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BUFFER EFFECT OF A WIDE RIVERBED SECTION ON SEDIMENT DISCHARGE

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Introduction

The continuity and periodicity of sediment production and transport processes have been discussed in the field of forest science since the 1950's. Representative concepts are "immunity of a basin" — i. e., "once slope failures, landslides and debris flows have occurred in a basin, the same kind of mass movements would not occur again for a long period of time" — proposed by KOIDE (1955) and "active and dormant rivers" — i. e., "there are two kinds of sediment transport processes in mountain rivers: one is an active river which transports sediment by small floods occurring several times a year, and the other is a dormant river which transports a large amount of sediment by a flood occurring once in several decades or several hundred years" — proposed by KAKI (1958). The word, immunity, was mainly used to express the sediment production characteristics, and active and dormant rivers were used for sediment transport.

Sediment produced by hillslope processes has been accumulated at the foot of a hillside slope and eventually this unstable sediment is scoured away by a successive flood. However, even if heavy rainfall hits a basin, a high magnitude event of sediment movement will not occur when unstable sediment is not accumulated at hillslopes or riverbeds. Sediment transported by a flood is retarded at such storage places as junctions of tributaries, sinuous channel courses and wide sections of riverbed. As well as the intensity of sediment production, the residence time of sediment at these storages and hillside slopes are related with the continuity and periodicity of the sediment transport process.

This paper focuses on a wide section of riverbed and its effects on the rate of sediment discharge. First of all, the actual conditions of the wide section were investigated at two field sites, and then numerical simulations were carried out based on the results of experiments. An important characteristic of mountain rivers is that there is a difference between the volumes of sediment production and potential transport (ASHIDA, 1985, p. 346). The theme of this paper is not to clarify the mechanism of sediment transport process, but to consider how effects of a wide section on sediment discharge are changed depending on the rate of sediment production from hillslopes and the lapse of time until sediment scoured away by a following flood. The existence of bedrock at or below the present riverbed is an important point in this study because it can be a reference point in a mountain river during several hundred years.

Sediment Storage at the Wide Section of a Mountain Riverbed

Field researches were carried out to understand the natural condition of the wide section and to do the dendrochronological analysis on flood-plain deposits. The rivers investigated are the Kaunnai River rising in Mt. Kaun (1954 m) and the Usubetsu River rising in Mt. Kimobetsu (1177 m). The catchment area of the Kaunnai River is about 53 km². The investigated site is located in the middle section of the Kaunnai River, where the river width is extended about 110 m and the riverbed slope is about 5%. The catchment area of the Usubetsu River and the average riverbed slope of the investigated reach are 65 km² and 4%, respectively. River morphology in a wide section of the Kaunnai River showed a braided pattern that meant the frequent shifting of channel courses. Figure 1 shows a riverbed cross-section and riparian forest on flood-plain deposits. The trees established on the deposit form an even-aged forest, with the age indicating the time of year when deposition occurred (Araya, 1971). In general, the variety of sediment ages and diversity of tree species increase in correspondence to the complexity of the river channel morphology (Nakamura 1986 a and Swanson *et al.*, 1986). An interaction between the terrestrial and aquatic systems is frequently observed in a wide section because of channel shifting and flood-plain inundation at high discharge. Most channel migrations in mountain rivers are caused by a large deposition of sediment which results in a complete and sudden abandonment of a part of the river's former course and in adoption of a new channel.

A wide and a narrow sections were chosen from the investigated reach of the Usubetsu River. The lengths of each section is 1.0 km, and the average

