Translation and Dispersion of Sediment Pulses Induced by an Extreme Rainfall in Mountain Rivers

Tomoyoshi Miyazaki,[1] Motohiro Kurebayasi,[2] Takashi Yamada[3] and Tomomi Marutani[3]
1) Shin engineering consultant Co., Ltd, JAPAN
2) Erosion and disaster prevention division, department of construction, pref. Hokkaido, JAPAN
3) Laboratory of Erosion Control, Graduate school of Agriculture, Hokkaido University, JAPAN

Abstract

Understanding linkage between channel process along a river course and hill-slope process with lateral sediment sources can be significant for management of sedimentary systems. The linkage, which is characterized by distribution of storm-induced sediment in a river channel, is often expressed as sediment pulse (wave). This paper examines the propagation of sediment pulse formed by storm-induced sediment flow in two river channels of Southern Hokkaido, and classifies the patterns of sediment pulse based on difference in the distribution of accumulated sediment volume. Longitudinal changes in sediment volume along a river channel were modified to a sediment mass curve. Auto-correlation and cross-correlation analyses were employed for examining sediment mass curves. The sediment pulses demonstrated with sediment mass curve was classified to four patterns, such as decreasing, increasing, intermediate and periodic types. Decreasing type along a transport-limited channel and increasing type along a supply-limited channel were dominated. Periodic type was not influenced by sedimentary link between channel and hill-slope but independently occurred by available sediment along a channel. Furthermore these types of sediment pulse were resulted to be influenced by channel width, channel slope and (quasi-)stream power. Although the highest peak of sediment pulse has demonstrated at the channel reach with wide section and/or gentle slope, it has shown dispersed and lower peak at the channel reach with larger stream power.

Keywords: sediment pulse, periodic or intermittent sediment supply, sediment mass curve, auto-correlation and cross-correlation analyses

Introduction

Preventive channel works for sediment disaster in a watershed depends on understanding magnitude and frequency of sediment discharge from mountainous river. It is difficult to predict sediment discharge, because intermittent sediment supplies from lateral sources result in discontinuous nature of sediment transport (Kasai *et al.*, 2004; Rice *et al.*, 1998). Sediment supplied from lateral sources is often transported with wave-like sediment lump. Therefore it is expressed as sediment pulse(wave). Large scale sediment pulses naturally occur in response to, for example, landslides (Sutherland *et al.*, 2002) and debris flows from tributaries. The pulses are also brought about by human activities such as hydraulic mining in the Sacrament Valley, California, United States of America (Gilbert, 1917). In recent years, the characteristics of sediment pulse propagation have been revealed by experiments (Cui *et al.*,2003a) and numerical analysis (Cui *et al.*, 2005). According to Lisle *et al.* (2001), a purely dispersive pulse is defined as one where the apex and trailing edge do not migrate downstream, and a translational pulse is one where all features, including leading and trailing edges, apex and centre of mass, advance downstream. Much is known about the river bed translation of alluvial sediment without any geological controls such as bedrock outcrops, large boulder and fine material mixture or longitudinal differences in channel width and bed slope. But less is known about influence of stream power, slope and channel width on translation and dispersion of sediment pulse. Therefore sediment delivery process linking with sediment supply might be investigated as changing sediment pulses along a channel.

The purpose of this paper is to understand the nature of sediment pulses and to examine the propagation of sediment pulses induced by an extreme rainfall in Osatsube and Chobonai Creek, Hokkaido, Japan. The results provide the relative information about the translation and dispersion of initial pulses from lateral sediment sources, and the wave behavior resulting from available alluvial sediment which has been formerly stored along the river channel. In addition, the sediment pulse propagation that changes by the difference in supply-limited and transport-limited condition is also discussed.

