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ENVIRONMENTAL—
GEOMORPHOLOGICAL
STUDIES ON EROSION
AND DEBRIS TRANSPORT

HIROSHI YAMAMOTO

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

In the humid region, landforms are made by erosion and debris transport due to rainfall and runoff water. The conditions of landforms and their changes are intimately related to the activities of plant, animal and human beings, since their ecosystems are controlled by the ground conditions such as basement rocks, topography and soil (Miyawaki, 1976). Human beings who have been damaged by severe erosion and debris transport brought by torrential floods (Ashida, 1985), always search for a better landuse in harmony with the ground conditions (Ide and Takeuchi, 1985). The prevention of the natural hazards related to erosion and debris transport is, therefore, an important task for the environmental geomorphology. For this purpose, a detailed analysis of the erosion and debris transport in the catchment area gives the fundamental for any prevention works. From this viewpoint, the present study treats with all kinds of slope erosion and debris transport, including mudflows, suspended-sediment flows and gravel transport by saltation. Processes of erosion and sediment transport on slope surfaces and those of gravel transport in channels are separately analysed through field observations and flume experiments.

1.2 Purpose and subject of the study

Generally, sediment transport in a river channel is divided into the following two modes: (1) mechanical transport: in which particle of sediment is transported by mudflow(multi-phase flow), suspension and saltation; and (2) chemical transport: in which materials are flowed in solution (Nomitsu and Seno, 1959; Takayama, 1974).

The purpose of this study is to clarify the principal processes of sediment transport such as mudflow, suspension and saltation. Figure 1-1 shows the purpose and subject of this study. The sediment transport in a channel is mutually related to the water runoff and erosion on slopes in the watershed. These processes are examined in a specific watershed from viewpoint of environmental-geomorphology.

In this study, the research watershed for mudflow is selected at the foot of Mt. Usu, where the ground surface is covered with the unstable thick tephra by the 1977-1978 eruption. The watershed for suspended-sediment transport is chosen in the northern part of Okinawa Island, where the deep red soil composed of fine materials is rapidly eroded on the broadly developed agricultural fields and housing sites.

Sediment transport by saltation usually occurs in the channel in the watershed where the coarse debris are

yielded. However, the direct measurements of saltation movement near the river bed are very difficult. Therefore, the saltation process was analysed in an artificial flume which simulates the channel in the watershed.

The these is composed of five chapters. Following to this introduction, Chapter 2 describes the slope erosion and mudflow occurrence in a watershed at the foot of Mt. Usu. Chapter 3 treats with the suspended sediment transport and the soil erosion processes in two watersheds of Okinawa Island. In Chapter 4, conditions of saltation mode in a flume are described, and the motion of gravel particle in saltation is analysed. Chapter 5 is the last one in which the results are summarized, and the distinction between three modes of sediment transport, mudflow, suspension and saltation is discussed.

CHAPTER 2

EROSION AND DEBRIS TRANSPORT ON SLOPE AND IN CHANNEL IN A WATERSHED AT THE FOOT OF MT. USU, HOKKAIDO

2.1 Introduction

The eruption of volcanos is often followed by new denudational processes, as exemplified by the eruptions of Paricutin, Mexico (Segerstrom, 1960, etc.), Irazu, Costa Rica (Waldron, 1967), Vulcan, New-Guinea (Ollier and Brown, 1971), Yakedake and Sakurajima, Japan (Yamauchi, 1978). On these volcanos, a temporal sequence is reported that the erosion was active for a short period just after the deposition of pyroclastic materials. However, erosion rate and the related sediment transport were not measured for a longer period from the eruption to the period of a decrease of erosion.

The first study area was chosen at the foot of the Usu Volcano, Southern Hokkaido, where the pumice and ash eruptions from 1977 to 1978 resulted in an accelerated erosion and the violent mudflow. The study area for the measurement of erosional processes was selected in the Nishiyama watershed, situating in the north-western slope of the somma of Mt. Usu, where were covered with the thick pumice and ash by the 1977-1978 activity (Figure 2-1). On the south facing slope of the watershed, an experimental slope and a small basin were set up in order to

measure the erosion rate and the surface runoff. On the valley floor, the geomorphic change and mudflow occurrence were surveyed along the channel course.

This chapter summarizes the main results of field observations on the erosion and debris transport in the Nishiyama watershed, which were already reported by the author in several papers such as Kadomura *et al.* (1978), Kadomura *et al.* (1980), Yamamoto (1984), Yamamoto *et al.* (1980), Yamamoto and Imagawa (1983).

2.2 Regional setting

The Nishiyama-gawa river collects the tributaries flowing down the northern slope of Mt. Nishiyama, the summit of which is 538 m a.s.l. It flows down the valley between Mt. Nishiyama and Mt. Konpira, then it change the flow direction northward and drains into the Lake Toya after flowing down the alluvial fan, where develop the Toyako Onsen Spa Town. The geology of the watershed is mainly composed of the somma lava of Mt. Usu.

Figure 2-2 shows the experimental slope and its surroundings. The experimental slope is a convex slope with a horizontal slope length of 110 m, a relative height of 61 m and a width of 25 m. Mean gradient of the upper part is 20 degrees and that of the lower part is 36 degrees. A small experimental watershed is established at the eastern side of the upper slope. Topography of the watershed is shown in Figure 2-3. The watershed

boundary is determined by a micro topography made by rill erosion. Runoff water is measured at the convergence point of rill network. The drainage area is 27.9 m² and the mean gradient is 20 degrees.

Climate of the study area is humid and cool-temperate, with the mean annual temperature of 6-8 °C and the mean annual precipitation of 1200-1400 mm. The minimum monthly temperature is as low as -7 °C in January, and the maximum monthly temperature reaches 21 °C in August. Winter days total 150 from November to March, with 60 ice days from mid-November to mid-February.

Before the 1977-1978 Eruption, most of the slopes were covered with dense natural forest of summer-green broadleaf trees such as Populus maximowiczii, Tilia maximowicziana, Acer mono, Ulmus davidiana var. japonica, etc. (Ito, 1978). Due to the tephra fall accompanied with rain on August 8 and 9 1977, leaves and small stems of the trees were perfectly fallen, leaving only the trunks. The floor plants such as sasa and fern were covered by the tephra.

2.3 Research method

Erosion depth: The erosion-pins, which have 5 mm diameter, and 65 cm length, were used to obtain data of ground lowering. Totally 65 erosion-pins were installed perpendicular to the ground surface in a grid system with

an interval of 10 m in the longitudinal direction, and with an interval of 5 m in the transverse direction. Measurement sites are shown in Figure 2-2. The erosion depth was obtained by the repeated measurement of the exposed length of erosion-pins from October 1977 to September 1982. The measurement was made by slide calipers.

Creep movement: The subsurface movement of tephra was surveyed by the Young-pit method improved by Ishii (1976). Dislocation of pins inserted into tephra layers and buried soil was measured at four sites :a, b, c, and d shown in Figure 2-2.

Rainfall: Rainfall amount was measured at a point 40 m south of the experimental slope from May 1978 to Dec. 1979, and at the upper part of the slope, from March 1980 to Aug. 1982.

Physical properties of tephra and transported sediment: Grain size distribution, water content, porosity, hydraulic conductivity, and pF water curve were measured in the laboratory. Measurement methods, sampling points, sampled tephra layer and sampling volume are summarized in Table 2-1. Infiltration volume was also measured by a cylinder method on a flat ground near the experimental slope.

Runoff water: Water from a small watershed was collected in 1977 and 1979, from the 1st layer, the 3rd layer, and the buried-soil layer by a inlet mouth with 50 cm wide and 5 cm high(Figure 2-3). Water amount was meas-

ured by a tipping bucket method. The inlet mouth was set in the tephra layer.

Geomorphic change of valley floor: Landforms along the valley floor were mapped at a scale of 1:1,000 by a plane tabling at an interval of two to three months from October 1977. Processes of temporal geomorphic change of the valley floor were obtained from the maps. Changes of the ground surface level along the valley floor were surveyed by the Laboratory of Civil Engineering, Hokkaido Development Bureau.

2.4 Deposition of tephra and its physical properties

The 1977-1978 activity of Usu Volcano is divided into two stages: the First Stage eruptions, which includes four large eruptions, lasted for one week from August 7 to 14, 1977 (Katsui et al., 1978); and the Second Stage eruptions, which are characterized by the phreatic explosions in November 1977 and by the phreatomagmatic and magmatic eruptions occurred in August and September 1978. Then the eruptive activity stopped in October 1978 (Niida et al., 1980).

Typical columnar sections of tephra deposit in the Nishiyama watershed are shown in Figure 2-4 and Photo 2-1. The tephra deposit is derived stratigraphically by the eruption units from the lower to the upper: US-1977-II erupted on August 8, US-1977-III on August 8 and 9, ash

on August 12, and fine ash by the phreato-magmaphreatic eruptions from March to October 1978. Mean depth of the tephra is 60 cm on the experimental slope, and 80 cm in the upper reach of R. Nishiyama. The total amount of the tephra deposits is $4.2 \times 10^5 \text{ m}^3$.

The two large eruptions of August 8 and 9, 1977 occurred during the rainfall, in which the fine ash was fallen after the deposition of coarse pumice. Then two cycles of stratified structure were formed in the tephra deposit. On the basis of the grain size distribution and materials, the tephra of these two large eruptions is subdivided into four layers from the upper to the lower: the 1st, 2nd, 3rd, and 4th layers. Grain size distribution of each layer is shown in Figure 2-4. The 1st and 3rd layers are mainly composed of ash. Mean diameter of the ash-rich layers is around 0.5 - 1.1 mm, while that of the pumice-rich 2nd and 4th layers is 3 - 4 mm.

Variation of tephra depth is small on the flat ground, but not on the slope. Cross sections of tephra deposits on the experimental slope are shown in Figure 2-5. Total depth of tephra is about 60 cm on the top of slope. Tephra depth is generally thin on the upper and convex slope, while it is thick on the lower and concave one. On the cliff and steep slope, the depth is only few centimetre. This shows the redistribution of tephra at the fall.

Physical properties of each tephra layer sampled in August and October, 1978 are shown in Table 2-2. Grain

size and porosity of the ash-rich 1st and 3rd layers are smaller than those of the pumice-rich 2nd and 4th layers. They show, therefore, different permeability and retentivity. Hydraulic conductivity of the pumice-rich layers is higher than 0.6 cm/sec. That of the ash-rich layers is in the order of 10^{-2} cm/sec or less. Ash-rich layers hold more water than the pumice-rich ones in high pF condition.

2.5 Erosion on the slope

2.5.1 Outline of erosion

Rainfalls which occurred immediately after the deposition of the tephra in August 1977, started a channel erosion, which formed rill and gully on slopes. Rill and gully are defined as follows (see Photo 2-2): rill is a channel which dissects the surface ash layer; gully is a larger one which erodes the 2nd pumice or lower layers. Rill begins at 1 m below the local divide.

Temporal change of erosion after October 1977 at the experimental slope is shown in Figure 2-6. The figure indicates the depth of ash, cumulative mean depth of erosion, freeze-thaw days and rainfall intensity. Change of erosion and deposition is as follows: (1) repeated ash-falls from the set up of pins to early August 1978, caused the deposition. Especially those on August 12 and

13 covered the ground surface with a depth of 38 mm; (2) after the middle of August, when ash fall stopped, erosion greatly proceeded and continued to the end of 1979. Mean erosion depth from August 13, 1978 to December 1979 was 66 mm, which equals to the annual mean erosion depth, 54 mm/yr; and (3) since 1980, the erosion was ceased.

Microtopography at the pin site is divided into the following five types: 1) convex slope of inter-rill area, 2) straight slope of inter-rill area, 3) concave slope of inter-rill area, 4) rill channel and 5) surface slide.

Figure 2-7 illustrates an annual change of their relative portion to the total area: site of rill channel increased in the period between the pin installation time and the autumn of 1978. Within that period, the area of water erosion extended. From winter 1978 to spring 1979, surface slides occurred. By the increase of rill and surface slide sites, inter-rill sites decreased between 1978 and 1979. Nevertheless, after the autumn 1979, the rill site inversely decreased, and the water erosion became inactive.

2.5.2 Erosion by rainwater and its relating factors

Sequence of erosion: Figure 2-8 shows a temporal change of mean cumulative erosion depth for each group of micro landform. From October 1977 to the first third of September 1978, the erosion is active on inter-rill slope, while the deposition occurred in rill. This means that

the eroded tephra from inter-rill area deposited in rill floor.

After the watershed was covered by fine ash with a depth of 38 mm, the erosion was accelerated by rain-water, and the erosion depth attained to 32-34 mm in the inter-rill area by November 1978, and to 56 mm in the rill area. During this period, micro rills were formed on the inter-rill slope, and three sites in the concave inter-rill slope changed to rill channel. In the gully, the erosion depth reached over 20 cm. Totally five erosion pins on the gully floor and talus site were flowed out from the slope. All of the sites on the slope were eroded in this period.

From November 1978 to December 1979, 8 to 12 mm of erosion occurred on the inter-rill slope. On the contrary, 13 mm of tephra deposited in rill channel. After 1980, no notable change occurred both on the inter-rill slope and rill channel.

The erosion after September 1978 was very active at first, and then ceased. The erosion sequence is therefore divided into two periods: the first period is from September to November 1978, and the second one, from November 1978 to December 1979. The relating factors on erosion are discussed below and erosion processes are synthesized.

Landform: Slope length from local divide to pin site and slope gradient at a pin site were measured. The

relationships between these landform conditions and the erosion depth are shown in Figures 2-9 and 2-10. In the first period, the erosion depth increases with the increase of slope length and gradient both on the inter-rill area and rill channel. In this period micro rills were formed on inter-rill area. It means that channel erosion became active.

In the second period, the erosion depth on inter-rill slope increases with the increase of gradient, but does not increase with the increase of slope length. This suggests that the surface erosion mainly occurred by raindrop action, because the erosive action by surface runoff usually increases downslope. As for rill sites, the erosion depth does not show a clear increase with the increase of slope length and gradient. Even the deposition occurred at some sites. This fact is explained by the exposure of highly permeable pumice layer on the rill floor. Since the rain water was infiltrated into the pumice layer, the erosive force of surface runoff in rill channel became small.