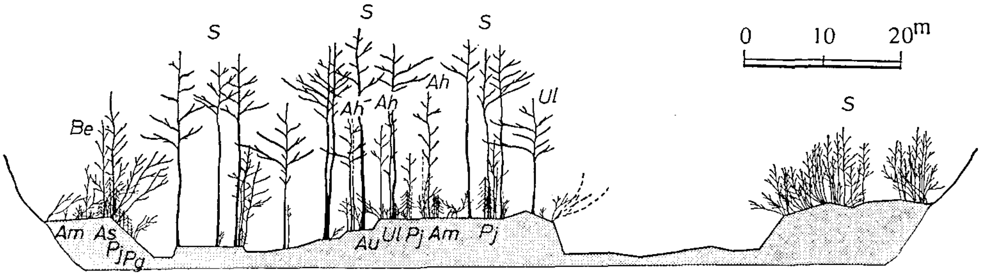

Fig. 1. Cross section of a riverbed with a forest established on the sediment: *Salix* spp. (s) — dominant species forming the upper layer of the forest; *Alnus hirsuta* (Ah), *Ulmus laciniata* (Ul) and *Betula ermanii* (Be) — middle layer; and *Ulmus laciniata*, *Acer mono* (Am) and *Acer ukurunduense* (Au) — lower layer *Abies sachalinensis* (As), *Picea jezoensis* (Pj) and *Picea glehnii* (Pg): Coniferous species which are estimated to have invaded with *Salix* spp. simultaneously.

widths of the wide and narrow sections are 71 m and 23 m, respectively, almost a three times difference in width. Typical parts of both sections are illustrated in Fig. 2.

Curves indicating the age distribution of cumulative sediment volume (cumulative curves) for both the wide and narrow sections were constructed using tree ring analyses of even-aged forests (Fig. 3). As described by NAKAMURA (1986 b), the cumulative curve is separated into right and left portions with a break point,

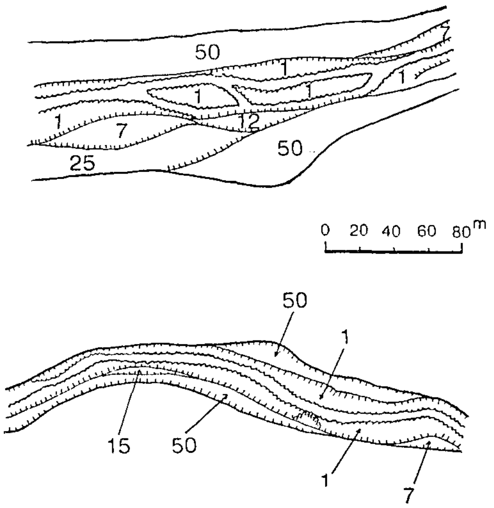

Fig. 2. Plan shapes of the wide (top) and narrow sections (bottom) investigated in the Usubetsu River. Numbers marked on deposits indicate the ages of sediment in year.

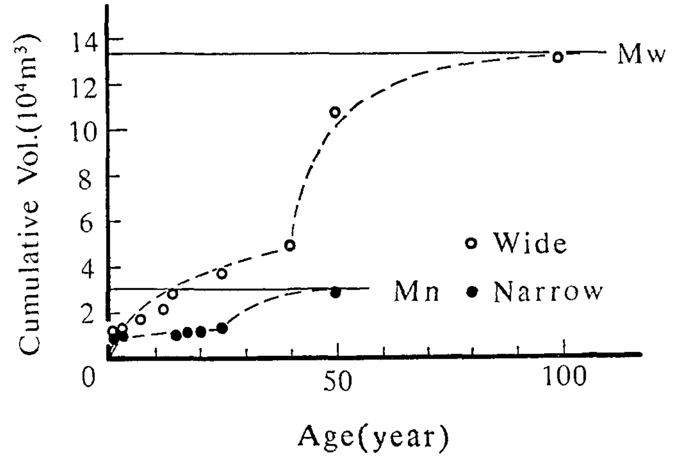

Fig. 3. Cumulative sediment volume versus age. The cumulative volume curves for both the wide and narrow sections were constructed based on the tree ring analyses of even-aged forests on deposits.

respectively representing an occurrence of a high magnitude event, and the sequential sediment movements which have occurred recently. Similar break points were recognized in two sections of the Usubetsu River.

Although the cumulative curves for the wide and narrow sections have similar overall shapes, the upper limit value and the position of the break points differ. A comparison of the cumulative curves suggests a difference in the relationship between the magnitude — represented by cumulative volume — and the frequency — related to age of sediment. For instance, a portion of the sediment which was transported by a large episodic event had remained for approximately 50 years in the narrow section and for 100 years in the wide section — as shown by the maximum age of the residual sediment. In addition to the age of sediment, the upper limits of cumulative volume differs.