pp. 331–341

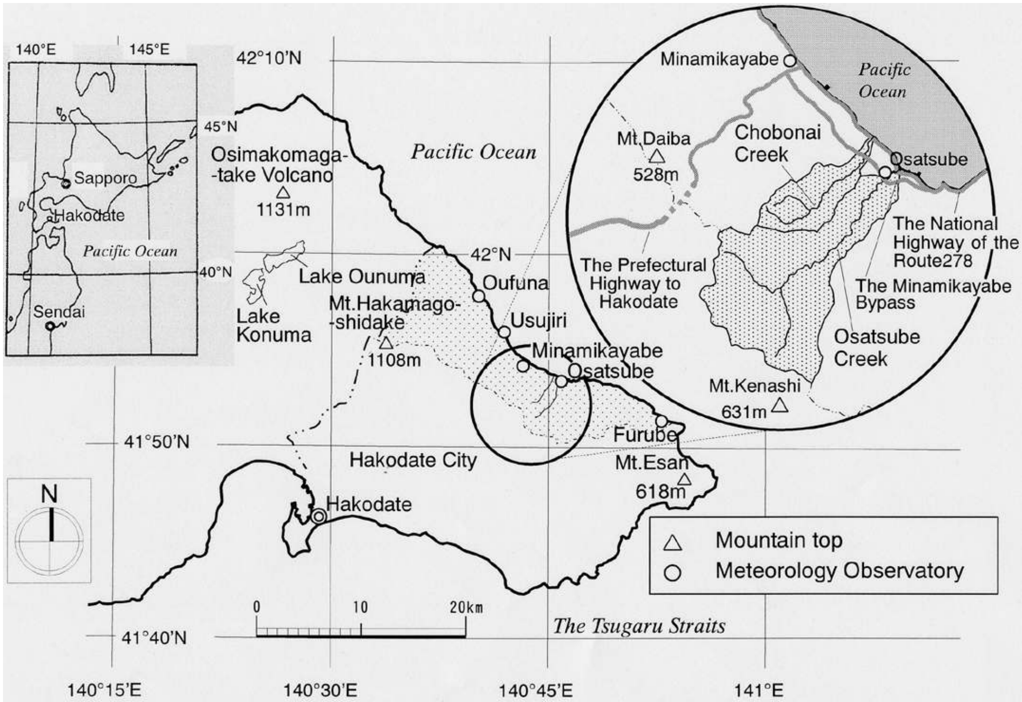

Fig. 1. Location of study catchments, Osatsube Creek and Chobonai Creek

Table 1. Geological and Hydrological characteristics of study catchments

Study catchment	Catchment area	Channel length	Shape factor of basin	Horton-Strahler's stream order	Stream frequency	Relief ratio	Geology	Erosion control facilities
	A(km^2)	L(km)	A/L^2	S_o	D_d(1/km)	I		
Chobonai Creek	2.68	4.0	0.17	3	3.7	0.14	Tertiary quartz-porphyry or dacitic propylite	Erosion control dam …9 Water intake weir ……1
Osatsube Creek	10.38	7.1	0.21	4	3.6	0.09	Tertiary quartz-porphyry or dacitic propylite	—

Study site

The study site is located on the southern region of Hokkaido, Japan (Fig.1). Osatsube and Chobonai Creek drain directly into the Pacific Ocean. Both catchments consist of Tertiary quartz-porphyry or dacitic propylite, and are covered with the summer-green forests. The characteristics of the study catchments are shown in Table1.

The 1998 typhoon caused shallow landslides and river bed erosion in the study catchments. The following flood delivered the generated sediment downstream. However some of sediment generated were transported out of the river mouth, and the rest were stored in the river channel. The total rainfall and the maximum hourly rainfall of this event were 292mm and 71mm, respectively at Osatsube Meteorology Observatory (Fig.2). And the 24hour rainfall at Osatsube, Minamikayabe, Usujiri and Furube is 290.5, 305.0, 299.5, 284.5 and 157.0mm, respectively. This extreme rainfall was the maximum record at Minamikayabe since 1966. The return period is calculated at 125years for the 24hour rainfall and 200years for the hourly rainfall.

Details of study catctments are illustrated in Fig.3, such as the confluence of tributaries, the erosion control facilities, the major sediment supplies from lateral sources, the sediment sampling points and the longitudinal profile from the river mouth. In Osatsube Creek, lateral sources, such as sediment discharge from the tributary and slope failure along the main channel, were the main sediment sources in the 1998 storm event. At that time there were no erosion control dams along the channel. In Chobonai Creek, available sediment sources along the main channel downstream of the water intake weir (2006m from the river mouth) dominated over lateral sources. Although lateral sediment sources have dominated upper reach of the weir as Osatsube Creek, the generated sediment was efficiently stored by erosion control dams in the range of storage capacities.

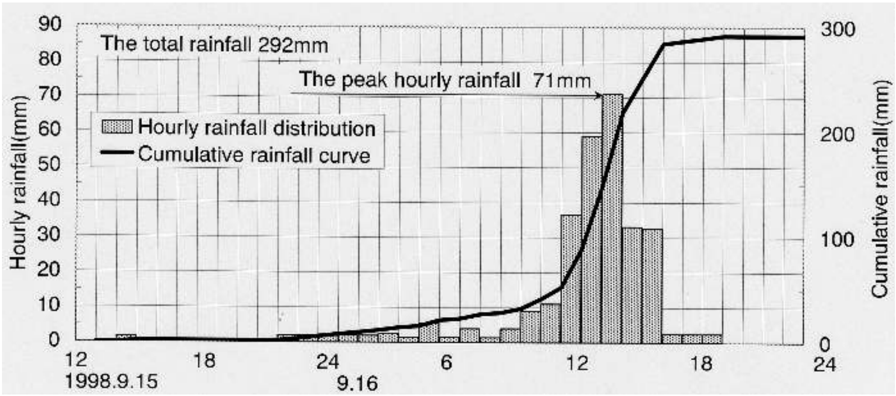

Fig. 2. Hourly rainfall distribution at the Osatsube Meteorology Observatory

Method

Sediment sources along the main channel are classified into the lateral sediment sources and available sediment of river bed material. The former includes (**1**) debris flow at the head water, (**2**) slope failure, (**3**) sediment discharge from the tributary, and the latter corresponds to (**4**) river bed and bank erosion (Fig.4).