Physical properties of tephra: Temporal changes of in porosity the first layer, saturated hydraulic conductivity, and cumulative infiltration depth for 10 minutes are shown in Figure 2-11. Just after the deposition of ash, the porosity of surface layer decreased at first, but increased to 57 % in August 1980.

After this, no great change occurred. Saturated hydraulic conductivity and cumulative infiltration depth

also annually increased. Saturated hydraulic conductivity was in the order of 10^{-5} cm/sec in October 1978 (Kono and Tohma, 1979), and became 7.5×10^{-3} cm/sec in September 1982. These changes on conductivity and porosity were derived from the increase of large pore; it was observed that the porosity increase was the result of the removal of fine particles into the lower pumice layer. Soluted constituents also removed from the tephra layer.

Relation of rainfall and surface runoff: Two examples of discharge hydrograph observed in 1979 and 1981 are shown in Figure 2-12, in which rainfall and discharge are shown as the intensity of 10 minutes. On October 19, 1979, the surface runoff started after the antecedent rainfall of 11.5 mm. Runoff water over 0.2 mm was derived by the rainfall over 2 mm. On August 23, 1981, most of the runoff occurred with the rainfall over 5 mm/10min and the quantity of runoff water was 0.1-0.2 mm/10 min.

Surface runoff ratios for the storm rainfall defined as the continuous rainfall without no-rainfall period for 3 hours, are 0.54-7.3 % in 1979 and 0.2-1.0 % in 1981. Annually, the surface runoff occurrences decreased. In 1982 the surface runoff was not observed, because most of rainfalls were weak, with the intensity below 3 mm/10min except for one with the intensity of 5.5 mm/10min.

The relationships between the rainfall and the surface runoff for 1979 and 1981 are shown in Figure 2-13. Although the plots are scattered, it is shown that

the higher intensity of rainfall is necessary for the occurrence of surface runoff. When the initial water content is in the saturated condition, a linear relationship between the rainfall and the runoff is recognized. For the runoff on October 19, 1979, the relationship is given by the equation

$$q=0.0794(r-0.245), \quad (1)$$

where q is the surface runoff intensity, in mm/10min, and r is the rainfall intensity, in mm/10min.

Also for the runoff over 2.5 mm/10min on August 23, 1981, it is

$$q=0.0286(r-1.69). \quad (2)$$

When the surface runoff was initiated on the inter-rill slope, the second term in the parenthesis in the equations is approximated to the final infiltration rate. The values are annually increasing. This tendency coincides with the increase both of the hydraulic conductivity and of the field infiltration rate. The coefficient of the parenthesis in the equations indicates the ratio of surface runoff. If all of runoff water from inter-rill area are drained, the surface runoff ratio approaches to 1. Nevertheless, the runoff ratio is less than 10 %. This fact shows that the water from inter-rill slope was infiltrated into rill floor, and the surface runoff water was restricted near the inlet mouth. The surface ratio measured in the watershed after 1979 was fairly low compared with that of Mt. Yakedake: 20-60 % (Okuda et al., 1979). Nevertheless, in late September 1978 the

surface runoff ratio was high, because the permeability of the surface ash layer was low, and the rill channels were buried or undeveloped.

Erosion processes: The erosion processes caused by rain water after September 1978 are summarized as follows:

(1) In the first period, from September 13 to November 1978, the surface runoff occurred on most of the slope, and the channel erosion in rill and gully increased by the heavy rainfall, because of the coverage with new ash layer and its low permeability with the order of 10^{-5} cm/sec.

(2) In the second period, from November 1978 to December 1979, only the channel erosion decreased and the sheet erosion by raindrop and surface flow occurred. Sediments transported from inter-rill slope were deposited on the rill floor due to the decrease of rill flow caused by a high infiltration of pumicious tephra layer.

(3) After 1980, the erosion on the inter-rill area ceased due to the decrease of surface runoff caused by the increase of permeability. The change of rill channel did not occur, because of the stop of water and sediment supply from inter-rill slope.

2.5.3 Surface landslide and creep movement

On the snow-melt season of 1979, small surface

slides occurred in 14 sites around the middle knick point and the lower steep portion (Figure 2-2).

The surface slides were located on the straight slope of inter-rill area. Most of the inter-rill area is in plan concave slope. Slope gradient of the slides ranges between 30 degrees and 45 degrees. Pumice and ash over the second layer slid to the lower slope. Mean depth of the slides is 16 cm. Length and width of the slides were both several meters. One of the surface slides occurred at the creep measurement site d, where two measurement pins installed into the tephra layer slid away.

Figure 2-14 illustrates a creep movement by the displacement of pin position at four sites. Slope angle and columnar section of tephra are also shown in this figure. The displacement parallel to the slope was large at the upper pumice layer in the warm season: May, August, and November, 1978. The movement was large at site b, and a reverse displacement occurred at site a, which is situated on the divide. In the melting season in May, 1979, each site turned back of 1-2 cm upslope compared from the point measured in the last autumn. This retrogression was large in the layers above the second layer.

The upward displacement perpendicular to the slope was 1-3 cm in the warm season at the upper slope sites and the downward displacement was less than 1 cm at the lower one. In the snow-melting season of 1979, all pins buried within 30 cm deep moved 2-4 cm upward. As the

depth of soil freezing was 35 cm in that winter, the third layer was still freezing in the snow-melting season. Therefore the upward displacement seems to have been caused by frost heaving.

The processes of surface slide are closely related to frost action. The displacement by the frost heaving reduces the bond between pumice particles and weakens the shear strength. Furthermore, pumice particles are easily frost-shattered due to a high porosity. Fukuda (1981) showed from the experiment that the pumice particles erupted in 1977 were shattered into finer particles up to 80 % in weight ratio after the 80 cycles of freezing and thawing. On the experiment slope, it is observed that the pumice particles of the second layer were shattered during the two winters of 1978 and 1979. This caused a decrease of shear strength in the pumiceous layer.

Figure 2-15 shows a water content of tephra layers from 1978 to 1980. In the warm season, water content was variable in the 1st layer, while it was mostly constant in the lower ones. In the snow-melting season of 1979, tephra layers above the frozen part had a high water content because of the thawing of the frozen tephra and the snow melting. On May 31, the water within the 1st and 2nd layers was in the condition of gravity water, judging from the transformation through water characteristic curve. Such water likely flowed along the upper surface of the frozen layer.

As the most of the slides were located on the plan concave slope, the snow-melting and thawing water seems to have concentrated at the sites of surface slide. This water concentration decreases the shear strength, as resulted in the surface slide.

2.6 Mudflow occurrence on valley floor

2.6.1 Change of valley floor and mudflow occurrence

Geomorphic changes along the main valley floor from August 1977 to May 1979 are shown in Figure 2-16. Just after the deposition of tephra in August 1977, the gully erosion and the pumice removal occurred discontinuously along the valley floor with the rainfalls. After that, any active geomorphic changes did not appear from October 1977 to the spring 1978.

After the snow-melt in 1978, the pumiceous deposits accumulated on the valley floor began to move about several tens meters by every rainfall. They formed a tongue-shaped flow mound. The uppermost part was consisted of a pumice rich layer of a few centimeters. The movement of the mound was very slow, and no water was observed at the surface. The pumiceous material of the mound seems to have been soaked by rainwater. This type of the movement can be regarded as a slow mass movement. Transported sediment by one removal was 5-10 m³.

By the early September, 1979, mudflows from tributaries reached the main channel. Along the main channel, gully erosion and downcutting of the valley floor were activated (Figures 2.16 b and c). Nevertheless, the occurrence of sediment transport was restricted within the valley floor.

On September 26, a mudflow went down the valley floor (Photo 2-3) and reached at the point which was only 90 m from the shore of the Lake Toya. At the steep reach of main valley, deposits of new tephra were eroded away, and the somma lava block was exposed by the downcutting. Along the channel bank, landslides of the upper tephra layers occurred due to the downcutting of the valley floor.

On October 16 and 24, large-scale mudflows, which flowed into the Lake Toya, took place. At the same time, valley floor was intensively downcutted and landslides along the main valley were enlarged. In the gullies cut on the steep slopes, new tephra was eroded and the former soil was exposed. Level change of the valley floor exceeded 2 m. Large amount of debris deposited at the gentle segment of valley floor with a gradient below 11 degrees. Nevertheless, in 1979 and after, no mudflow occurred within the upper watershed. It is largely because of the completion of an intensive sabo works.

Temporal changes of rainfall in three mudflows and the occurrence of mudflows are shown in Figure 2-17. Each mudflow passed the sabo dam situating at the valley

mouth just after the rainfall with maximum 10-minute intensity. The maximum 10-minute intensity was 5.0 mm on September 26, and 6.5 mm on October 16. Although the values on September 26 and October 16 were not so big, these maximum 10-minute intensities exceeded the surface infiltration intensity. The rain water, which could not infiltrate into tephra layers, started rill and gully erosion and concentrated into valley floor to generate mudflows.

2.6.2 Properties of mudflow deposits

Mudflow deposits were subdivided into two layers: the lower mixed layer, which was composed of the mixture of pumice and ash, and the upper pumiceous layer, which covered the surface of mudflow. The mudflow materials were mainly derived from new tephra. Longitudinal variations in grain density, mean grain size, silt-clay ratio, and sorting ratio of mudflow are shown in Fig. 2-18. Mean grain density of the deposits flowed on September 26 and October 24 was 1.99 and 2.20, respectively. Its longitudinal variation was small: range of variation was 0.21 and 0.14. Mean grain size decreased along the flow path downstream. This tendency was derived from the increase of fine particles less than silt size. Judging from these characteristics, flow condition remained almost the same along the flow path.

Properties of mudflow deposits were temporally changed. The later mudflow increased solid volume and grain density. The mudflow deposits transported in August-early September had coarse particles mainly composed of pumice. However, the grain size of the mudflow became finer due to the incorporation and mixture of finer tephra layers, as shown in the triangular diagram of Figure 2-19.

2.6.3 Sediment budget and sediment concentration of mudflow

Sediment budget: Volume of erosion and deposition in the Upper Nishiyama watershed from September to October 1978 is shown in Table 2-3. Sediment removal along the main valley floor was calculated by the product of areal change of cross section and the segment length (20 m). The volume of the eroded material was 3,300 m³ and the volume of deposition was 11,800 m³. Net change was 8,500 m³ in deposition. Most of this volume was deposited at the checkdams which were constructed at the interval of 30-50 m before the mudflow occurrence.

In the tributaries, active incision as deep as 4-5 m was promoted by the mudflow occurrence. Volume of erosion from these tributaries was 45,000 m³, which was estimated by Yamaoka *et al.* (1979) from the measurements of longitudinal profile. However, on the basis of the measurement on experiment slope, the amount of eroded

volume on slope was calculated as 21,000 m³ from crest and inter-rill slope, 18,000 m³ from rill and 39,000 m³ from gully.

Sediment concentration: Surface runoff, sediment volume and sediment concentration for the mudflows which went down to the alluvial fan from the Upper Nishiyama watershed are shown in Table 2-4. Sediment volume deposited on valley flat and alluvial fan on August 26 was 1,200 m³. The mudflow on October 16 showed the mixture of pumice and logs with the muddy water, but had no distinct rise of mudflow.

From an 8-mm movie film taken at the 150 m point from the lake shore, surface velocity of the flow was measured as 3-4 m/s. According to the eyewitness's account, the mudflow on October 24 rushed down the valley and the velocity was 8-10 m/s. The peak discharge was estimated as 110 m³/s (Yamaoka *et al.*, 1979). Sediment volume flowed down on October 16 and 24 was 17,200 m³ and 103,000 m³, respectively. The total volume flowed by three mudflows is estimated as 121,400 m³. Therefore, 25 % of tephra in the Upper reach of the Nishiyama, where the amount of tephra fall was 4.8×10^5 m³, flowed out by the mudflows from August to October, 1978.

Surface runoff and sediment concentration are estimated as follows: judging from the condition of ground surface and flash flood, surface runoff can be regarded as Horton's overland flow, since Horton's flow occurs when rainfall intensity is so high that not all the water

can infiltrate. The volume of the surface runoff is calculated from the rainfall amount subtracted by the infiltration capacity. Mudflow was formed by erosion and transport of tephra on the slope and valley floor at the same time of the surface runoff generation. Therefore, the volume concentration of sediment within the mudflow is calculated from the equation:

$$cv = Rs / (Rp + Rs)$$

where Rs is the amount of transported sediment, and Rp is the amount of surface runoff.

Although the sediment concentration of mudflow which occurred on Sept. 26 is 0.29, that of October 16 and 24 is 0.82 and 0.89 respectively. Such a high concentration of sediment distinguishes the mudflow from any other modes of sediment transport.

2.7 Conclusions

In the Nishiyama watershed, thickly covered with pyroclastic materials mainly composed of pumice and ash due to the 1977-1978 eruption of Mt. Usu, the slope erosion and mudflow transport were surveyed. Slope erosion began within two months after the deposition of ash on September 12 and 13, 1978. Rill and gully erosion were ceased due to a high infiltration of a pumiceous layer which was exposed on the floor of rill and gully channel. Inter-rill erosion was ceased one year later

by a decrease of surface runoff due to an increase of permeability in the surface ash layer. Tephra layers which were upheaved during the freezing period, caused surface slides in the melting season on the lower slope.

On the valley floor, large-scale mudflows occurred three times within the period from September to October 1978. Preceding the mudflow occurrence, the slopes were thickly covered with fine ash, and the unstable sediments accumulated on the valley floor moved downstream by slow mass movement. The mudflows were triggered by the rainfalls with the intensity of over 5-6 mm/10min. The velocities of the mudflows were 3 m/s and 8-10 m/s on the alluvial fan. Sediment concentration exceeded 0.8 for the mudflows occurred in October 1978. Such a high volume of sediment concentration distinguishes the mudflow from any other modes of sediment transport.