Assuming a steady state condition for the left part of the cumulative curve, the residence times for the recent storage process were evaluated using "reservoir theory" (DIETRICH *et al.*, 1982, p. 5-23; NAKAMURA, 1986 b). The residence times, calculated on sediment whose age is equal to or less than the break points, are 7 years in the narrow section and 11 years in the wide section. It was confirmed from the field research results that wide sections influence the sediment transport process by storing a large amount of sediment, resulting in extended residence time; also, these effects may be changed by the relationship between the magnitude of sediment movement and the capacity of the riverbed. This point is further discussed in the latter parts.

Experimental Study

The actual river morphologies in the wide sections are quite complex as described in Figs. 1 and 2. At the present stage, it is too difficult to simulate the complex sediment hydraulics, and therefore, the conditions for experiments and following numerical simulations were simplified. In the experiment, the effects of the wide section, according to changes of sediment discharge rate in a hydraulic event, are discussed. Experiments on the effects of a low-dam series were carried out by the staff of the Civil Engineering Research Institute of the Hokkaido Development Bureau. In the case of one experiment, the width of the lower reach was three times that of the upper reach, without the use of check dams; this condition is appropriate for experimentally determining the effect of a wide section of riverbed. The author borrowed the data on these experiments with the permission of the Institute. The flume used for experiments is illustrated in Fig. 4.

The length and width of the flume in the upper reach are 500 cm and 30 cm, respectively; and in the lower reach, they are 180 cm and 90 cm, respectively. The slopes of the upper and lower flumes can be varied, in the above mentioned case, they were set at 1/10 for the upper reach and 1/30 for the lower reach.

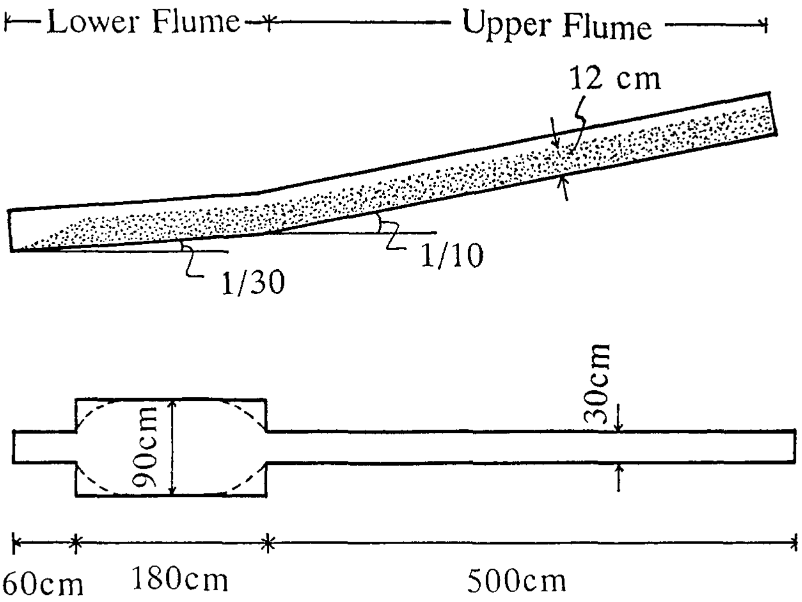

Fig. 4. Experiment flume used for investigating the effects of a wide section. The lower flume is three times wider with a slope one third that of the upper flume. The dashed line shows the width for the numerical simulation.

The water discharge rate was 3.0 ℓ/sec; it was supplied for ten minutes. The bed load material comprised a mixed sediment with maximum, minimum and average sizes of 9.54 mm, 0.1 mm and 1.4 mm, respectively. The thickness of bed load material was 12 cm, and no sediment was supplied from the upper edge of the flume.

In the above case, the bed material was scoured gradually in the upper reach with the flume floor becoming visible at the upper end of the flume. On the other hand, sediment gradually deposited in the lower reach, the width increasing to three times the former. The deformation of the riverbed at one cross section (located 40 cm downstream from the junction of the upper and lower flumes) during the experiment is shown in Fig. 5. The final shape of the riverbed (after 10 minutes) was measured directly, but the deformation of the riverbed during the experiment was indirectly measured using photographs.