To estimate the amount of yielded sediment in 1998 typhoon event, field survey and aerial photographs taken in August, 1993 and May, 1999 were employed. Amount of yielded sediment from hillslopes was delivered downstream. The amount is calculated by taking deposited volume at the base of slopes away from the whole slope failure volume. On the other hand, the scoured and accumulated sediment volume along the channel were calculated from cross-section survey with 50–100m interval and longitudinal elevation measurement. Dendro- and tephro-chronology using tree rings, tree roots washed out by flood flow or buried by accumulated sediment and tephra originated from Oshima-komagatake volcano eruption in 1929 were employed for dating of sedimentation and scouring. Sediment budgets are expressed as follows:

$$\begin{aligned} Q^k &= Q^{k+1} + G_k^{k+1} - D_k^{k+1} \\ &= Q^{k+1} + (G_{bk}^{k+1} + G_{hk}^{k+1} + Q_{trk}^{k+1}) - (D_{mk}^{k+1} + D_{trk}^{k+1}) \end{aligned} \tag{1}$$

where Q^k = the local sediment discharge at the kth cross-section upstream from the river mouth, G_k^{k+1} = the amount of yielded sediment from the kth cross-section to the (k+1)th cross-section, D_k^{k+1} = the accumulated sediment volume, G_{bk}^{k+1} = the amount of yielded sediment of river bed and bank erosion, G_{hk}^{k+1} = the amount of yielded sediment of slope failure, Q_{trk}^{k+1} = the sediment discharge from the tributary, D_{mk}^{k+1} = the accumulated sediment volume along the main channel, D_{trk}^{k+1} = the accumulated sediment volume at the confluence. All the values of the sediment volume are ones per 100m.

Although sediment budgets reveal the volumetric changes in local sediment, translation process between accumulated and dispersed sediment is still unknown. To understand the translation process and the routing of sediment pulses is the key issue of sediment delivery prediction. We approximated the distribution of accumulated sediment volume which showed the propagation of sediment pulse to the longitudinal curve and defined that as "sediment mass curve" (Fig.10). It can be considered that the patterns of sediment mass curve were classified by analyzing the sediment volume distribution in discretized form with auto-correlation and cross-correlation analyses. The auto-correlation coefficient is expressed as:

$$\begin{aligned} r_k &= \frac{\sum_{i=1}^{n-k}(y_i - m_k)(y_{i+k} - n_k)}{\sqrt{\sum_{i=1}^{n-k}(y_i - m_k)^2}\sqrt{\sum_{i=1}^{n-k}(y_{i+k} - n_k)^2}} \\ \delta &= l \cdot k \quad m = \sum_{i=1}^{n-k} y_i/(n-k) \quad n = \sum_{i=1}^{n-k} y_{i+k}/(n-k) \end{aligned} \tag{2}$$

where δ = phase lag by space (m), n = number of data and l = an interval of data (100m). The cross-correlation coefficient is calculated by converting y_{i+k} in Eq.(2) to x_{i+k}.

The other variables which are adopted in this calculation are channel width and stream power. Channel width was measured as the bankful width of the 1998 flooding. Stream power Ω(W/m) is an expression for