CHAPTER 3

EROSION AND SUSPENDED-SEDIMENT TRANSPORT IN THE WATERSHEDS IN THE NORTHERN PART OF OKINAWA ISLANDS

3.1 Introduction

Since the late 1960's, the exploitation of pinery has been introduced on mountain slopes in the Northern part of Okinawa Island. Formerly, these areas were covered by woodland and paddy field which occupied the lower reaches of watersheds. For the pinery exploitation, mountain slope was cut by bulldozers, and the wet lowland was reclaimed. From the late 1970's, the land transformation for the construction of villa and housing sites newly started, also by using the heavy machinery in large areas of Okinawa.

These artificial transformations of the land brought about a severe soil erosion which was provoked by a remarkable change of land use. Most of the eroded sediments supplied from the bare land were transported rapidly to the sea as suspended load. The suspended sediment caused a silting problem in the lagoons of a coral reef coast. In order to prevent the environmental deterioration, it is necessary to clarify the processes both of erosion on bare land and of sediment transport in channels in the watershed.

Actions of raindrop, overland flow on inter-rill

area and channel flow in rill are the main processes which induce the soil erosion (Meyer, et al., 1975; Kirkby, 1980). Studies to make clear each process were conducted by Mihara (1951), Meyer and Monke (1965), Kashiwaya (1980) and others. Eroded soil particles are transported from the source area through the stream channels with various scales to the sea. Although the suspended-sediment transport processes were analysed by many researchers (eg. Straub, 1932; Campbell and Bauder, 1940), most of studies were done only at one point in a watershed. The relation between these processes and the total sediment transport from the watershed has never been clarified.

The purpose of this study is (1) to make clear the erosion processes on inter-rill area and in rill, and (2) to investigate the processes of suspended-sediment transport in a different scales of streams. For the first purpose, the erosion rates on inter-rill area and in rill were measured in the Sanchina watershed. The area is shown in Figure 3-1. As for the second, the study streams for suspended-sediment transport were selected in the Sanchina and the Higashi-Yabu watersheds, which are shown in Figures 3-1 and 3-2.

3.2 Regional setting

The Sanchina watershed: The Sanchina drains the

hilly land and flows to the East China Sea (Figure 3-1). The surface area totals 0.98 km². The climate of the area is humid subtropical with mean annual rainfall of about 2,800 mm, permitting the growth of dense lucidophyllous forests.

The bedrock geology of the watershed is phyllite and green schist of Mesozoic age. These rocks are deeply weathered to the depth of 20-30 m under a gently sloping land surface of 180-250 m above sea-level. The landforms are the remnants of the marine terraces consisting of the Pleistocene deposits (Hanzawa, 1935). Red-yellowish soil with gleyed A horizon develops on the terrace surface. The gleyed A horizon overlain by a thick Ao horizon, is formed by breaching under the moist dense forest (Kurotori and Kojima, 1969). The B horizon contains over 60 % of clay.

Since April 1972, 13.9% of the forest in the watershed has been cleared for the purpose of villa construction. The clearance was achieved mostly on the gently sloping land-surface. After the forest clearance, the superficial Pleistocene deposits and weathering mantle were removed by bulldozers. These man-made bare land suffered an artificial truncation of soil profile, where the B and C horizon of soil is exposed on the ground surface.

The Higashi-Yabu watershed : The Higashi-Yabu is situated in the north of Nago city as shown in Figure 3-

2. The study area is the upper reach of Higashi-Yabu, upstream from the Shirokane bridge, which is site 1 in Figures 3-2 and 3-3. The surface area totals 4 km². At 260 m upstream from the Shirokane bridge, the Bimata, a tributary river, joins to the main one. Both are the fifth-order stream ordered in the map of 1: 5,000 scale.

The bedrock of the watershed is phyllite, which is weathered deeply of more than 30 m. Gentle slope, which spreads in the upper reaches of the watershed, is covered with gravel layers of a few metres in thickness. A marsh occupies the lowland along the main stream of Higashi-Yabu. It was formerly used as a paddy field. Cultivation of rice was abandoned after the introduction of pineapple plantation. On the floods, the lowland is inundated to a depth of 1 to 2 m. A stream of the Bimata incises the weathered phyllite, with a steep slope at the both sides.

The mean annual rainfall measured at a meteorological observatory 900 m away from this basin is 2,400 mm.

Soils are classified into three groups: upland reddish soil, hillside yellowish soil, and depositional lowland soil. The reddish soil with gleyed A horizon develops on a gently sloping land surface, where pineapple and sugercane fields spread broadly. Strong human impacts cause the destruction of soil horizons, and the serious soil erosion.

Most of the soils in this basin were truncated and

new parent materials were added by the human intervention. Bambusa glaucescens community and Miscanthus sinensis community occupy the abandoned areas in pineapple fields and on road cuttings. These are the areas which experienced a large-scale land-transformation 5-15 years ago. The A horizon was taken out of these areas by soil erosion. On the ground surface of the cultivated pinery, B and BC horizons of the reddish soil are exposed.

3. 3 Research method

Hillslope erosion : Figure 3-4 illustrates schematically the landforms developing on bare land. Rill is defined as a shallow channel continuously connecting from upslope to downslope. This figure shows a second-order rill watershed, which is ordered by Strahler's (1952) method. The bare land area except for rill channel is defined as inter-rill area which is also divided into segments of the 1st, 2nd and 3rd orders: The location and gradient at any points on the segment divide are given by a divide segment length L_i and the divide segment gradient S_i , as defined by Tokunaga (1984). A rill form is expressed by a total rill length TL , the gradient of rill bed S_r , and the rill drainage area A . Cross sectional form of rill is expressed by rill width W_r , rill perimeter length P_r and cross sectional area of rill C_r . Overland flow on inter-rill area is called as the inter-

rill flow, and that on rill, the rill flow.

Erosion rate is defined as the erosion depth divided by the measurement period. Erosion depth on the inter-rill, which is expressed as the ground lowering in the vertical direction, was obtained by the repeated measurement of exposed length of erosion-pins installed into the ground surface in June 1974. Measurements were made in October 1974, June 1975 and August 1976. Mean erosion depth in rill was calculated from the division of cross-sectional area of rill by the perimeter length of rill. Cross-sectional area of rill was measured in the 23 measurement points within rill watersheds. Measurement period was from August 1972 to October 1974.

Suspended-sediment transport: On the basis of the landuse survey, two small third-order watersheds were selected: watershed IV, located in the Bimata and watershed V, which situated in the Higashi-Yabu (Figure 3-2). Bare land and pinery spread broadly in these two small watersheds, where the erosional landforms were mapped on slopes. In the third-order streams, water discharge and suspended-sediment concentration were surveyed in 1975.

These measurement points were set on the Higashi-Yabu (Figures 3-2 and 3-3). As for the fifth-order stream, water discharge and suspended-sediment concentration of the Bimata were measured at site 2. As the access to site 3 in the Higashi-Yabu river was very difficult on the occasion of flood, most of the measurements were

carried out at site 1 instead of site 3.

3.4 Erosion on the slope

3.4.1 Inter-rill erosion

Figure 3-5 shows three profiles of the first-order divide segment on inter-rill areas: I1, I2 and I3. They have a slightly concave or convex form. Measurement results on rill site are shown in Table 3-1.

The relationships between the inter-rill erosion rate E_i and both divide segment length l_i and divide segment gradient S_i are shown in Figure 3-6. Although a deposition occurs at the upper part of I1 and I3, there is no clear increase of E_i with the increase of l_i . Similarly, the increasing tendency is not clear, although E_i seems to increase slightly with the increase of S_i .

Coefficient of variation of E_i ranges from 0.6 to 1.1 as shown in Table 3-1. This suggests that the erosive action on the first-order divide segment is nearly uniform, as indicated by Schumm (1956), in which erosion rates were measured on inter-rill area. Schumm (1956) thought that the erosive action is achieved by the subdivided flow or the surge and flow. Nevertheless, when raindrop action was cut by a screen net covering the ground surface, the erosion on inter-rill area was reduced by 10 % compared with the case with the raindrop action (Meyer et al., 1975).

3.4.2 Rill erosion

Rill networks developing on the bare land of the third-order rill watershed are shown in Figure 3-7. Measurement results of rill site are shown in Table 3-2.

Cross-sections of rills are shown in Figure 3-8 and Photo 3-1: upstream, they show a saucer-like form, and change to a box-like form downstream. In order to analyse the form change, the ratio of mean depth H_r to width W_r is calculated. The relation between the depth/width ratio and the total rill length TL is shown in Figure 3-9. The figure indicates that the depth/width ratio increases with the increase of TL ; rill increases the depth more rapidly than the width along the channel.

Figure 3-10 summarizes the relations of rill erosion rate E_r to total rill length TL and to rill bed gradient S_r . Although the data points are scattered, E_r increases with the increase of TL in every group. The increase rate of E_r is lowered with the increase of TL . On the other hand, E_r seems to increase with the increase of S_r at the same TL (Figure 3-10 right).

The product of rill watershed area (A) and the rill bed gradient (S_r) is adopted as a proportional parameter of total stream power; that is a potential energy expenditure per unit rill length (eg; Bagnold, 1966). Relation of rill erosion rate E_r to the product $A \cdot S_r$ is shown in Figure 3-11. The differences between the site groups disappeared, and as a whole, E_r increases with the in-

crease of $A \cdot S_r$. The increase rate of E_r decreases with the increase of $A \cdot S_r$. The rill erosion is most active in the beginning stage of the increase of rill watershed area and rill bed gradient.

3.5 Suspended-sediment transport

3.5.1 Erosion and suspended-sediment transport on slope

Rill and gully erosion in the third-order watershed V is shown in Figure 3-12. Soil erosion is most active on the bare land and the pineapple field where the pineapples were planted 1-2 year before. Figure 3-13 shows a distribution of micro rill on a pineapple field. When it rains with a minimum intensity 2-3 mm/10 min., rain water flows in rill on the slope with a high concentration of suspended-sediment.

B and BC layers of the forest soil contains clay particles over 60 %, as shown in Figure 3-14. On the inter-rill area, the percentage of clay particle decreases to 40-50 %. Removal of fine materials proceeds on the rill bed and gully bed. These changes are owing to the wash of fine materials by rain splash, inter-rill and rill flows. Certainly, a sediment concentration of rill flow is very high, and it ranges from 12 g/l to 17 g/l, which is equivalent to a relatively higher concentration in the lower reach of the Sanchina. Grain size distribution of suspended-sediment is shown in Figure 3-15, in

which most of the sediments are composed the silt and clay particles.

3.5.2 Suspended-sediment transport in streams

At every rainfall, eroded materials are transported as suspended-sediment (Photo 3-2). Figure 3-16 shows a hydrograph and a temporal change of suspended-sediment concentration on the 11th of August 1975 in the third-order watershed V.

The peak discharge stage reached $0.011 \text{ m}^3/\text{s}$ for the rainfall of 2.7 mm from 11:40 to 11:50, and $0.036 \text{ m}^3/\text{s}$ for the rainfall of 5.7 mm from 12:15 to 12:30. They were 11 and 24 times greater than the discharge of low stage ($0.015 \text{ m}^3/\text{s}$), respectively. The highest concentration of suspended sediment was 20 g/l in the case of runoff of the latter rainfall. Total amount of the suspended sediment transported by both rainfalls was 230 kg ($4.3 \text{ t}/\text{km}^2$).

Hydrograph and a temporal change of suspended-sediment load for the fifth-order watershed on the 21th to 24th of October 1975 are shown in Figure 3-17. Water discharge is in the order of $0.1\text{--}0.2 \text{ m}^3/\text{s}$ in the low stage. In the main tributary of the Higashi-Yabu(QI) the water discharge increases gradually. On the other hand, in the Bimata watershed(QII), flash flood suddenly appears and discharge becomes in the order of $1 \text{ m}^3/\text{s}$. Suspended-sediment concentration increases very rapidly with the

increase of discharge. These abrupt increase of discharge and sediment are explained by the convergence of floods with high suspended load from tributaries.

When the discharge of the Bimata is over $4 \text{ m}^3/\text{s}$, the water comes into the marsh of the main tributary. Therefore, the marsh is inundated with runoff water from the main tributary and the Bimata. Since most of suspended-sediments from the main tributary deposited in the marsh land, suspended-load at Shirokane bridge (Q_{sI}) is mainly composed of the load from the Bimata.

Figures 3-18 and 3-19 show the relation between water discharge and both suspended-sediment discharge and suspended-sediment concentration. At Shirokane bridge the suspended-sediment discharge increases with the increase of discharge at the beginning of flood. When the rainfall intensity become weak and the flood from the Bimata watershed is reduced, the sediment discharge suddenly drops.

Cross-sectional distribution of flow velocity and suspended-sediment concentration at Shirokane bridge are shown in Figures 3-20 and 3-21. In this condition, the water stage is high, and the water discharge is $2.0 \text{ m}^3/\text{s}$. Above the channel bed, flow velocity changes from 0 to $0.6 \text{ m}^3/\text{s}$, and there exists a strong shear. Over this shearing layer, a high velocity area spreads.

Suspended-sediment concentration is high at shearing layer and also at the high velocity area. Higher concen-

traton of suspended sediments attains to 0.20 g/l, which corresponds to the order of 10 g/l (10^{-3} sediment concentration). Near to the water surface, a high suspended-sediment concentration is sporadically distributed. Such a spot of high concentration seems to be caused by the boiling.

3.6 Conclusions

In the northern part of Okinawa Island, where deeply weathered reddish soil develops, soil erosion processes on bare land and suspended-sediment transport in streams were investigated. Inter-rill erosion almost uniformly works on the slope of the first-order divide segment. Rill erosion rate increases with the increase of the product of rill watershed area and rill bed gradient. Nevertheless, the increase rate is lowered with the increase of the product.

As the slope materials are mainly composed of clay and silt, the sediment delivered from bare land and pineapple field are transported as suspended load by a relatively weak rainfall with the intensity of 2-3 mm/10min. In the cross-section of stream channel, suspended-sediment concentration is high in the shearing layer near the channel bed, and also in a high velocity area above it. Concentration of suspended-sediment attains to the order of 10 g/l (= 10^{-3} in sediment concentration) in rill and channel flows.