The riverbed was gradually aggraded at the above location, reaching a peak three minutes after the beginning. Subsequently, the gradual degradation of the riverbed was coupled with the exposure of the floor of the upper flume. In particular, the central part of the riverbed became scoured, resulting in the depression between the ridges shown in Fig. 5. In mountain rivers, the appearance of bedrock after a flood is observed frequently, as demonstrated in the experiment. This bedrock serves as a lower limit of river degradation over

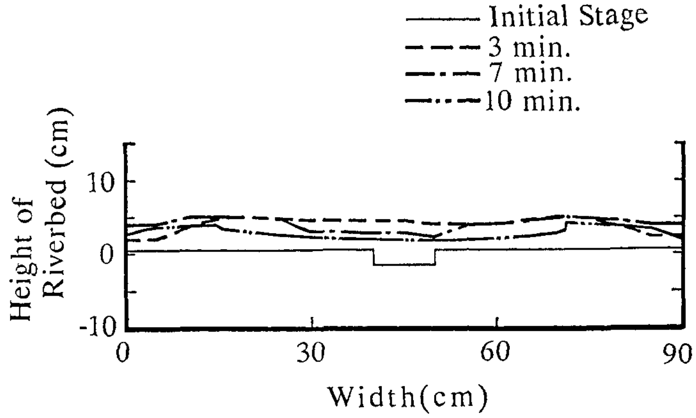

Fig. 5. Cross sections of the riverbed at 40 cm downstream from the junction of flumes. The riverbed was gradually aggraded until it reached about 5 cm above the initial stage; subsequently degradation occurred.

several hundred years. This is quite a different situation from a river flowing through an alluvial fan, because its reference point is the sea level.

In the case studied, the wide section served to store sediment during the period when a large volume of the bed load was being transported (0–3 min.). The same wide section had its sediment flushed out during the period when the bed load being transported had decreased (4–10 min.). Consequently, the sediment discharge was retarded at the wide section, resulting in the peak volumetric rate of sediment transported through the section being lowered.

Numerical simulation

Not only in a short period, as in the above experiment, but it is also important to analyze the effects of a wide section in such a long period as a hundred years during which several tens of floods will occur. To understand the effects in a long time series, the sediment transport is modeled using the following basic equations (FUKUDA and SHIMIZU, 1986):

$$\frac{\partial}{\partial x}(Bhu)=0 \tag{1}$$

$$\frac{\partial z}{\partial x}+\frac{\partial h}{\partial x}+\frac{\partial}{\partial x}\left(\frac{Q^2}{2gB^2h^2}\right)+\frac{n^2Q^2}{B^2h^{10/3}}=0 \tag{2}$$

$$\frac{\partial z}{\partial t}+\frac{1}{(1-\lambda)B}\frac{\partial}{\partial x}(q_B\cdot B)=0 \tag{3}$$

where B, river width; h, average depth of the water flow; u, average flow velocity; z, height of the riverbed from the base level; x, distance from the edge of the upper flume; Q, water discharge; g, acceleration of gravity; t, time; n, Manning's roughness coefficient ; λ, porosity of the bed material ; and q_B, the rate of the bed load transport per unit time and unit width. Equation (1) shows the continuity for water, Eq. (2) is the motion equation, and Eq. (3) shows the continuity for sediment transport. The conditions were simplified by assuming that velocities and depths were uniformly distributed in a cross-section. In general, riverbed material (mixed sediment), tends to become sorted during experiment. In the above case, however, the water discharge was large enough to cause all sizes of bed material to be transported to the lower reach. For this reason, changes in size distribution over time were ignored and calculations were performed in terms of the average diameter, d.

The rate of bed load transport was calculated by a type of MEYER PETER-MULLER equation (MEYER PETER and MULLER, 1948) :

$$q_B/\sqrt{(\sigma/\rho-1)\,gd^3}=\alpha\,(\tau_*-\tau_{*c})^{\beta} \tag{4}$$

where ρ is water density, σ is sediment density, d is the mean diameter of bed material, τ_* is a nondimentional tractive force, τ_{*c} is a nondimentional critical tractive force. Constants α and β were determined to be 40 and 2.1, respectively, from the experiments (FUKUDA and SHIMIZU, 1986). When the river width is abruptly changed, the shadow areas which do not affect the changes of the riverbed are generated. Therefore, the calculation was carried out with the