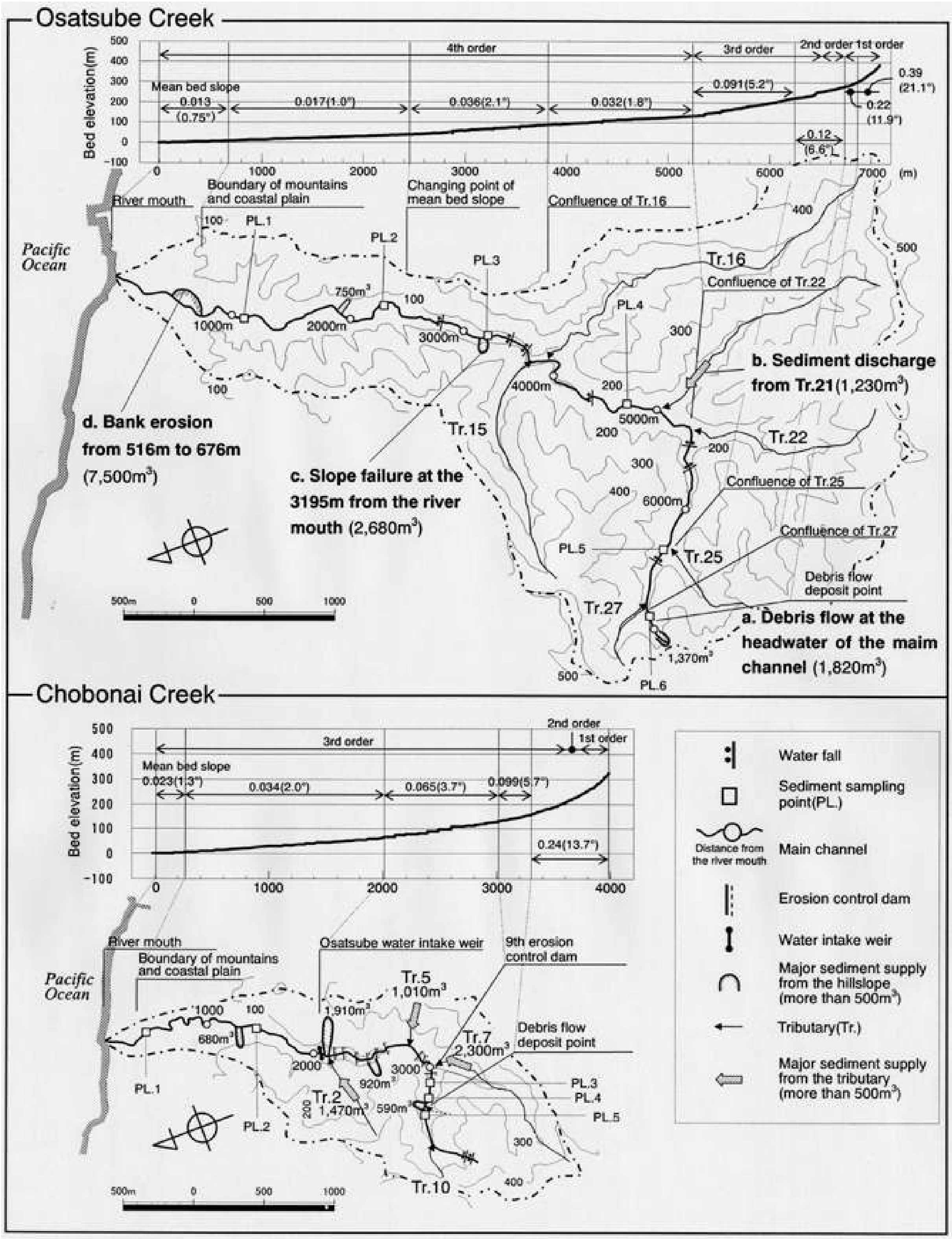

Fig. 3. Details and longitudinal profile of Study catchment, and sediment sampling points

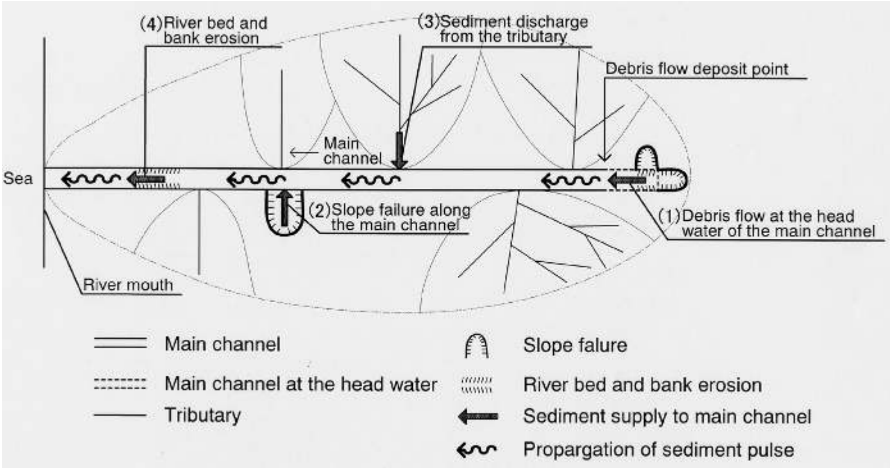

Fig. 4. Catchment diagram dominated by lateral sediment sources

the rate of potential energy expenditure per unit length of channel (Knighton, 1998), and is defined as:

$$\Omega = \rho g \cdot Q \cdot I \tag{3}$$

where ρ = density of water (1000kg/m^3), g = acceleration of gravity (9.8m/s^2), Q = discharge (m^3/s) and I = channel slope. In this paper, in order to estimate not a moment value but cumulative one of stream power, quasi-stream-power Ps(m^3) is defined as:

$$Ps = A \cdot R_{24} \cdot I \times 10^3 \propto \int \Omega dt \tag{4}$$

where A = catchment area (km^2), R_{24} = rainfall for the 24hours (mm) and t = time (s).

Results

Longitudinal changes in accumulated and supplied sediment volume

The Osatsube Creek was laterally confined and forced by bedrock outcrops. The rate of bedrock outcrop reach in the total channel reach was 54Over 1000m^3 initial sediment pulses were composed of 4 pulses: **a**. debris flow at the headwater of the main channel, **b**. sediment discharge from Tr.21, **c**. slope failure at the 3195m from the river mouth and **d**. bank erosion from 516m to 676m, where the top of the highest bank was 7m high; about 5 times the flood water depth (Fig.5). Each sediment pulse was translated and dispersed downstream of the sediment source. In the case of the bank erosion (d.), the slight backwater effect caused sediment deposition upstream of its input point. In Osatsube Creek, 2 or 3 peaks of accumulated sediment volume for each pulse were observed against the travel distance downstream from the input point (Fig.5, Table2).

In the Chobonai Creek, several sediment pulses were dominantly originated from the available sediment of channel bed downstream of the water intake weir (2006m from the river mouth). Three peaks of sediment pulses were observed at intervals of about 600m there (Fig.5, Table2). In order to analyze the periodical changes in sediment volume, the observation data from 0m to 2000m in the Chobonai Creek are adopted in the next auto-correlation and cross-correlation analyses.

Auto-correlation analysis of accumulated sediment volume

In the Osatsube Creek, the auto-correlation coefficient decreases as the phase lag increases. The coefficient was identified to be equivalent to zero with the 300–400m lag. Therefore it is understood that the accumulated sediment volume does not change periodically and initial pulse from lateral sediment sources is irregularly yielded into the channel (Fig.6). On the other hand, in the Chobonai Creek, the auto-correlation coefficient is changing periodically, and the wave length of the accumulated sediment volume is ranged between 600–700m (Fig.7, Table3). In addition, that of the supplied sediment volume is also changing periodically and the wave length is ranged between 300–400m. It is considered that not only the accumulated sediment volume but also the supplied sediment volume shows the periodical change in the Chobonai Creek.