CHAPTER 4

TRANSPORT OF GRAVEL PARTICLES IN AN ARTIFICIAL FLUME

4.1 Introduction

Studies on the erosion and debris transport in the field which are described in the previous chapter, have made clear how the sediments are yielded from the mountain slope, and how they are transported into the stream channel through rills and gullies. In the stream channel, the sediment transport processes involve there different modes: mudflow, suspension and saltation. Although field observations revealed a relation between the suspended sediment concentration and a flow velocity, it is very difficult to clarify the particle movement of suspended materials in a channel. Similar difficulty arises in the study of mudflows in which all particle, ranging from silt or clay to huge blocks, are mixed, and transported together in mass. Therefore, the present study treats with the particle movement in channel during the sediment transport only in the case of saltation.

In chapter 4, the process of saltation is analyzed by a flume experiment. Since the saltation is the major process for the transportation of coarser particles, the gravel particles are used for the experiment. The gravel particle movement has been investigated by many researchers such as Kishi and Fukuoka(1966), Tsuchiya and

Aoyama(1970), Parsons(1972), Nakagawa et al.(1978), Ikeda et al.(1979), Sumer and Deigaard(1981). However, most of the studies, except Sumer and Deigaard(1981), have measured the movement of gravel particles, in downward and upward directions; particle movement in transverse direction have not been treated. Sumer and Deigaard(1981) observed the motion of heavy particles near the bottom. In their study, a stereo-photogrammetric system was used to record the three-dimensional motion of a single particle. However no systematic analysis of the particle motion was attempted.

The particle motion was often observed on a fixed bottom, smooth or rough, but no experiment was made on a movable bed, where the channel form is determined through the particle motion.

The aim of the present study is to make clear the process of gravel transport in a channel with a movable bed. In order to analyse in detail the motion of the gravel particles, tracer gravel particles were flown in a artificial flume in which the steady-state condition was realized. The movement of tracer gravel particles were surveyed stereo-photogrammetrically by using two video-cameras.

4.2 Experiment method

4.2.1 Facility and material

Experiment facility for gravel transport is shown in Figure 4-1. The artificial flume is 7.8 m long, 6 cm wide and 40 cm deep. Side walls are made with plates of transparent acrylic plastics to observe the gravel movement. Base of the flume is fixed horizontally. The channel slope is determined by the deposition of gravel particles. Water is supplied from the tank set at the uppermost part of the flume, and water discharge is measured by using a triangular weir and a point gauge.

Gravel particles are stored in a hopper over the stilling pool, and supplied on a turn table. The amount of gravel feeding is scratched from the table. Sediment (gravel) discharge is measured at the end of flume. The measurement period is from 3 to 5 minutes.

In this experiment, two coordinate systems x, y, z and x_s, y_s, z_s are set to describe the channel form and the particle position (Figure 4-2).

Two video-cameras was set up beside the flume to take photographs of gravel path between the distance $x=3.2$ m and 3.6 m (Figure 4-3). The two cameras are put 20 cm apart in z direction. Cameras used in this experiment are CCD-V900 made by Sony.

Gravel particles are mainly shale and sandstone including chart of 8 %. They are Pleistocene terrace gravel, which are prepared by sieving with the mesh opening 4.5 mm and 5.4 mm. Properties of the gravel is

shown in Table 4-1: grain density is 2.63; mean mass of one particle is 0.19 g; mean volume is 0.072 cm^3 . Histograms in axis length of gravel particles are shown in Figure 4-4; mean length of a-axis is 7.5 mm, b-axis is 5.5 mm and c-axis is 3.6 mm. Gravel has a slightly long and platy form.

4.2.2 Experiment procedure

Experiment conditions are shown in Table 4-2. Water discharge was changed in 4 levels: 1.9 l/s, 2.5 l/s, 3.0 l/s and 3.4 l/s. Gravel feed is almost constant within the range between 1.4 g/s and 1.7 g/s. After the water and the gravel are continuously supplied for 2 to 3 hours, the gravel discharge becomes equal to the amount of feeding. Then the form of channel bed and water surface were measured, and the movement of gravel particles was photographed.

Height of water surface and channel bed were measured at 27 points from $x = 0 \text{ m}$ at an interval of 30 cm, to calculate mean gradient of channel bed and water surface, and water depth. Mean of wetted perimeter P , hydraulic radius R and cross sectional area A_s were calculated from the water depth. Mean velocity along the channel bed, V_s , was obtained from water discharge Q divided by cross-sectional area A_s .

Gravel particle movement was obtained by pursuing the tracer gravel particles which were painted in yellow.

The tracer gravel particles were dropped from the inlet of flume. Their movement were photographed at the shutter speed of $1/250$ second by two video-cameras which were synchronized. A video field, which is a picture taken at $1/60$ second interval by video camera, is transferred to a display of personal computer. Position of tracer gravel is measured on the display by Mouse.

An example of a still picture is shown in Photo 4-1. The simultaneity of two fields taken by different video cameras was identified by the clock timer photographed on the fields. Three-dimensional position of gravel particle was determined by analytical photogrammetry. In the calculation of photographic survey, a software which was made by Japan Society of Photogrammetry was used. The repeated measurements of gravel particle position were made for 10 gravels in each Run. Then the sequential gravel positions were obtained.

4.3 Channel form and flow

Channel form, flow and sediment discharge of each Run are shown in Table 4-3. Form of channel bed and water surface is straight, and these two forms are almost parallel as shown in Figure 4-5: mean gradients of channel bed is 0.0203 for Run 1, and that of water surface is 0.0204. Nevertheless, there exists small ruggedness on the bed: dune with a relative height of 5

mm and ripples with a wavy form.

Among four Runs, the gradient of bed and water surface decreases with the increase of discharge. On the contrary the cross-sectional area increases with the increase of water depth, hydraulic radius and wetted perimeter. The flow is in a uniform flow condition, since the bed and water surface are parallel.

In Run 1, mean depth is 4.4 cm and hydraulic radius is 1.8 cm. Mean velocity is 73.5 cm/s and flow Reynolds number Re is 12600. Therefore, the flow is obviously in a turbulent condition. As Froude number, Fr , is 1.8, the flow is in a shooting condition.

With the increase of discharge, both the velocity and the hydraulic radius increase. Therefore, the Re increases, while the Fr is constant. The flow turbulence increases with the increase of discharge in spite of the decrease of channel bed gradient.

4.4 Movement of gravel particles

4.4.1 Mode of gravel particle motion

An example of gravel particle path is shown in Figure 4-6. A circle shows a gravel particle position at every point of a $1/60$ second interval. On the basis of particle allocation relative to the channel bed, four modes of gravel particle movement such as

saltation, rolling, vibration and rotation were recognized.

Saltation is a motion that the gravel particle moves upward far from the channel bed. Rolling is a motion that the gravel particle is contact with the channel bed. In this motion, the contact was judged from the condition that the distance between the gravel particle and the channel bed is within 3 mm which is a half length of b-axis. Vibration is a motion that the gravel particle changes its position periodically in contact with the channel bed. Rotation is a motion that the gravel particle itself rotates around its axis.

During the movement, the mode of gravel particle motions changes as follows: when the gravel particle begins to move, it begins the vibration, which changes to the saltation or rolling motion; the switch between each motion is abrupt; when the gravel particle stops, the saltation and rolling change to vibration at first.

Therefore, the vibration occurs between the motions of saltation and rolling and the halt. Both the saltation and the rolling contribute the particle transport, however, most of the motion (over 90 %) is composed of saltation.

Gravel particle motion is examined in each mode. As the gravel particle moves along the inclined channel bed, xs axis corresponds to the downward the direction, ys axis, the transverse direction from right bank to

the left and z_s axis, perpendicular to the channel bed in the upward direction.

Saltation: Figure 4-6 is an example that a gravel particle is at the center of channel floor. The gravel particle moves upward after taking off the bed, and simultaneously changes the position rightward in the stream direction. As it moves downward and reaches the floor, it turns the position leftward. In this movement, the gravel particle rotates in $ys-zs$ plane; the leftward rotation and the rightward rotation appear alternately.

This motion indicates that the gravel particle takes a spiral path. Mean transport length of one saltation is 10-80 mm in x_s direction, 9-20 mm in ys direction and 2-10 mm in z_s direction. Dislocation in ys direction is restricted in a narrow band, which will be described later.

When a gravel particle moves oblique to the stream direction, it also takes a spiral motion (Figure 4-7). However, in the case that gravel particle comes into contact with the wall of right or left sides, the movement is somewhat different. A gravel particle which contacts with the left-side wall is shown in Figure 4-8. After the contact, the gravel particle moves to the right-side wall with a downward movement. On the contrary, a gravel particle which reaches the right-side wall moves to the left-side one with a upward movement (Figure 4-9).

These observations reveal that the gravel orbit is asymmetrical in the cross-section of the channel. Gravel particle takes a spiral path with an rightward inclination both to a stream direction and side walls. If the wetted perimeter is represented by a channel bed, the gravel particle moves downstream along the direction of wetted perimeter in a transverse direction, and along the direction of hydraulic radius in up- and downward directions.

Rolling: A gravel particle moves downstream with a small fluctuation in a transverse direction. The gravel particle moves continuously in contact with the channel floor.

Vibration: This motion occurs only in a transverse direction. The gravel particle does not move downstream. It vibrates in a direction of hydraulic radius.

4.4.2 Distribution of gravel particles in motion

Figures 4-10a, b and c show the position of all gravel particles in saltation plotted in a cross-section of the channel: Figure 4-10a shows the case that gravel particle move in the center of the channel; Figure 4-10b show the case that a gravel particle moves parallel to the stream with a slight shift in three clusters. When the gravel particle move oblique to the stream, they shows a concentrating distribution, although the clusters

are unclear (Figure 4-10c).

All of the gravel particle position of Run 1 are plotted in Figure 4-11. When the boundaries of cluster distribution are drawn with broken-lines, it is found that the lines extend to the direction of hydraulic radius, and that the height of saltation motion is about a half of hydraulic radius, R . When the solid-lines are drawn at an interval of $1/2 R$ along the wetted perimeter from the water surface at right-hand side to the direction of hydraulic radius, they coincide well with the boundary of each cluster. This fact reveals that the range of $1/2 R$ is a unit of gravel transport; this unit is named as the transport belt. When the gravel particles move parallel to the stream as shown in Figure 4-6, the gravel path is concentrated in one transport belt. On the other hand, when the gravel particles are transported oblique to the stream (Figure 4-7), there appear two or three transport belts, and the gravel particles change their moving path from one transport belt to the adjacent one.

In the rolling, gravel particle positions are distributed within the range of $1/2 R$ in the cross-section of channel. As the gravel particles are transported downstream, gravel particle positions scatter along the stream direction. The gravel particles which are in the motion of vibration are also distributed within the range of $1/2 R$ in the cross-section.

4.5 Gravel movement and channel form

The experiments revealed that the saltation transports the gravel particles in repetition of spiral motion, and that the most of the gravel particles are transported parallel to the stream. Kinoshita (1957) pointed out that, in a deep flow with a small width-depth ratio, gravel particle movement is straight, and the longitudinal grooves are formed on the channel floor. In the present experiment, channel forms in a transverse direction were not surveyed. However, a wavy limit of gravel particle positions, shown in Figure 4-11, seems to indicate the initial form of groove on the channel floor.

A transverse movement of gravel particles from one side-wall to the other also characterizes the gravel motion. Such a movement, oblique to the stream flow, was regarded by Kinoshita (1957) as an important factor to form bars. The present experiment shows that the oblique movement also takes a spiral motion, in which the transverse rightward spin is dominant. Such a biased spiral motion seems to be necessary for the formation of bars.

The flume experiment also revealed that the minimum width of saltation motion is less than the size of hydraulic radius, most probably the half of the radius. This fact can be explained by the formation of eddies smaller than those which were recognized on water sur-

face during the flood and which are named as the longitudinal eddies. In the natural rivers, Kinoshita(1967) found that the parallel cycloidal flows are formed by the longitudinal eddies. However, further investigation are necessary to explain the saltation motion by the eddies smaller than the longitudinal ones.

4.6 Conclusions

Gravel particle motions in a flume were investigated at every 1/60 second, and gravel particle orbit and distribution were observed. The water and the gravel were constantly supplied in the flume. After a steady-state of channel flow was realized, the movements of tracer gravel particles were surveyed by a stereo-photogrammetry using video cameras.

The experiment revealed (1) that gravel particles take a spiral motion in saltation: when a gravel particle takes off the channel bed, it moves rightward in the stream; then it moves downward and reaches the floor; the orbit is asymmetrical in channel; (2) that the minimum width of saltation motion in the transverse direction is less than the hydraulic radius; (3) that the distribution of gravel position is concentrated near the channel bed; and (4) that the volumetric concentration of gravel in running water is as low as $(1.6-3.2)/10,000$.

The sediment concentration of gravel shown in the

experiment is the least value in the three debris transport modes; mudflow, suspension and saltation. In the saltation movement, a single particle moves more freely than in other transport modes under the low concentration level. The spiral motion of gravel particles, therefore, seems to be related to the low concentration of sediment transport in a channel.

CHAPTER 5

CONCLUSIONS

The present study treats with the erosion processes on slope and related sediment transport in channel in watersheds. Two field observations, one in Hokkaido, the other in Okinawa Island, cover the whole processes of erosion and sediment transport in watersheds. Two basic processes of sediment transport, mudflow (multi-phase flow) and suspension were analyzed from these field data, and the one, saltation, was analyzed by flume experiment. The thesis is composed of five chapters.

Chapter 1 is an introduction of the study, in which the purpose and the environmental-geomorphological significance of the study are described. Figure 1-1 shows the three basic modes of debris transport in channel and the erosion on slope.

Chapter 2 describes the study of the Nishiyama watershed, at the foot of Usu Volcano, which was thickly covered with tephra by the 1977-1978 eruption of Mt. Usu. On the slope, erosion and surface runoff processes were measured, and along the valley, landform changes and mudflow occurrence were investigated. The erosion processes and the debris transport in the watershed are summarized as follows:

(1) Within two months after the deposition of fine ash, surface runoff generates with the minimum rainfall

with the intensity of 5mm/10min due to the covers of fine ash with low permeability.

