volume on the reach.

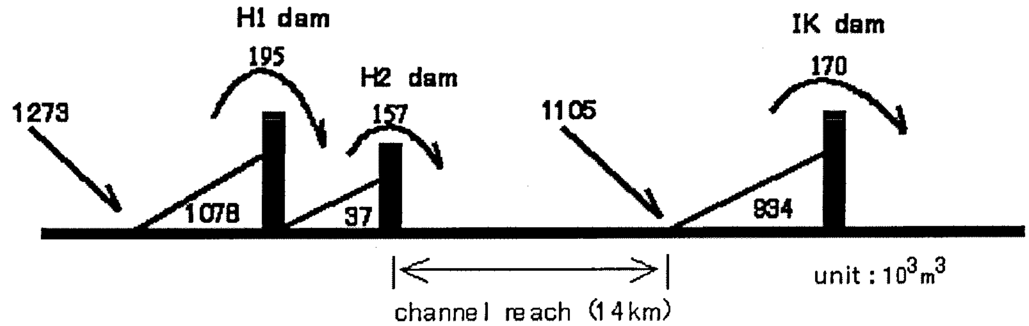

Fig. 3 Mean of annual sediment budgets from 1967 to 1991 in the upper basin of the Oi River

Figure 3 shows the mean of the annual sediment budgets from 1967 to 1991 in the upper basin of the Oi River. The annual sediment yield from the upper basin of IK dam is 2,380,000 m^3 on average. The sediment produced in the upper basin deposits mostly in H1, H2, and IK reservoirs, and only 170,000 m^3 of the sediment runs off from IK dam. However, we must note the variation of the annual sediment yield (Table 2, Fig. 4). For example, the sediment volumes produced in 1982 and 1983 were 8,400,000 and 6,700, 000, which were three or four times the average volume.

Changes of the Annual Volume of Bed Material Load Transported in the Upper Stream of the Oi River

The sediment produced from the hillslope, riverbank, and riverbed is transported in the stream in the form of wash load, and bed material load including the bed load and suspended load (Kitsukawa, 1985). It is therefore important that we identify the ratio of bed material load to wash load in order to examine the sediment budget and routing. The ratio of bed material load to wash load is 0.14: 1 at the channel flowing only into H1 reservoir, according to a model for reservoir deposition reported by Ezaki (1966). However, the wash load in Ezaki's ratio may have included the suspended load, and this ratio should therefore be verified in the future by monitoring data. I used that ratio as a first approximation to estimate the bed material load at the upper channels to H1 and IK reservoirs only since I had no other ratio information.