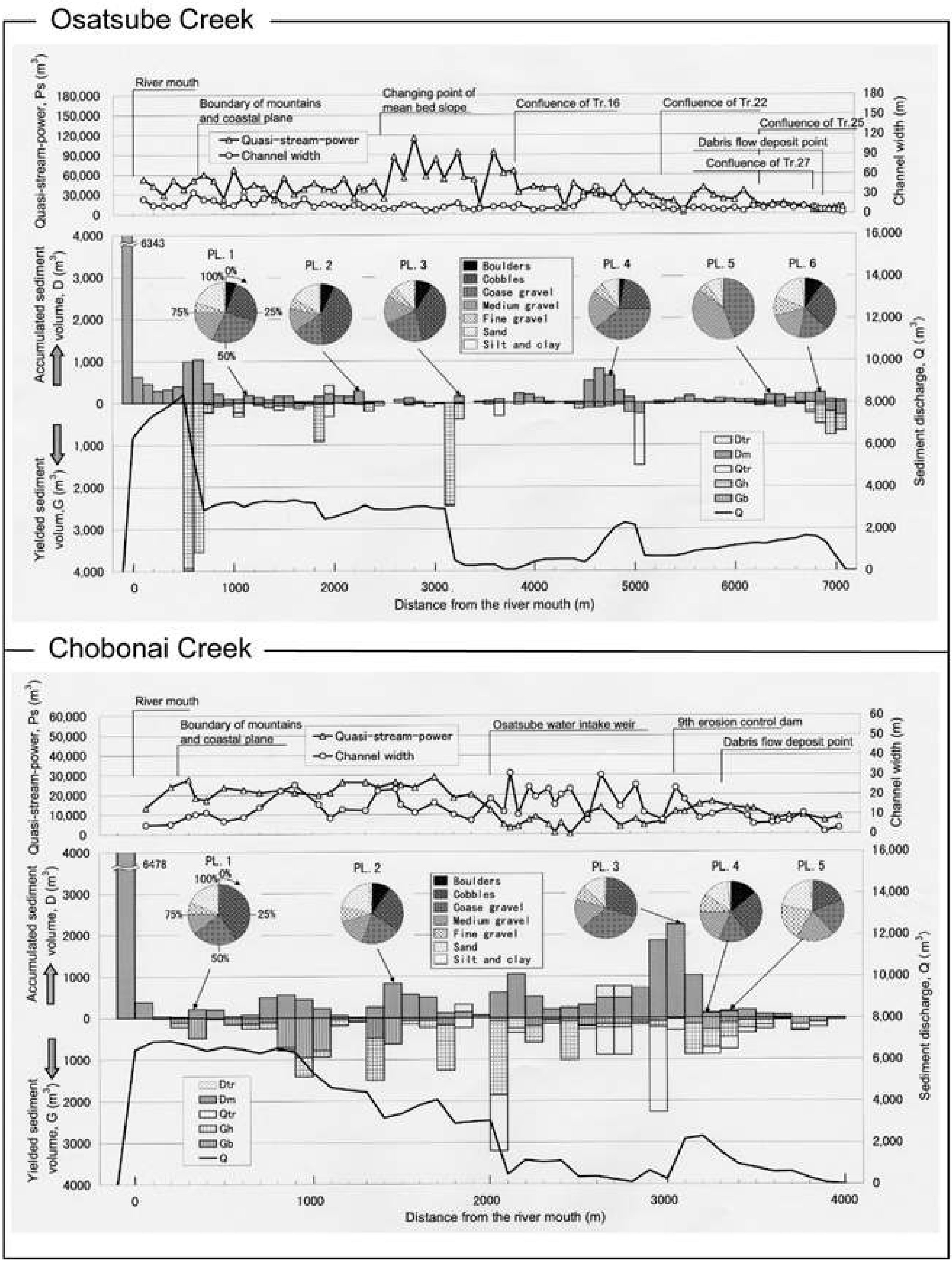

Fig. 5. Longitudinal changes in accumulated and yielded sediment volumes, particle sizes and quasi-stream power along Osatsube Creek and Chobonai Creek. Stacked bar gragh data are Dtr: accumulated sediment volume at the confluence, Dm: accumulated sediment volume along the main channel, Qtr: sediment discharge from the tributary, Gh: sediment generation by slope failure along the main channnel and Gb: river bed and bank erosion. Pie graphs indicate particle size distributions and percents(%) of particle size classes in figures. Each particle size class is as follows: boulders; more than 300mm, cobbles; 75–300mm, coarse gravel; 19–75mm, medium gravel; 4.75–19mm, fine gravel; 2–4.75mm, sand; 0.075–2mm and silt and clay; less than 0.075mm.