(2) Erosion landforms of rill and gully were formed by the surface runoff, and a huge amount of debris was supplied to the valley floor.

(3) The debris accumulated on the valley floor was transported further downstream by a high-concentrated mudflows as a multi-phase flow at the rainfall with the intensity of 5-20 mm/10 min.

Chapter 3 describes the study of the watersheds in the northern part of Okinawa Island, where a deeply weathered reddish soil develops. Detail observations of the slope erosion processes and the sediment transport in channels in the watersheds with a wide occupation of man-made bare land and pineapple fields, revealed that (1) surface runoff starts by the minimum rainfall with the intensity of 2 mm/10 min; (2) on the inter-rill slope, the erosion almost uniformly works, and in rill channel, the erosion rate increases with the increase of the product of rill watershed area and rill bed gradient, while the increase rate is lowered with the intensity of the product; and (3) as the slope soil is composed of fine materials with the diameter less than 0.1mm, most of the eroded sediment is transported as suspended-sediment, which are rolled up to the water surface from the bottom of the channel.

Chapter 4 is devoted to the analysis of the motion of gravel particle in saltation. Particle motion in an

artificial flume was traced by a stereo-photogrammetry, by using two video-cameras. The experiments made clear that (1) the gravel particles take a spiral motion in saltation; (2) the particles move within a "transport belt", the transverse width of which is proportional to the length of hydraulic radius; and (3) the volumetric concentration is much lower than in the other sediment transports analyzed in the previous chapters.

Chapter 5 is a conclusive one in which all results of the preceding chapters are summarized, and the characteristics of sediment transport modes treated in this study are synthesized from viewpoints of the debris supply, particle property, flow condition, and sediment concentration.

5.1 Erosion processes on slopes

Slope conditions relating to debris transport are summarized in Table 5-1.

Active slope erosion began within two months after the deposition of ash on September 12 and 13, 1978. Fine ash and coarse pumice layers which covered the slope prepared the erosion. Particularly, a very fine ash erupted on September 12 and 13, 1978 which had a low porosity of 47 % and also a low hydraulic conductivity as low as 10^{-5} cm/s order, generated three mudflows which were triggered by the rainfall intensity over 5 mm/10 min. The rainfall on the slope deposit composed of fine ash with a low permeability caused a surface runoff and

both rill and inter-rill erosion. However, the slope conditions were rapidly changed due to the exposure of permeable pumiceous layer on the floor of rill and gully channel. The occurrence of mudflow is therefore controlled by the permeability of the surface material on slope, because the rainfall intensities for triggering these mudflows are similar.

In the watershed, in the northern part of Okinawa Island where deeply weathered reddish soil develops, soil erosion occurs on bare land, pineapple fields and housing sites, and it results in a suspended-sediment transport in a channel. Erosion processes on the slope involve rill and inter-rill erosions. Rill erosion rate increases with the increase of the product of rill watershed area and rill bed gradient.

The slope materials, which are composed of the weathered fine clay and silt, are closely related to these active erosions. The weathering depth is over 20-30m on the gently sloping surface. The weathered slope materials are compact and the hydraulic conductivity is the order of 10^{-5} - 10^{-7} cm/s. By the forest clearance and the large-scale land-transformation, the compact and less-permeable reddish soil is broadly exposed. Due to the low permeability, with a rainfall of minimum intensity 2-3 mm/10 min, the surface runoff with suspended-sediment transport starts in rill. High content of silt and clay in the red soil is easily suspended in running water. Suspended-sediment transport in a channel is, therefore, the basic

processes operating in the watershed in the Okinawa Island.

Mudflow occurrences are relatively infrequent, because the accumulation of unstable materials on slope is rare in natural conditions except in the case of volcanic eruption. On the other hand, when the silt-rich subsoil layers are exposed by human activities, the occurrence of suspended-sediment transport is very frequent due to the existence of a huge amount of suspendable material and a frequent rainfall of relatively low intensity.

5.2 Debris transport in channels

Characteristics of three basic modes of debris transport in channels are summarized in Table 5-2. Velocity of mudflow is as high as 3-10 m/s. The velocity is fairly high beyond the critical velocity 0.3-0.4 m/s, which is determined by particle size in Hjulstrom's diagram. Discharge is 7-96 m³/s, which is also high compared with that in watersheds of the same size.

A high value of sorting index, shows that the mudflows run down on the alluvial fan as a multi-phase flow. Volumetric concentration is also high, and it exceeds 0.3. These high concentrated- and ill sorted-conditions of flow with a high speed suggest that the debris incorporate in mudflow were fluidized, and that both liquid water and solid debris flowed in mass. It is

estimated that the debris were transported as a cluster or a clod, not as a single particle. As the grain density of pumice particle is lower than the other massive particles, pumice particle seems to help the fluidization.

Flow velocity with suspended-sediment ranges from 0.5 to 0.8 m/s. This velocity is slightly higher than the critical velocity of suspended material, mainly composed of clay and silt. The suspended-sediments are transported in a well sorted condition. During the transportation, an area of highly concentrated sediment is broad from bottom to surface in the cross-section of a channel, where the concentration is higher near the bottom. Suspended particles seems to be repeatedly rolled up and down in the channel during the transportation.

Flow velocity with saltated-sediment is 0.7-0.8m/s, which is slightly higher than the critical velocity. Volumetric concentration is the least within the three transport modes, and the transport area is restricted to near the bottom. However, the lowest volumetric concentration allows the particles the spiral motion to move in a transverse direction.

Each sediment transport condition, mudflow (multi-phase flow), suspension and saltation, is distinguished by a relation between discharge and volumetric concentration(Figure 5-1). With the increase of discharge, the concentration increases. As described in the preceding

chapters, the occurrence conditions of mudflows, suspension and saltation are also different. Such a difference explains well the characteristics of relation between discharge and volumetric concentration.

However, the transport of debris in a channel is performed by a combination of processes. In this study, although a saltation process was analyzed in detail, mudflow (multi-phase flow) and suspension process were not treated, because of the lack of observation technology. For the better understanding of the debris transport in a channel, further studies are necessary, especially on the physical mechanism of mudflow (multi-phase flow) and suspension processes.

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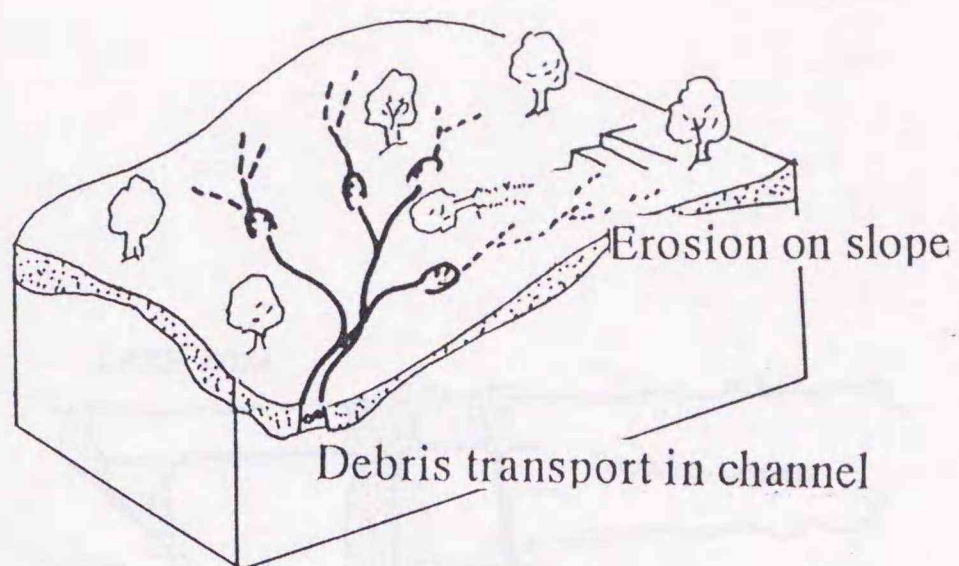
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Theme	Environmental-geomorphological processes in a watershed		
Purpose	Erosion on slope Rill erosion Inter-rill erosion ↓ ↓ Debris transport in channel Multi-phase flow Suspension Saltation		
Subjective phenomena	Erosion & Mudflow	Erosion & Suspended load	Saltation movement
Area or facility	Foot of Mt. Usu	Northern part of Okinawa Is.	Artificial flume

Figure 1-1 Purpose and subject of the study.

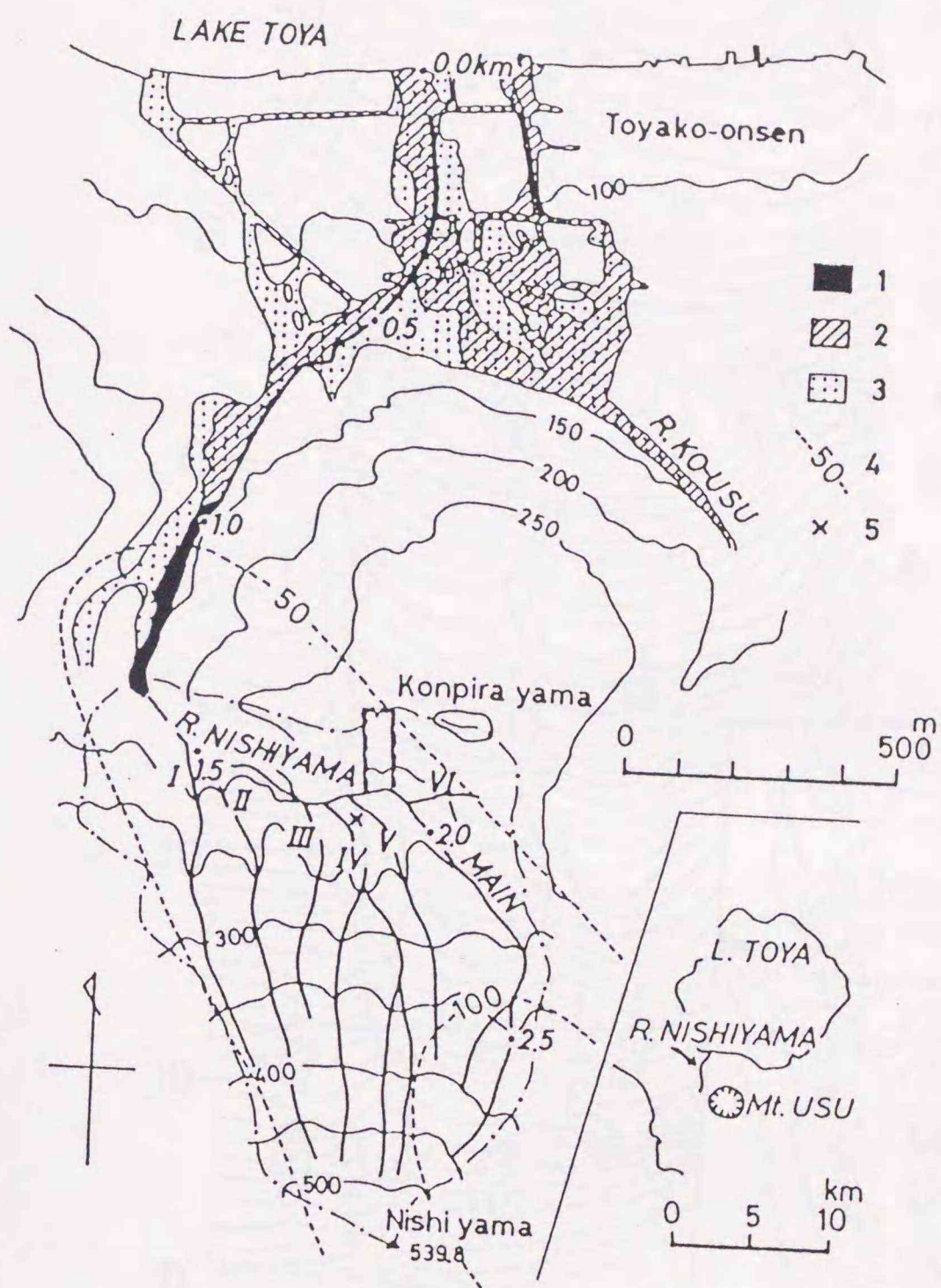


Figure 2-1 Nishiyama watershed and mudflow spread onto the alluvial fan at Toyako-onsen. Contour interval 50 m. Here, 1, 2 and 3 show the spreads of mudflows occurred on September 26 and October 16 and 24, 1978, respectively, 4: Isopach of the 1977 tephra (in cm), 5: Rain-gauge.