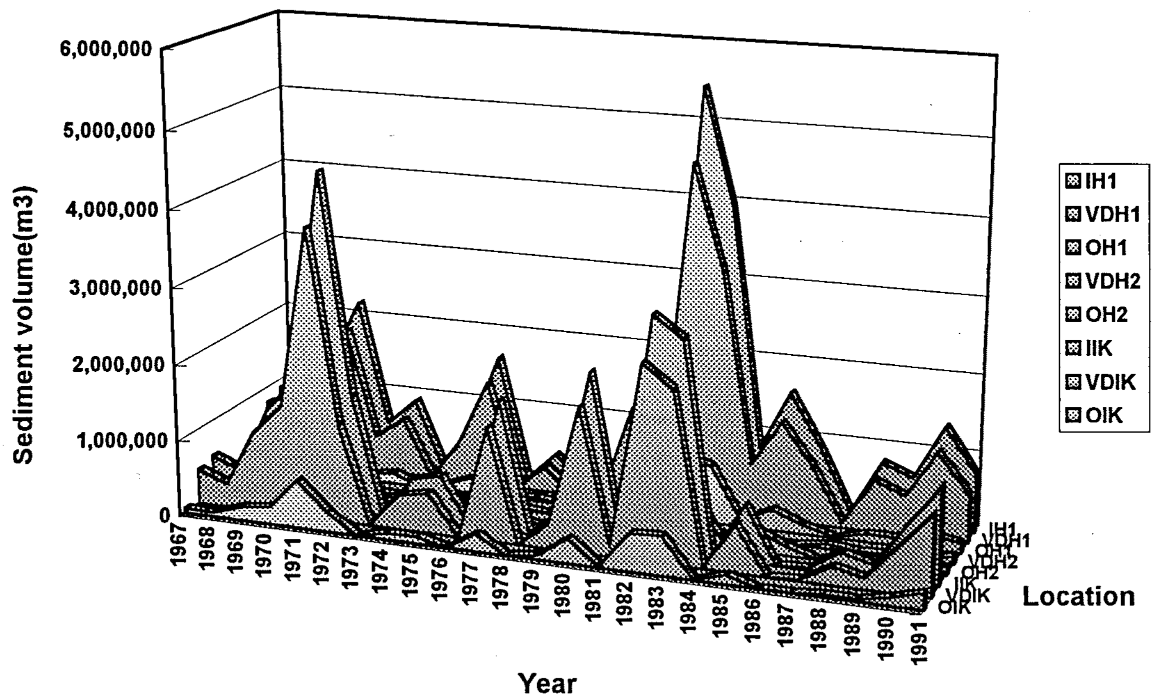

Fig. 4 Changes of annual sediment budgets in the upper basin of the Oi River

I estimated the mean annual volume of bed material load from 1967 to 1991 to be 150,000 m^3 at the upper channel to H1 reservoir and 130,000 m^3 at the upper channel to IK reservoir (Table 2, Fig. 5). Although these values include the load from direct slopes and small tributaries to the reservoirs, they are regarded in this study as entering from the main channel to the reservoirs. Fig. 5 indicates that the annual volume of bed material load at the upper channel to H1 reservoir was 650,000 m^3 in

1982, which is 4.3 times the mean value. The volume was 470,000 m^3 in 1983, which is 3.1 times the mean value; the volume rapidly decreased thereafter to near the mean value. A similar tendency appears in the changes of the annual volume of bed material load at the upper channel to IK reservoir. The annual volume at the upper channel to IK reservoir was 360,000 m^3 in 1982, which is 2.7 times the mean value; the volume was 330,000 m^3 in 1983, 2.5 times the mean value.

Monitors of channel responses to floods in the Higashigouchi River, located in the vicinity of H1 reservoir (Fig. 1), indicated that the river experienced a 933 mm rainfall during three days in August 1982. This catastrophic flood and its associated sediment input caused 210,000 m^3 of bed load sediment to deposit temporarily in the research section (1.1 km), which is the unconstrained reach. The streambed in the research section aggraded by 2 to 8 m from pre-1982 levels. Following this flood, the streambed degraded during five successive floods from 1982 to 1985. The 1982 deposits decreased exponentially and were mostly eroded by 1985 (Maita, 1988). This suggests that more than 210,000 m^3 of sediment eroded from hillslopes, steep debris fans, and floodplains moved down the streambed in the research section as a "sediment wave"(Madej *et al.*, 1996). The changes in total load and bed material load of the upper stream of the Oi River in several successive years after 1982, shown in Figs. 4 and 5, were similar to those of the Higashigouchi River. This suggests that a catastrophic flood and its associated sediment input also occurred in the upper basin of the Oi River in August 1982, and the massive sediment moved downward in the upper channels to H1 and IK reservoirs as sediment waves during subsequent floods.

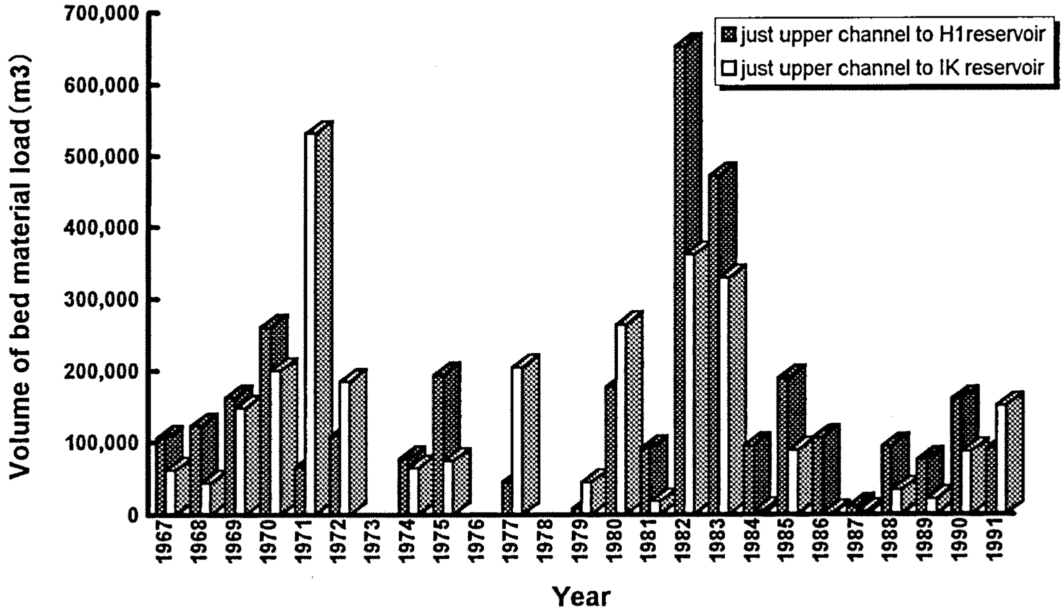

Fig. 5 Changes of annual volume of bed material load at the upper channel H1 and IK reservoirs