Table 2. Results of supplied sediment volume, quasi-stream power and peak of accumulated sediment volume in both catchments

Sediment pulse	Supplied sediment volume G(m³)	section	Quasi-stream power Ps(×10³m³)	Ps/G	Peak of accumulated sediment volume				Notes
Osatsube Creek	volume as single initial sediment pulse					Travel distance (m)	Peak volume D_P(m³)	D_P/G	
a. Debris flow at the headwater of the main channel	1,820	5200m~6872m	4~40	2~22	1st peak	36	236	0.13	Peaks decreased downstream
					2nd peak	522	179	0.10	
					3rd peak	1,322	160	0.09	
b. Sediment discharge from Tr.21	1,230	3800m~5027m	9~47	7~38	1st peak	0	0	0.00	Peaks decreased after those increased
					2nd peak	377	801	0.65	
					3rd peak	1,177	220	0.18	
c. Slope failure at the 3195m from the river mouth	2,680	2000m~3195m	24~115	9~43	1st peak	0	0	0.00	Peaks increased downstream
					2nd peak	445	121	0.05	
					3rd peak	945	281	0.10	
d. Bank erosion from516m to 676m	7,500	0m~676m	29~53	4~7	1st peak	8	924	0.12	Peaks decreased downstream
					2nd peak	546	620	0.08	
					3rd peak	—	—	—	
Chobonai Creek	total volume as mixed sediment pulses				deposited section		Peak volume D_P(m³)	D_P/G	
Mixed sediment pulses induced by lateral sediment sources	13,370	2006m~3316m	0~16	0~1	Logitudinal deposited section with maximum sediment volume (3000m~3100m)		2,246	0.17	Accoumulated sediment volume concentrated upstream of 9th erosion control dam
Mixed Sediment pulses mostly induced by available sediment along the main channel	8,880	0m~2006m	13~29	1~3	**1)** 1300m~1700m		826	0.09	Mixed sediment pulses accumulated periodicaly along the main channel
					2) 700m~1100m		564	0.06	
					3) 300m~500m		220	0.02	

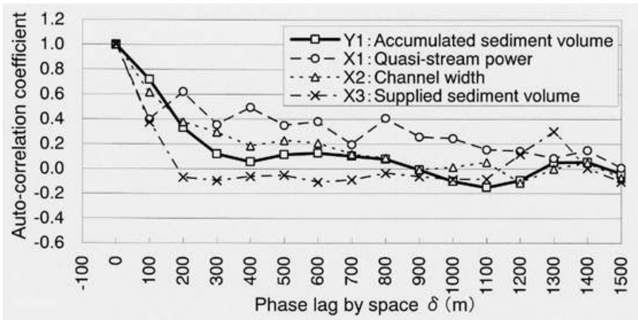

Fig. 6. Auto-correlation coefficient of accumulated sediment volume, quasi-stream power, channel width and supplied sediment volume plotted against phase lag in distance at Osatsube Creek

Cross-correlation analysis between accumulated and supplied sediment volume

The phase lags with the relatively high cross-correlation coefficient in the Osatsube Creek are shown in Fig.8 and Table3. In the figure, the phase lags correspond with the travel distance of each sediment pulse downstream from the sediment sources. Idealized model of the sediment pulse demonstrated by sediment mass curve was shown in Fig.10. By adopting the sediment mass curve in the analyses, the concentration of deposition mass in the sediment delivery process can be emphasized and analyzed although the apex of sediment pulse becomes low or vague at the distant point from the input point or the widely spreading section. In the Chobonai Creek, the phase lags do not directly correspond with the travel distance because several sediment pulses originated from available sediment were at last overlapped (Fig.9, Table3). The phase lags are dominated by the travel distance of the sediment pulses or the wave length of accumulated or supplied sediment volumes. The periodical sediment mass curve in the Chobonai Creek consists of two sediment pulses or more.

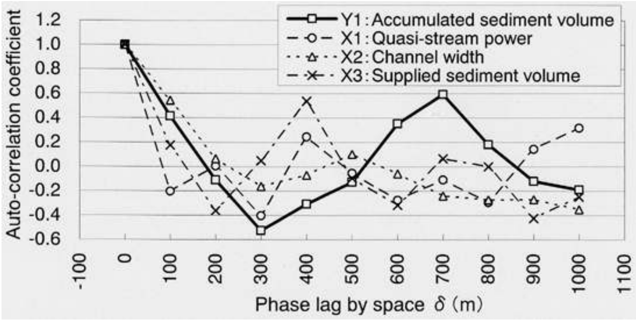

Fig. 7. Auto-correlation coefficient of accumulated sediment volume, quasi-stream power, channel width and supplied sediment volume plotted against phase lag in distance at Chobonai Creek

Table 3. Results of auto-correlation and cross-correlation analyses

Study Catchment	Sediment sources	Wave length analysed by auto-correlation coefficient λ(m)		Phase lag by space with relatively,high cross-correlation coefficient δ (m)		
		Accumelated sediment volume(Y1)	Supplied sediment volume(X3)			
Osatsube Creek	(1)Dabris flow at the headwater of the main channel (2)Slope failure along the main channel (3)Sediment discharge from the tributary	—	—	0～100	400～500	1200～1300
Chobonai Creek	(4)River bed and bank erosion	600～700	300～400	0～300	600	900～1000