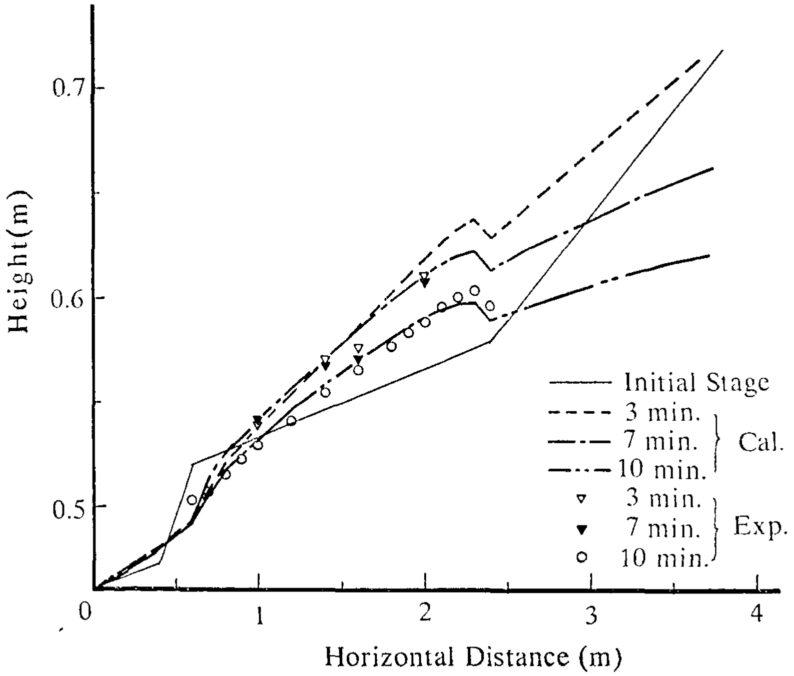

Fig. 6. Changes in longitudinal profile of riverbed — Comparison of the results of experiments and simulations.

channel width gradually widening and gradually contracting as shown by the dashed line of Fig. 4.

The results of the calculation were compared longitudinally with those of the experiment (Fig. 6). As mentioned before, the shape data at 3 and 7 minutes contain estimation (from photographs) errors, while direct measurements were made on the final shape (10 minutes later). The profile calculated by this model indicates that the riverbed had formed the steepest slope 3 to 4 minutes later; subsequently, degradation resulted from the decrease in sediment supply from the upper flume. This tendency approximately corresponds to actual experiment data, and it was determined to analyze the effects of a wide section in a long time series using this model.

Long-term effects of a wide section

The conditions of the numerical simulation were determined by the trial and error method. The water was supplied for five minutes at 2.0 ℓ/sec. The condition of the flume was almost the same as the former experiment, besides the initial slope. The initial slope conditions were 1/20 for both the upper and lower flumes, and the width of the riverbed was 30 cm for the upper flume and 90 cm for the lower flume. The thickness of the bed material was 12 cm initially. The objective of this simulation is to estimate a long-term effect of a wide section on sediment discharge. The total time span of the simulation was assumed to be about one hundred and fifty years and the return period of each water flow was five years. Therefore, the calculation was repeated thirty-one times, including the first flow, with the water discharge being fixed at 2.0 ℓ/sec.

The simulation supposes that the upper flume is the sediment production reach with an annual produce of 0.005 cm of sediment in depth. Consequently, sediment accumulation on the upper flume bed before each flow varied depending on the time interval, ΔT (year), the time lapse between given two adjacent flows. It means that the height of the riverbed before each flow was time-proportionally aggraded with the annual rate of 0.005 cm in the upper flume. The problem is how to determine the recurrence-intervals; in this simulation, ΔT is generated from random digits forming a normal distribution with a mean value and standard deviation of 5.0-years and 3.0-years, respectively. The sediment movements occur once in 5 years in average, but the variations in recurrence caused by the probability distribution alter the initial condition of the sediment accumulation in each flow.