If channel recovery associated with a sediment wave is defined as a return to the previous or average sediment transport rate (Madej, 1996), the recovery time at the upper channels to H1 and IK reservoirs could have been three years, from 1982 to 1984, based on the channel recovery data of the Higashigouchu River (Maita, 1988) and the changes shown in Fig. 5. Hence, the volume of sediment produced in the upper basin of H1 dam (318 km^2) by the 1982 event could be estimated to be

10,150,000 m^3, and the volume of bed material load transported in the upper stream of H1 dam during three years could be estimated to be 1,220,000 m^3. The sediment volume of the direct basin of IK dam (130 km^2) could be estimated to be 5,790,000 m^3, and the volume of bed material load transported in the reach between just downstream of H2 dam and just upstream of IK reservoir could be estimated to be 690,000 m^3.

The bed material load in the reach between just downstream of H2 dam and just upstream of IK reservoir (Fig. 1) is supplied only from the direct basin of IK dam; the sediment supplied from H2 dam to the reach is only wash load. In addition, the direct basin consists almost entirely of the Higashigouchi (28 km^2), Kogouchi (20 km^2), and Myojindani (28 km^2) basins (Fig. 1). As mentioned above, more than 210,000 m^3 of sediment in the Higashigouchi basin, derived from many sources by the 1982 event, moved down the streambed in the research section as a sediment wave during subsequent floods. Thus, 690,000 m^3 of bed load material in the reach between just downstream of H2 dam and just upstream of IK reservoir is a reasonable value, at least on the order level, if the Kogouchi and Myojindani Rivers are similar to the Higashigouchi River in terms of sediment supply and transport caused by the 1982 event and the subsequent events. This suggests that the ratio of bed load to wash load by Ezaki (1966) may not be completely erroneous as a first approximation for the actual ratio. Fine material loads, such as a wash load and some part of a suspended load, are thus considerably higher than the ratio we assumed, even in the upper stream of the basin. However the ratio of fine material load to bed load still remains a topic for future field research.

POTENTIAL SEDIMENT YIELD DUE TO SHALLOW LANDSLIDE OF THE UPPER BASIN OF THE OI RIVER

Drainage Net Analysis

A drainage net analysis was performed for 17 watersheds in the upper basin of the Oi River (Fig. 1) using maps with a 1:50,000 scale to examine the relationships between the number of streams and the order of streams under the Horton- Strahler ordering system (Gordon et al., 1992).

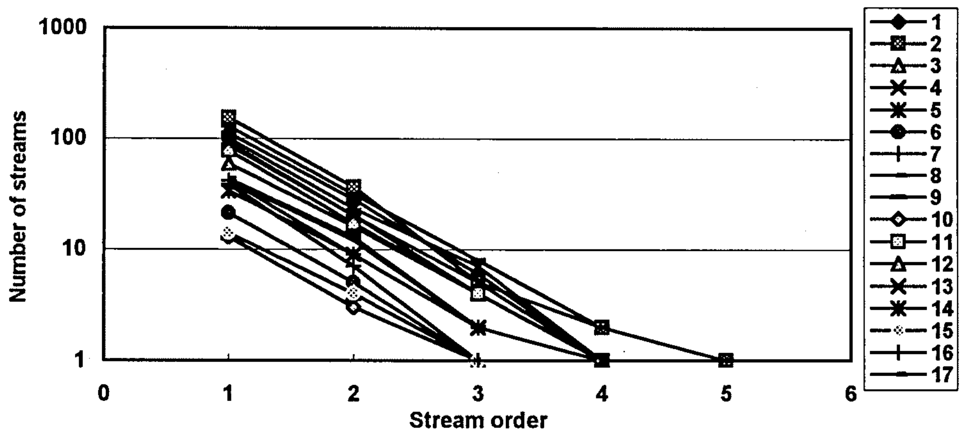

Fig. 6 Relationships between the number of streams and the order of streams
1:Higashimata. 2:Nishimata. 3:Okunishigochi. 4:Akaishizawa. 5:Hijirizawa. 6:Hikagesawa. 7:Kamikouchizawa. 8:Nitakouchizawa. 9:Shinanomatakouchi. 10:Tashirozawa. 12:Myojindani. 13:Kogochigawa. 14:Higashigochisawa. 15:Nakanosyukusawa. 16:Syonosawa. 17:Kurasawa.

The results indicate that Horton's first law (the law of the number of streams) mostly holds in the upper stream of the Oi River (Fig. 6). The average of the bifurcation ratio is 4.2.