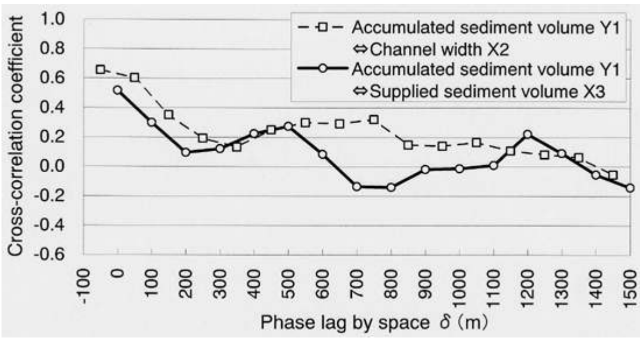

Fig. 8. Cross-correlation coefficient between accumulated and supplied sediment volumes plotted against phase lag distance at Osatsube Creek

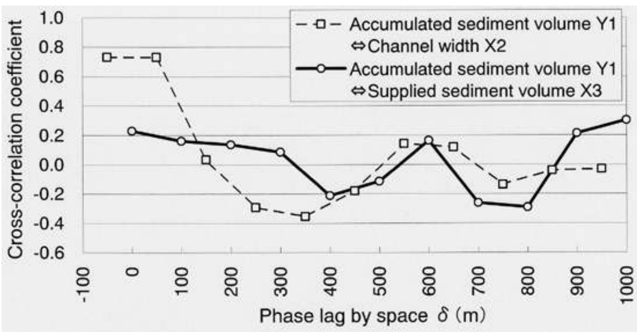

Fig. 9. Cross-correlation coefficient between accumulated and supplied sediment volumes plotted against phase lag distance at Chobonai Creek

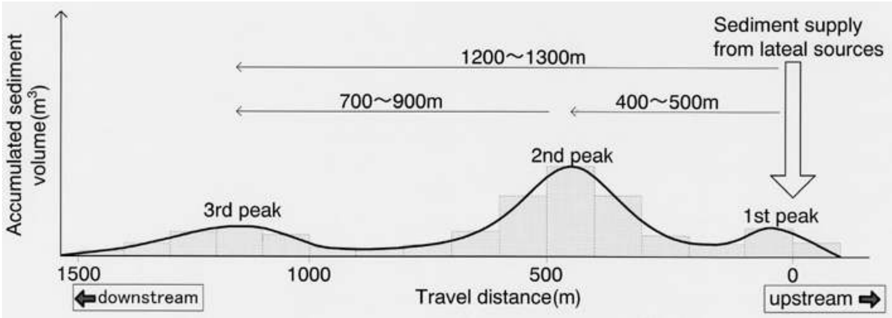

Fig. 10. Idealized model of the sediment pulse demonstrated by sediment mass curve

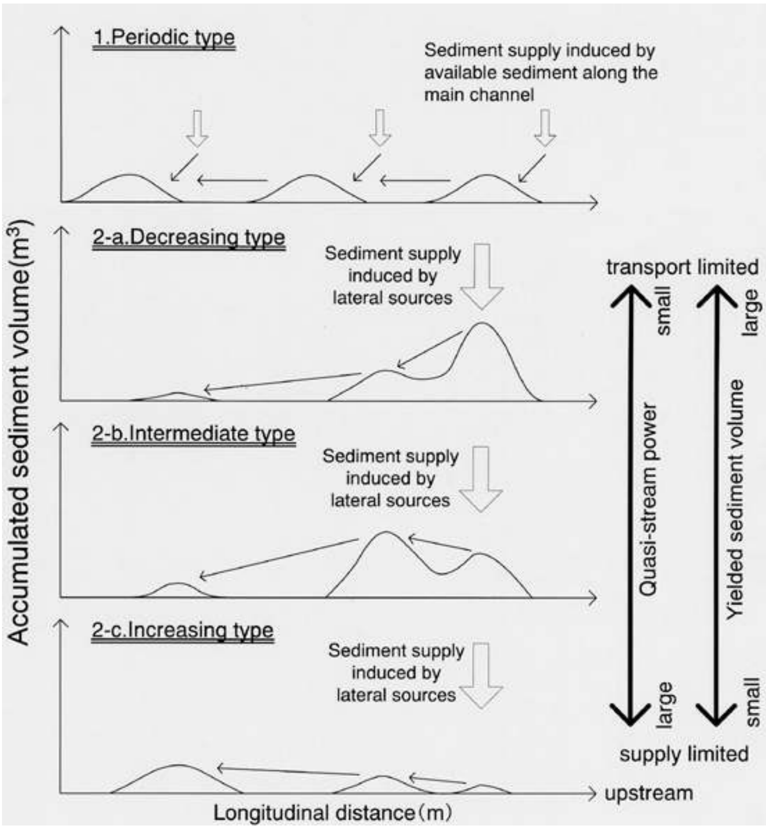

Fig. 11. Classification of sediment pulses demonstrated with sediment mass curve into four patterns, such as decreasing, increasing, intermediate and periodic types

Discussion and conclusion

Classification of sediment pulses demonstrated with sediment mass curve

The sediment mass curves are approximately identified into two patterns (Fig.11). One of them is "the periodic type (**type1**)", in which sediment was originated from available sediment of channel bed and is characterized by the periodical changes in accumulated and supplied sediment volume such as Nakamura's example (1988). It is considered that the characteristics of **type1** indicates the reworking of the sediment pulses which have been stored along the river channel after the initial pulses from lateral sediment sources were supplied into the main channel.