Influx and efflux volume of sediment were chronologically arranged in Fig. 7. Each vertical line in the upper diagram represents the total volume of sediment which flowed into the wide section in one flow. The lower diagram, similarly, shows the total volume which flowed out of the wide section. In three cases, long recurrence-intervals caused influx volumes exceeding a fairly large value of

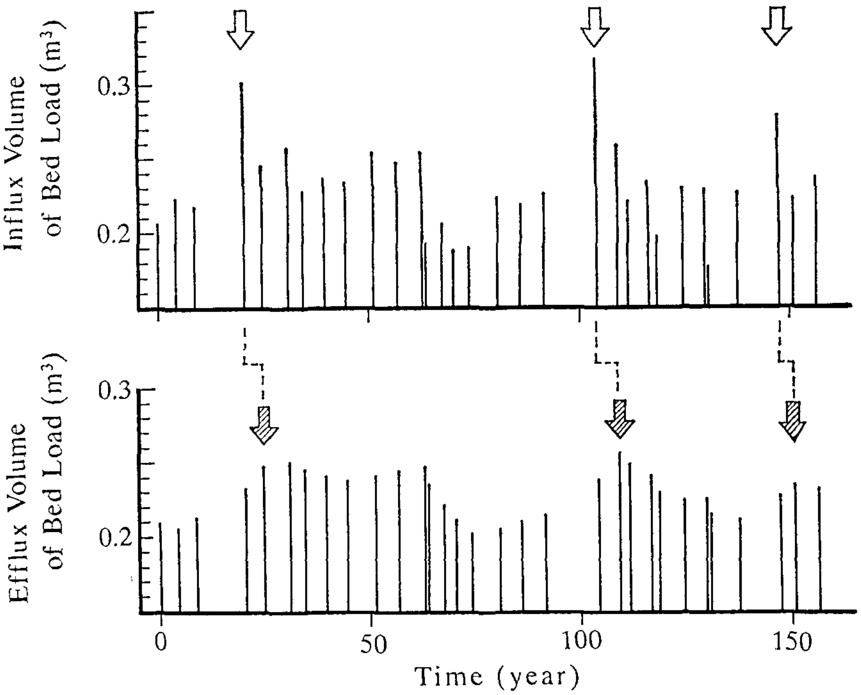

Fig. 7. Effects of a wide section in a long time series according to the numerical simulation. Three major flows — indicated by arrows — were controlled by sediment storage effects, resulting in smaller variances in efflux volume.

0.26 m^3. The efflux volumes corresponding to the above three cases, however, were lowered to less than 0.24 m^3; large amounts of sediment were flushed out in the succeeding flows — shown by arrows. It indicates that the depositional tendency was dominant when the influx rate of sediment was high, with this trend changing to scouring when the transport rate became low. There were five cases in which influx volume did not exceed 0.2 m^3: 64, 70, 74, 118 and 130 years. In these cases, the wide section released previously deposited sediment, resulting in high efflux volume transport rates as shown in the lower diagram. This means a regularizing effect.

A comparative simulation, in which the width of the entire flume was uniform (30 cm), having no widening, was carried out. Conditions of previous simulation other than flume width remained unchanged. Results are shown in Fig. 8. Similar to the case with a wide section, large magnitudes of sediment movement (indicated by arrows) occurred after long time intervals. A large part of the bed load was flushed away without being stored in the uniform section, resulting in higher transport rates of efflux volume in comparison with the wide section case. Because the influences of sediment deposition at the flume junction were gradually extended over the upper flume, the influx volumes were slightly different between