Potential Sediment Yield Due to Shallow Landslides

Horton's first law can be adapted in the upper stream of the Oi River, and thus the number of zero order streams can be calculated using the 4.2 bifurcation ratio if the law can be extended to a zero order stream (Tsukamoto et al., 1976). The resultant number for the upper basin of H2 dam basin (329.2km^2) is 5489. Tsukamoto (1998) reported that the sediment yield of a basin (V) can be expressed as equation (3) if a shallow landslide caused by heavy rainfall occurs in a zero order basin. V becomes the potential sediment yield if f equals 1.

$$V = f \cdot N \cdot k \cdot a \cdot h \quad \text{---- (3)}$$

Where f is the ratio of the number of zero order basins in which a landslide occurs to the total number of zero order basins in the objective basin, k is the ratio of the area of a landslide in a zero order basin to the overall area of the zero order basin, A is the area of the objective basin, N is the total number of zero order basins in the objective basin, h is the average depth of the landslides, and a is the supposition area of a zero order basin, calculated by dividing A by N.

Tsukamoto (1998) reported that K can be equal to 0.1. It can then be supposed that h equals 1 m due to shallow landslides. f is equal to 1 for an estimation of the potential sediment yield. Therefore, the potential sediment yield in the upper basin of H2 dam (329.2km^2) can be estimated as 32,920,000 m^3. The mean annual sediment yield at H2 dam is 1,270,000 m^3, since the yield at H1 dam nearly equals the yield at H2 dam, as described above (Table 2). We can convert the volume into the weight to compare the potential sediment yield with the annual sediment yield. The annual sediment yield at H2 dam can be estimated as 1,900,000 tons if the bulk density of the sediment deposited in the reservoirs is assumed to be 1.5 ton/m^3. In contrast, the potential sediment yield at H2 dam can be estimated at 36,200,000 tons, since the bulk density of the soil of the hillslope is 1.1 ton/m^3 based on the soil porosity being estimated at 0.58 (Maita et al., 1984). Hence, an average sediment of 5 percent of the potential sediment yield runs off at the H2 reservoir annually. Also this percentage indicates that the value of f in equation (3) is 0.05. This suggests that landslides occur annually in 5 percent of the total number of zero order basins, because an equilibrium can be assumed for the sediment yield and transport from the standpoint of the long-term average. The sediment yield in the upper basin of H2 dam from the 1982 event can be estimated to be 10,150,000 m^3 (15,220,000 tons), which is almost half of the potential sediment yield. This may suggest that the method based on an analysis of a zero order basin is valid for estimating the potential sediment yield. The original sediment source comes from slope failure in hillslopes, and thus the potential sediment yield plays an important role in understanding sediment delivery for the catchment scale.

CONCLUSIONS

Sediment budgets using reservoir sedimentation data revealed that the average annual sediment yield in the upper basin of the Oi River (upper basin of IK dam, 459 km^2) was 2,380,000 m^3 (the specific sediment yield was 5200 m^3/ km^2/year), and most of the sediment deposited in the three reservoirs of H1, H2, and IK, with only 7 percent (170, 000 m^3) running off from IK dam. A 5200 m^3/ km^2/year of the specific sediment yield indicated that the upper basin of the Oi River has one of the highest rates of sediment production in Japan. The event caused by heavy rainfall in August 1982 may have produced about 16,000,000 m^3 of sediment in the upper basin of the Oi River (upper basin of IK dam), and this sediment may have been transported to each reservoir by successive floods for several years after the event.

A sediment budget analysis that included the ratio of bed material load to wash load in reservoir sedimentation data suggested that fine material loads, such as a wash load and some parts of a suspended load, would be considerably higher than the ratio we assume, even in the upper stream of the basin. However, the ratio of fine material load to bed load remains a topic for future field research due to the limitations of this analysis using reservoir sedimentation data.

An analysis of potential sediment yield based on a zero order basin revealed that an average sediment of 5 percent of the potential sediment yield of 32,920,000 m^3 (36,200,000 tons) may run off at the H2 reservoir annually, and landslides may occur annually in 5 percent of the total number of zero order basins. The sediment yield in the upper basin of H2 dam brought by the 1982 event can be estimated to be 10,150,000 m^3 (15,220,000 tons), which is almost half of the potential sediment yield. This may suggest that the method based on an analysis of a zero order basin is valid for estimating the potential sediment yield. The original sediment source is slope failure in hillslopes, and thus the potential sediment yield plays an important role in understanding sediment delivery for the catchment scale. The results of this study may have important implications for the catchment scale to mitigate sediment disasters and maintain a stable environment.

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