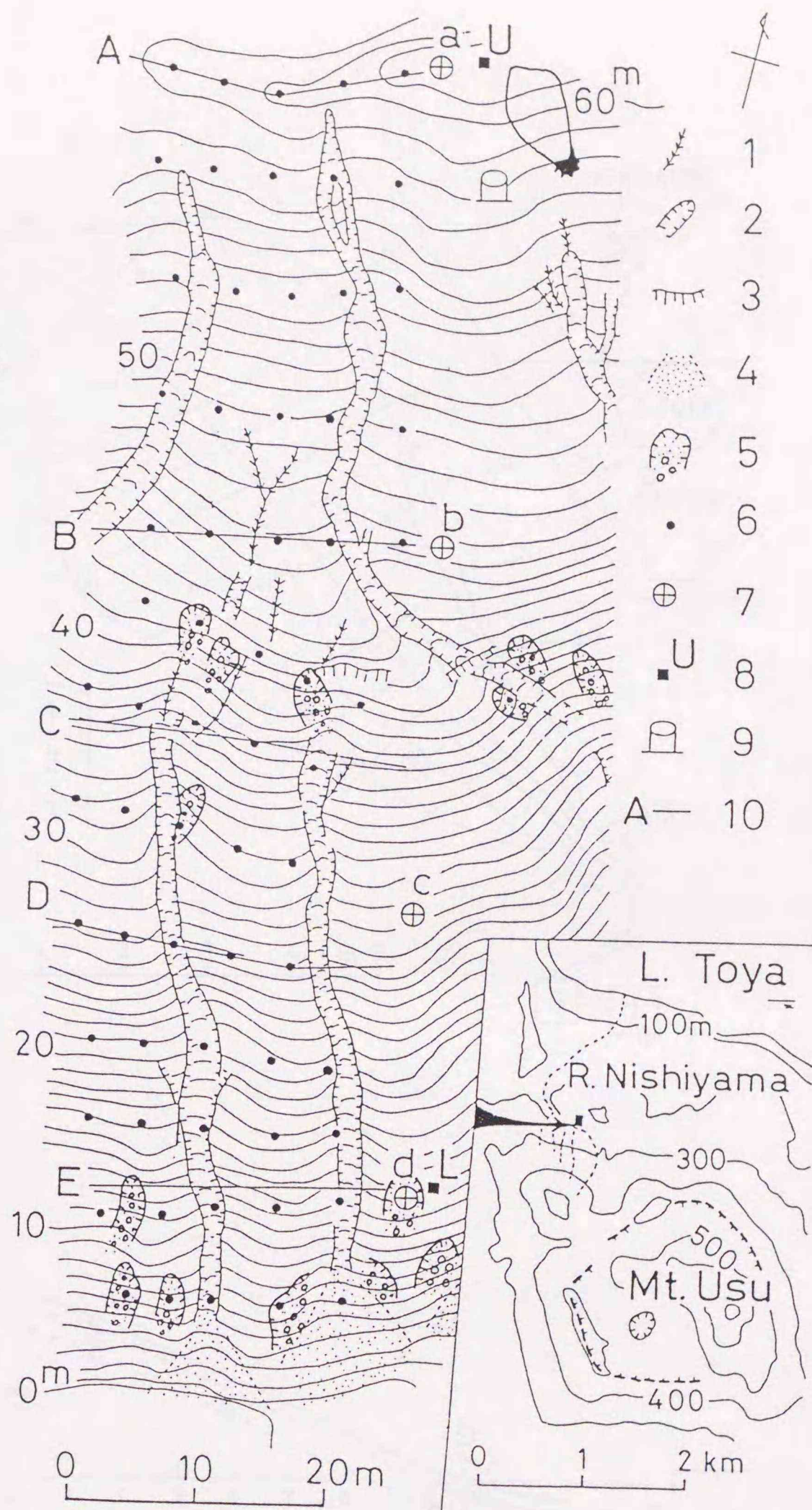


Figure 2-2 Topographic map of the experiment slope. 1: Main rill, 2: Gully, 3: Cliff, 4: Talus cone, 5: Surface-slide, 6: Erosion-pin site, 7: Creep observation points, 8: Sampling points of tephra for grain size analysis, 9: Rain gauge used from Mar. 1980 to Sep. 1982. (Measurement from the slope), 10: Cross section lines. Contours and micro-features are as of July, 1979. (The survey was made by plane tabling and by a HTM-type slope profiler. Contour interval is 1 meter).

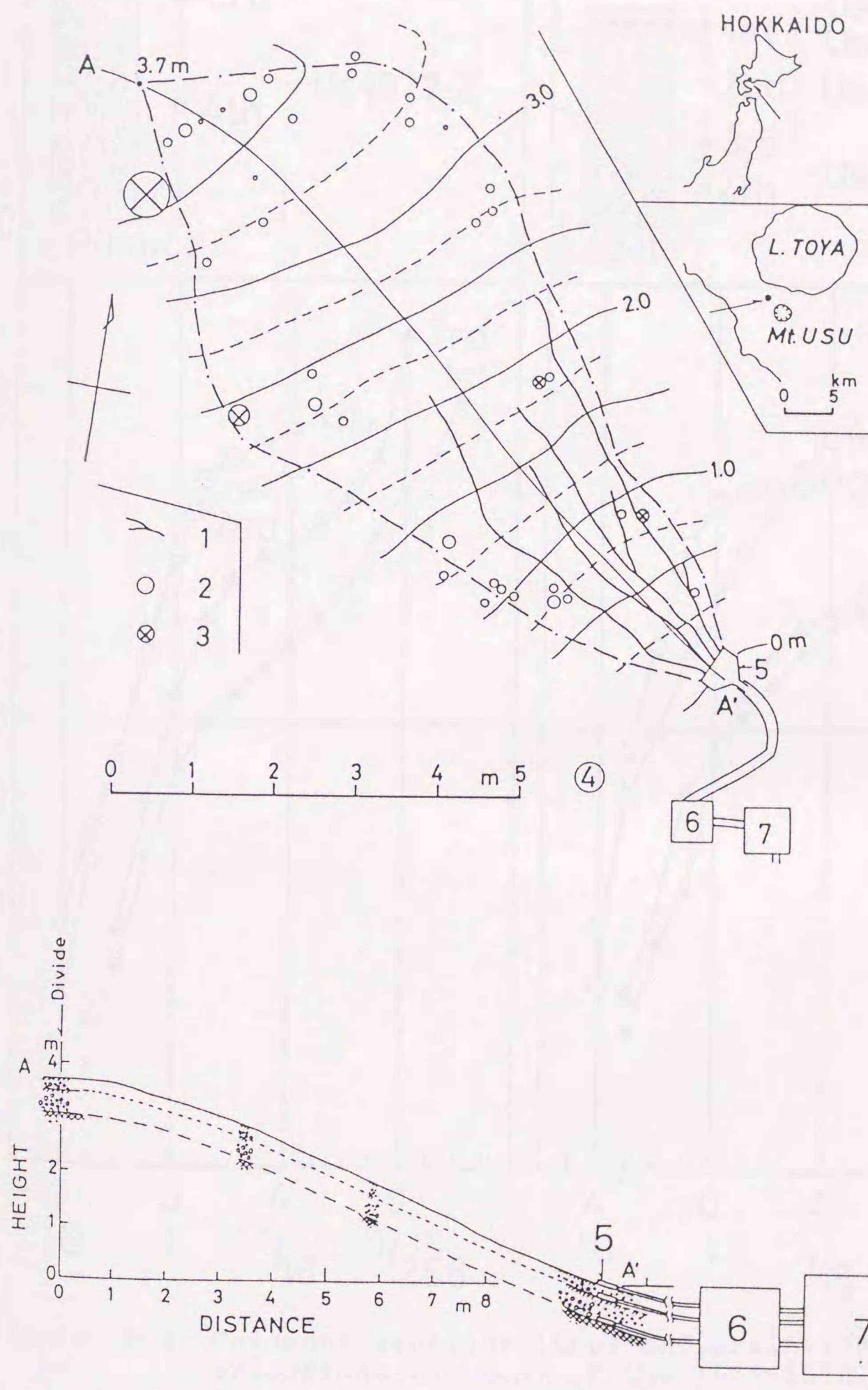


Figure 2-3 Small experimental watershed and its cross section.
 1: rill, 2: tree (active), 3: tree (dead),
 4: rain gauge, 5: collecting trough, 6:
 sediment trap, 7: tipping buckets and re-
 corders.

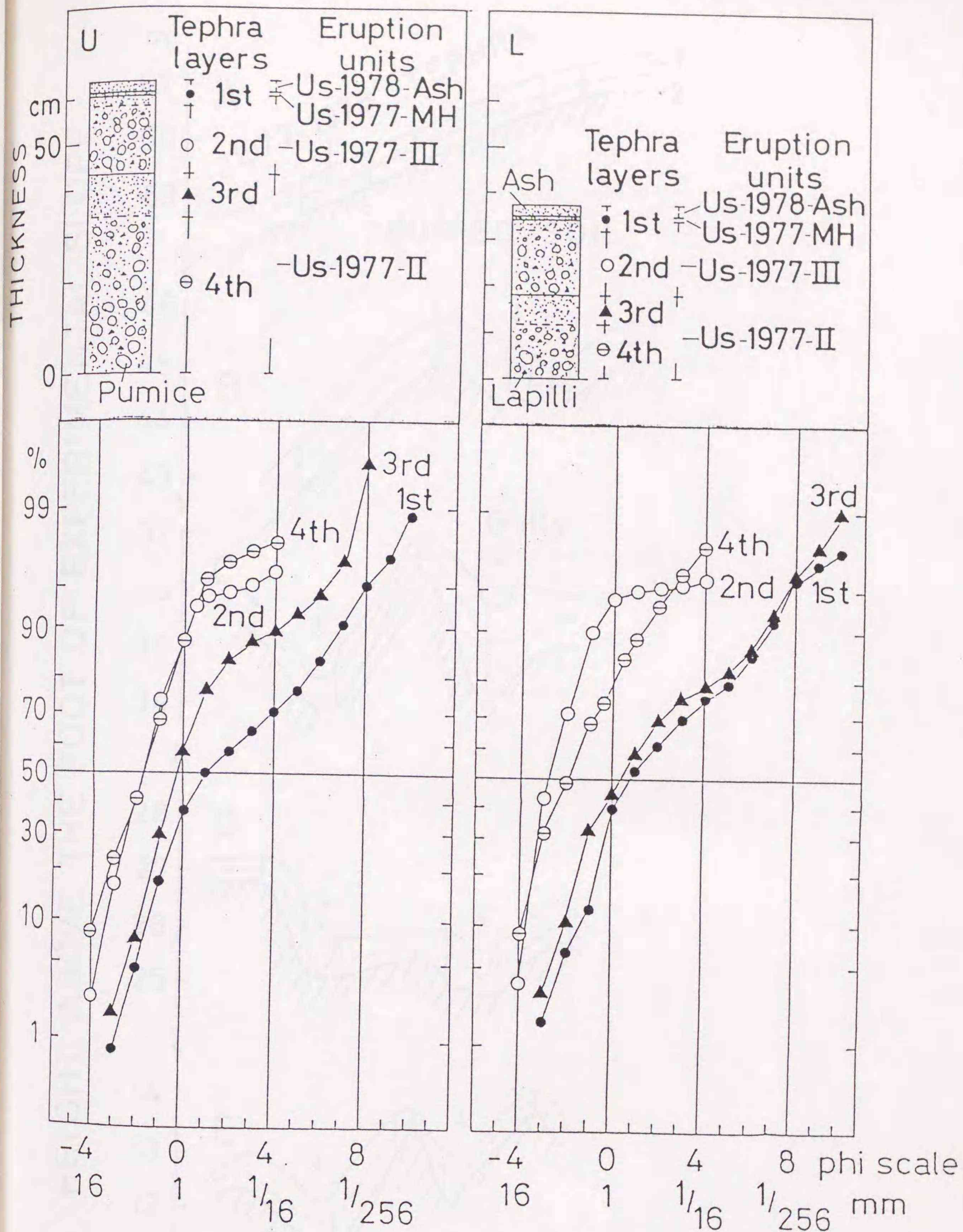


Figure 2-4 Columnar sections (top) and grain-size distributions (bottom) of the 1977-1978 tephra. Samples were collected during September-October 1978 on the upper slope (U) and the lower slope (L) as shown in Figure 2-2. The tephra is subdivided into four layers by the texture and composition. The correlation of tephra layers to eruption unit is also shown in the figure, besides the columnar sections. The definition of Eruption units follows Niida et al. (1980, 1982).

HEIGHT ABOVE THE FOOT OF EXPERIMENTAL SLOPE

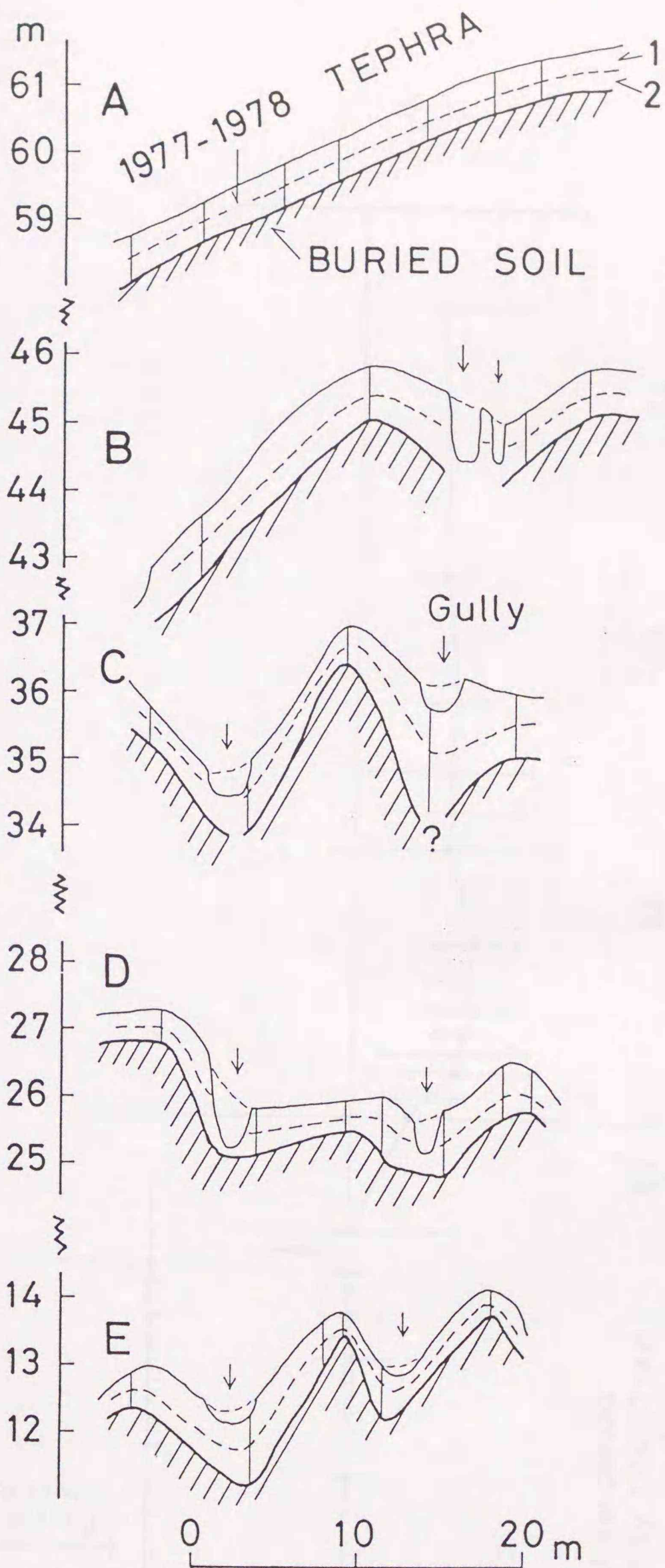


Figure 2-5 Cross sections and tephra deposits on the experimental slope. The location of the section lines is shown in Figure 2-2. 1: Tephra younger than Us-1977-II, 2: Us-1977-II.