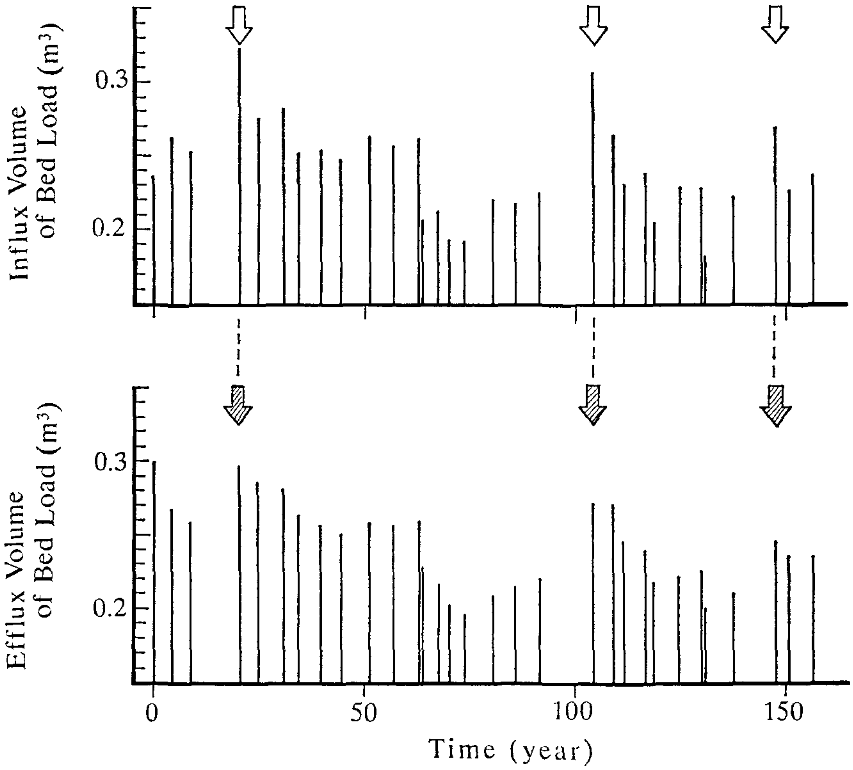

Fig. 8. Numerical simulation results — uniform width over the entire flume. The regularization in sediment transport rates for three major flows were relatively small in comparison with the wide case.

the wide and uniform section cases.

As a criterion of the buffer effect, the decreasing rate of the coefficient of variation between influx and efflux volumes was introduced. The coefficient of variation of influx volumes in the wide section case was 0.132, and that of efflux volume was, as small as, 0.067. In the uniform section case, the coefficient of influx and efflux volumes are 0.132 and 0.116, respectively. Consequently, the buffer effect of the wide section is 1.97, and that of the uniform section is 1.14, that is, almost a two times difference in value. As a result of this effect, maximum volume was lowered from 0.32 m^3 to 0.26 m^3, by passing through the wide section, while it was lowered from 0.32 m^3 to 0.30 m^3 in the uniform case.

There were five flows of bed load movements from 90 to 117 years; the profiles of the riverbed during this period are shown in Fig. 9. The slopes of the riverbed in the wide section were steeper than those in the uniform section because of the reduction of tractive force. The riverbed aggradation at the second flow had formed the steepest slope; subsequently, the riverbed was degraded sequentially by the third to fifth flows. MAITA (1986) investigated the

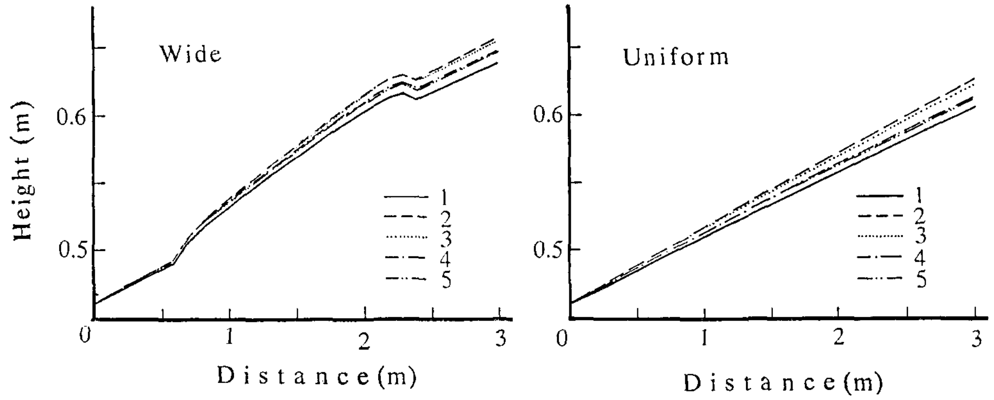

Fig. 9. Changes in riverbed profile. Five flows were chosen — 90 to 117 years — to investigate the conditions of the sequence from river aggradation to degradation. Numbers indicate the order of occurrences, and each profile was calculated after each flow. The zero point in abscissa is the end of the lower flume.

riverbed change in the field, and found that a sediment accumulation caused by a rapid aggradation tends to decrease exponentially through successive floods. Although the longitudinal profiles of the riverbed were different in two cases, the degrees of aggradation and degradation were quite similar in both cases, with the lower end of the reach being the point of reference. However, on the areas generated upstream of the reference point, the wide section is almost three times larger than the uniform section. Consequently, it is a reasonable estimation that the main element which determines the buffer effect is the area formed upstream of the reference point.