The other is "the initial type (**type2**)" originated from the lateral sediment sources. Considering the height of the peaks in sediment mass curve, initial type (**type2**) is subdivided into the three types: such as decreasing type (**type2-a**), intermediate type (**type2-b**) and increasing type (**type2-c**). Comparing these three types with the ratio (Ps/G) of quasi-stream-power Ps to supplied sediment volume G, Ps/G of **type2-a**,

type2-b and **type2-c** is ranged to 2–22, 7–38 and 9–43, respectively (see Ps/G at Table2). Ps/G implies the balance between the sediment transport capacity and the sediment supply; the large Ps/G indicates supply limited condition and small Ps/G does transport limited condition. The decreasing type (**type2-a**) is observed when Ps/G is relatively small and the height of the first peak becomes high because of the excess of supplied sediment volume (transport limited). The lager Ps/G becomes, the lower the first peak becomes (supply limited), and the sediment mass curve is transformed from decreasing type (**type2-a**) to increasing type (**type2-c**).

Influence of stream power, slope and channel width on sediment mass curve

The longitudinal profile of a sediment pulse in mountain river is approximately expressed in the experiments or the numerical analyses. In those examinations the apex does not move downstream so far from the input point and the thickness of the sediment is thinning to the leading edge. That is to say, the sediment pulse is not translative but dispersive in the case of supercritical flow; Froude number is not less than 1.0 (Lisle *et al.*, 2001). The Osatsube Creek shows locally more than 1/100 bed slope and more than 1.0 (1.0–2.1) in Froude number at the peak discharge, which has been calculated from the flood evidences at the 7 cross-sections. The inference from the hydraulic condition coincides the observation by the field survey of the Osatsube Creek where the sediment pulses from the lateral sediment sources disperse within 1,200–1,600m downstream of the input point.

Meanwhile the sediment pulse was demonstrated as a single curve with increasing and decreasing path, the sediment mass curve derived from the sediment pulse expressed three peaks downstream from sediment source (Fig.11). Such difference as the two interpretations can be understood to be controlled by the change of the topography and the flood hydrograph rather than the travel distance. Under the topographical conditions, such as widely spread channel width or locally gentle bed slope downstream, the sediment mass curve concentrates and the peak of that rose high, because the acceleration of sediment accumulation occurs. On the other hand, increasing stream power initiated from the confluence points induce the sediment mass curve to be dispersed. Changes in discharge can be affected to the particle size distribution. The debris flow deposit at the headwater in the Osatsube Creek was expressed as the first peak of sediment mass curve and the succeeding flood flow with the lower sediment concentration was supposed to have secondarily scoured away the sediment from the debris flow deposition. The particle size (Fig.5 PL.5) of the second peak which was the secondary deposition was becoming finer than that (Fig.5 PL.6) of the first peak.

It is suggested that the characteristics of sediment transport is managed by the wave-like formation after the initial pulse from lateral sediment sources are supplied. Sediment delivery and fining process can be examined using sediment mass curve based on sediment pulse analyses. Identifying which is the main sediment source, the reworking of river bed material or the supply from lateral sediment, is also important for reconstructing sediment budget model.

References

Cui Y., Parkar G., Lisle T.E., Gott J., Hansler-Bal M.E., Pizzuto J.E., Allmendinger N.E., Reed J.M. (2003): Sediment pulses mountain rivers:1. Experiments, Water Resources Research, Vol.39 No.9, p3-1–3-12.

Cui Y., Parkar G. (2005): Numerical model of sediment pulses and sediment-supply disturbances in mountain rivers, Journal of Hydraulic Engineering, Vol.131 No.8, p.646–656.

Gilbert G.K. (1917): Hydraulic mining debris in the Sierra Nevada, U.S. Geological Survey Prof. Paper, Vol.105, 154pp.

Hakodate district public works management office (2003a): The report of the disaster and the unusual sediment discharge (in Osatsube Creek), pp.96. (in Japanese)

Hakodate district public works management office (2003b): The report of the disaster and the unusual sediment discharge (in Chobonai Creek), pp.85. (in Japanese)

Kasai M., Marutani T., Brierley G. (2004): Patterns of sediment slug translation and dispersion following typhoon-induced disturbance, Oyabu Creek, Kyushu, Japan, Earth Surface Processes and Landforms, 29, p.59–76.

Knighton D. (1998): *Fluvial Forms and Processes*, Arnold, pp.106.

Lisle T.E., Cui Y., Parker G., Pizzuto J.E., Dodd A.M. (2001): The dominane of dispersion in the evolution of bed material waves in gravel-bed rivers, Earth Surface Processes and Landforms, 26, p.1409–1420.

Nakamura F. (1988): Chronological analyses in river channel morphology and sediment transport process in mountainous river basins, Reprinted from the Research Bulletins of the College Experiment Forest, Faculty of Agriculture, Hokkaido University, Vol.45 No.2, p.301–369. (in Japanese with English abstract)

Rice S. and Church M. (1998): Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links, Earth Surface Processes and Landforms, 23, p.345–363.

Sutherland D.G., Ball M.H., Hilton S.J. and Lisle T.E. (2002): Evolution of a landslide-induced sediment wave in the Navarro River, California, Geological Society of America Bulletin, Vol.114 No.8, p.1036–1048.