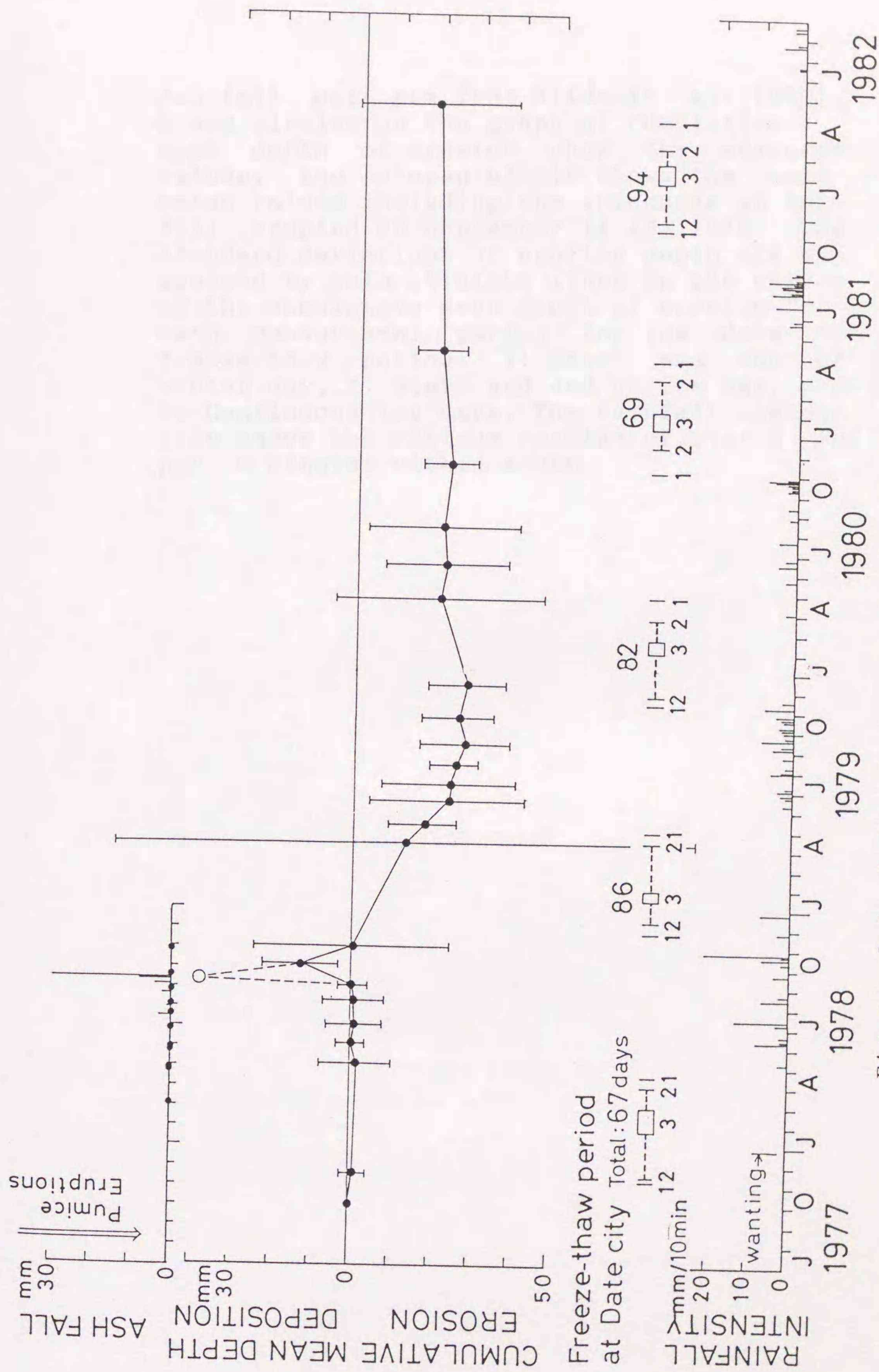


Figure 2-6 Temporal changes in the thickness of pumice- and ash-fall, in the cumulative mean depth of erosion, in the freeze-thaw period and in the rainfall intensity during the period from 1978 to 1982. (continued)

Ash-fall data are from Niida et al. (1980). Black circles on the graph of cumulative mean depth of erosion show the measured values, and an open circle shows the estimated values including the thickness of ash-fall erupted on September 12-13, 1978. The standard deviations of erosion depth are expressed by thin straight lines on the curves of the cumulative mean depth of erosion for each measurement period. For the data of freeze-thaw period, 1: Start and end of winter day, 2: Start and end of ice day, and 3: Continuous ice days. The rainfall intensity shows the maximum reading of over 2 mm per 10 minutes within a day.

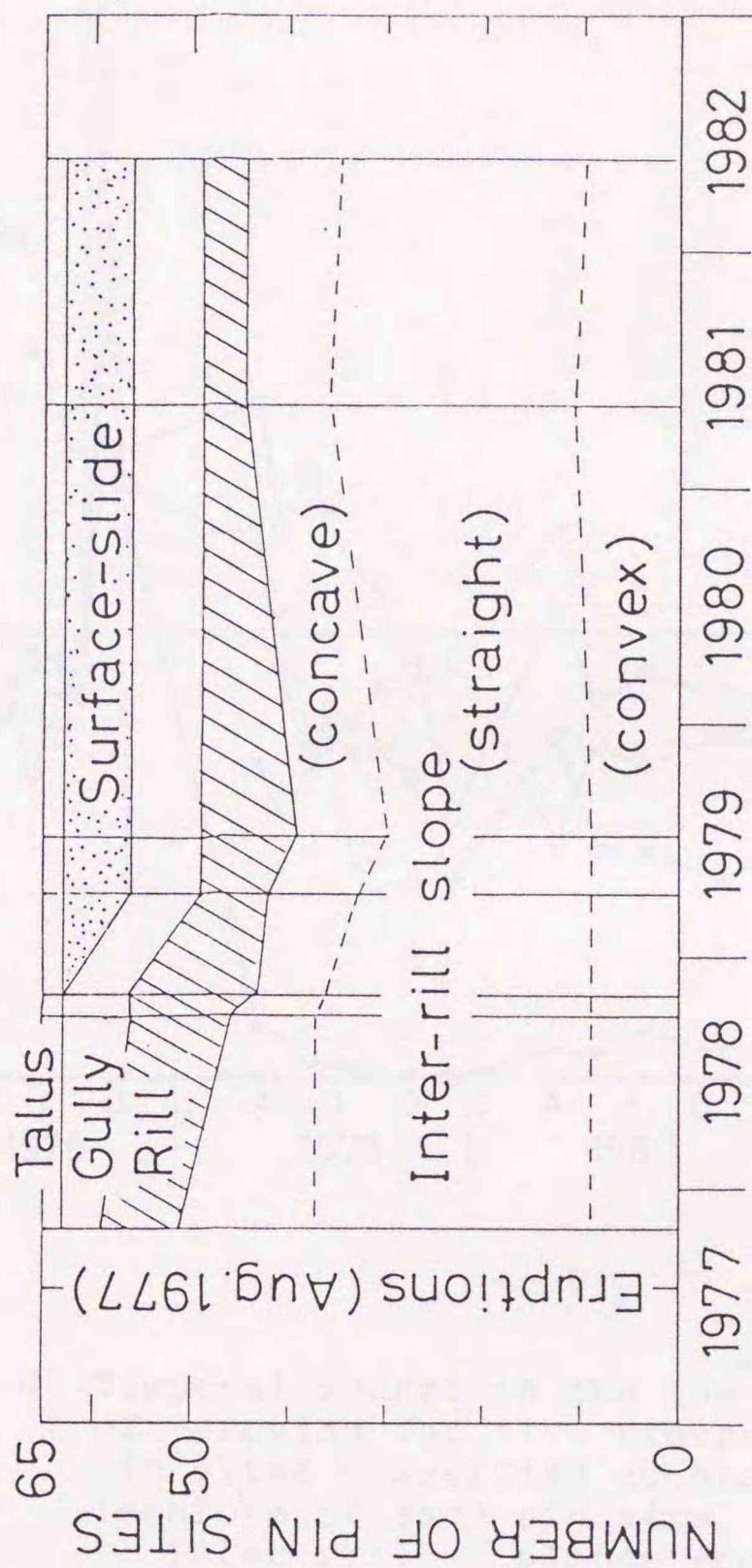


Figure 2-7 Temporal change in the number of the five groups of pin sites classified according to the micro landform of each pin site.

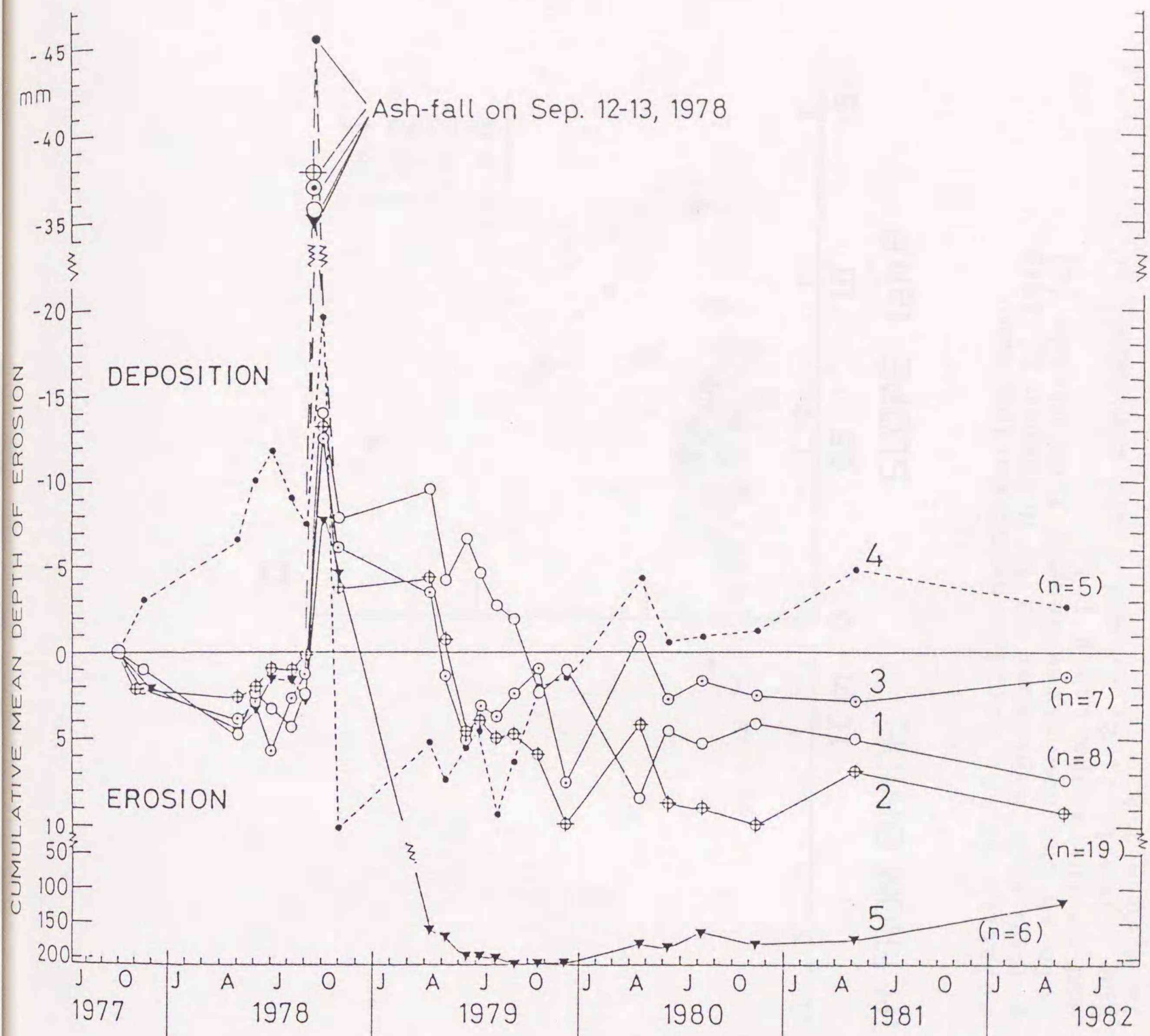


Figure 2-8 Temporal change in the cumulative mean depth of erosion for five groups of the erosion-pin sites classified according to the micro-landform of each pin site.
 1: Inter-rill slopes (convex in profile),
 2: Inter-rill slopes (straight), 3: Inter-rill slopes (concave), 4: Rills, 5: Surface-slides. n: Number of the erosion-pin sites of each micro landform.