Discussion

A continuous survey on the deformation of a riverbed has shown that the riverbed is sometimes degraded and sometimes aggraded ; occurrences seem to alternate over time. The surveying results of the Furano River are shown in Fig. 10. The white and shaded bars indicate the net changes of the cross sectional area, from down- to upstream, in 1980 and in 1981, respectively. Zero level in the diagram shows either no change of riverbed or a balance between the deposited and scoured area. The phases of 1980 and 1981 movements, as shown by the averaging curves, completely changed from scouring to deposition, and vice versa.

The sediment movement in a mountain river is characterized by temporary settling and removal on the riverbed, which results in a temporal alternation of scouring and deposition occurring at the same location. The amplitude of the alternating fluctuation is large in a wide section — especially marked in the deposited volume. Consequently, a temporal storage of a large amount of sedi-

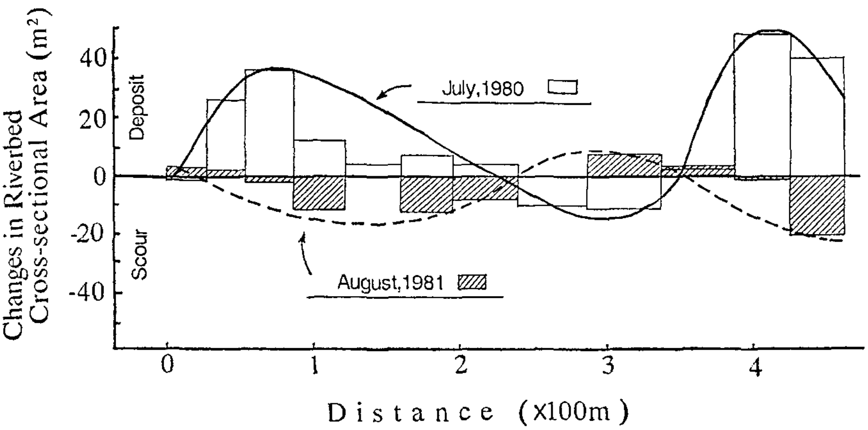

Fig. 10. Changes in riverbed cross-sectional area. The abscissa indicates the distance from the downstream end, and the ordinate indicates the differences of cross-sectional areas before and after the 1980 movement, and the 1981 movement.

ment and a relatively steady efflux to the lower reach lead to a long residence time.

In actual rivers, the transport rate will become low even though the water discharge is recorded at a high level, if unstable sediment has neither been produced from the hillslopes nor has been accumulated on the riverbed. The rates of sediment production, storage and transport are complicatedly correlated in a basin forming a system. A wide section in a mountain river becomes a kind of buffer zone, which reduces variance in sediment transport rates.

Acknowledgments

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Abstract

Sediment storages in a river channel are typically observed at the foot of hillside slopes and where the river morphology changes, such as a sinuous river section, a wide section of river, and a junction with tributaries. This paper focuses on a wide section and its effects on sediment discharge. The actual channel morphology observed in the wide sections were complex due to frequent

channel migrations. The maximum age, total amount, and residence time of flood-plain deposits were evaluated for the wide and narrow sections of the Usubetsu River. This comparison indicated that the wide section has stored a large amount of sediment as flood-plain deposits, which result in a long residence time of sediment.

Experiments and numerical simulations were carried out to estimate the effects of a wide section on sediment discharge in two cases. The first case is assuming a short period of days which contains one peak of discharge, the second case is assuming such a long time as a hundred years during which several tens of floods will occur. An important characteristic of mountain rivers is that there is a difference between the volumes of sediment production and potential transport. In experiments and simulations, therefore, the influx volume was changed according to the conditions of sediment accumulation in the upper production reach. The experiments demonstrated that the wide section served to store sediment when a large volume of bed load was transported, and served to flush it out when transport rate had decreased. The results of simulations, comparing the effects of the wide and uniform sections, showed that the wide section functions as a buffer zone, reducing the variances of sediment discharge and lowering the maximum discharge rate. It was clarified that this buffer effect was determined by the upstream area of reference points created by bedrocks.

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