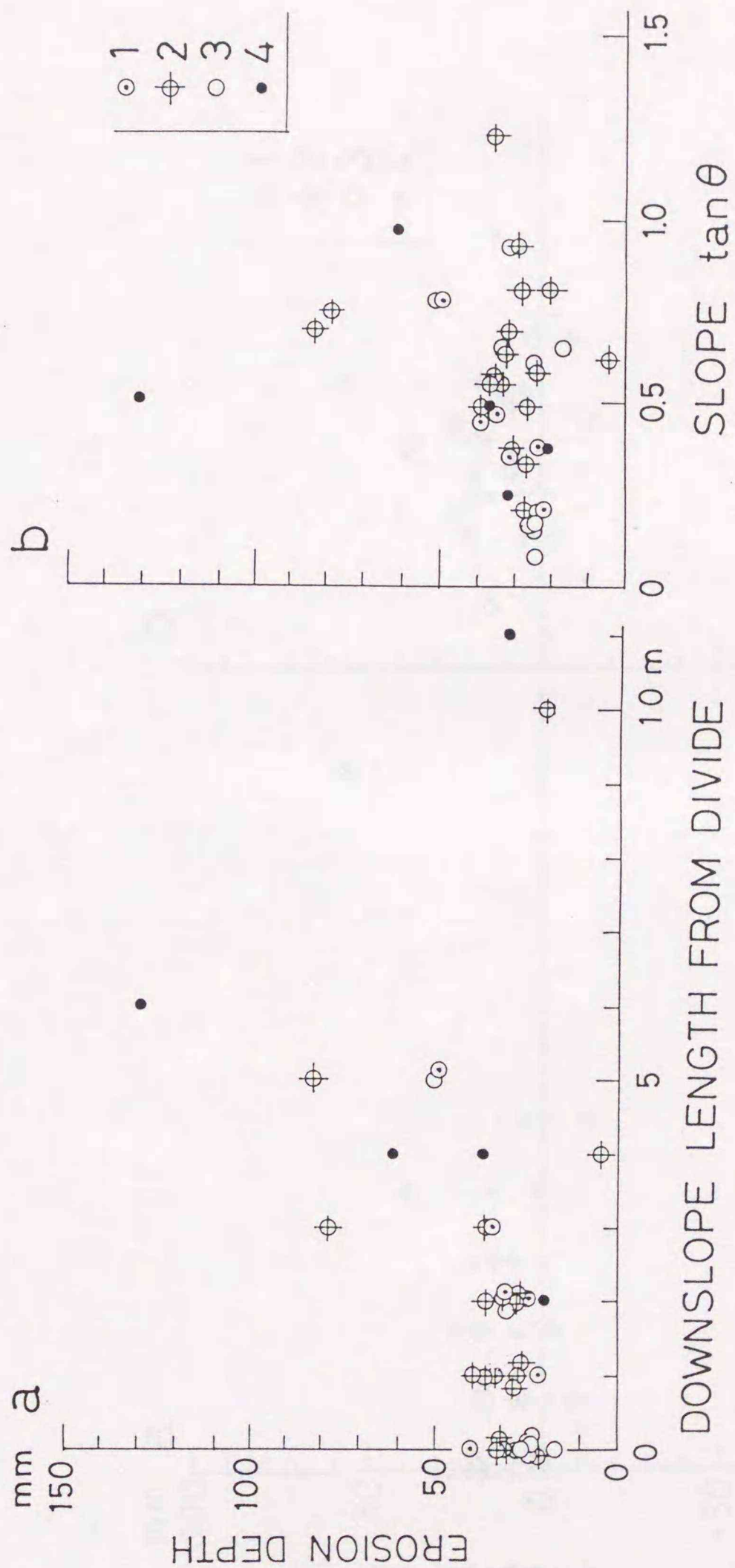


Figure 2-9 Relation of the erosion depth during the period from September 13 to November 1, 1978 both to the downslope length from divide (a) and to the slope $\tan \theta$ (b). The symbols 1, 2, 3, and 4 are the same as in Figure 2-8.

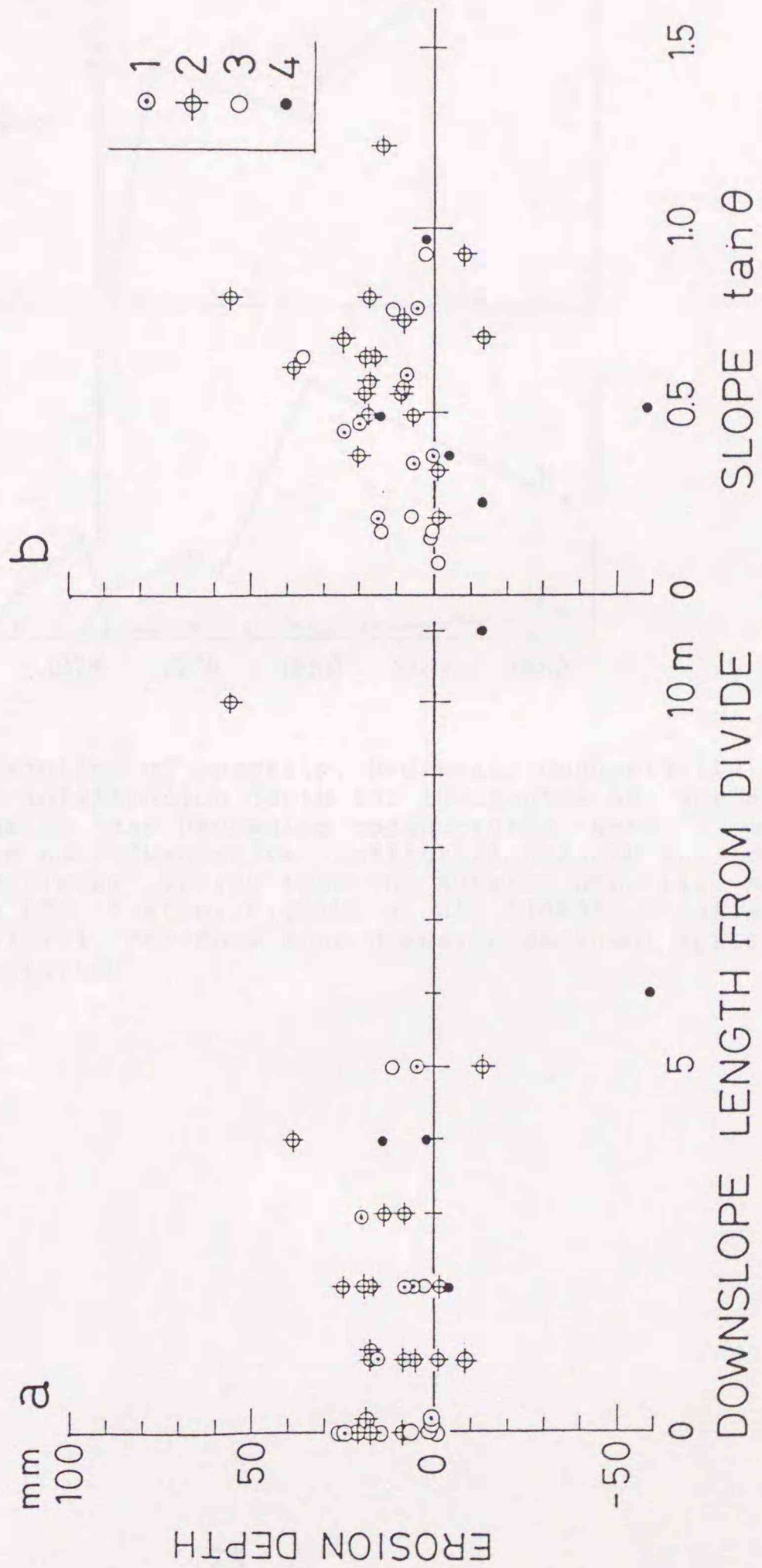


Figure 2-10 Diagram showing the same relationships as shown in Figure 2-9, except for the period from November 1, 1978 to December 6, 1979.

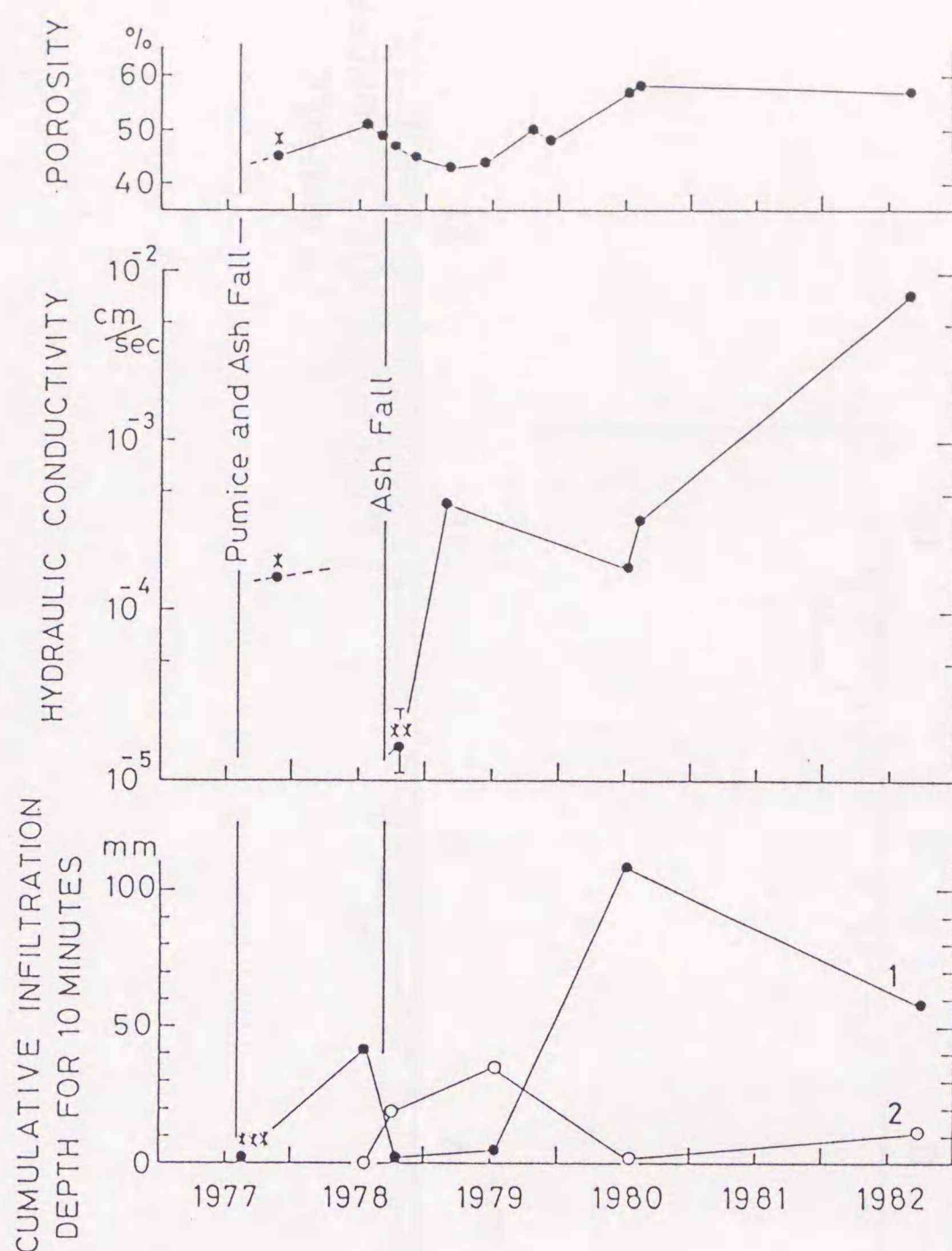


Figure 2-11 Temporal variation of porosity, hydraulic conductivity and cumulative infiltration depth for 10-minutes of surface tephra. Porosity and hydraulic conductivity were measured using 100cc can. Cumulative infiltration depth was measured using a cylinder buried into the surface ash (1) and the middle ash (2). *:after Nishibu et al. (1980), **:after Kono and Tohma (1979), ***:data from Hokkaido national agricultural experiment station.

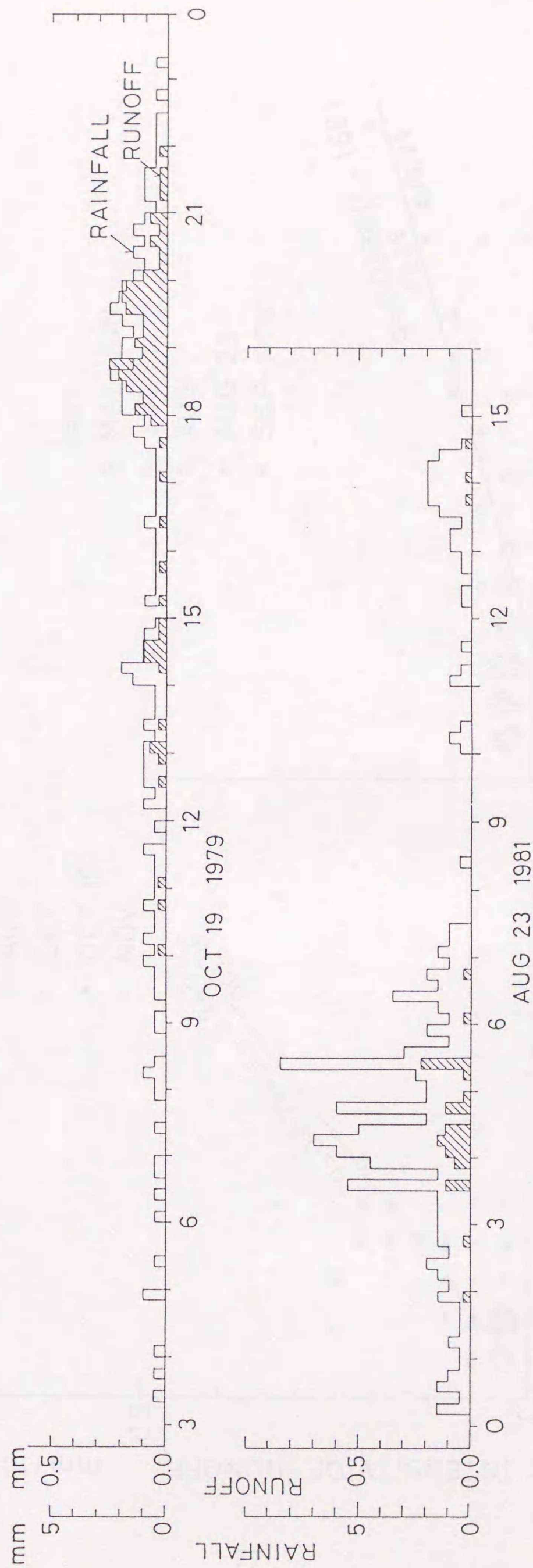


Figure 2-12 Two examples of discharge hydrograph for the events, October 19, 1979 and August 23, 1981.

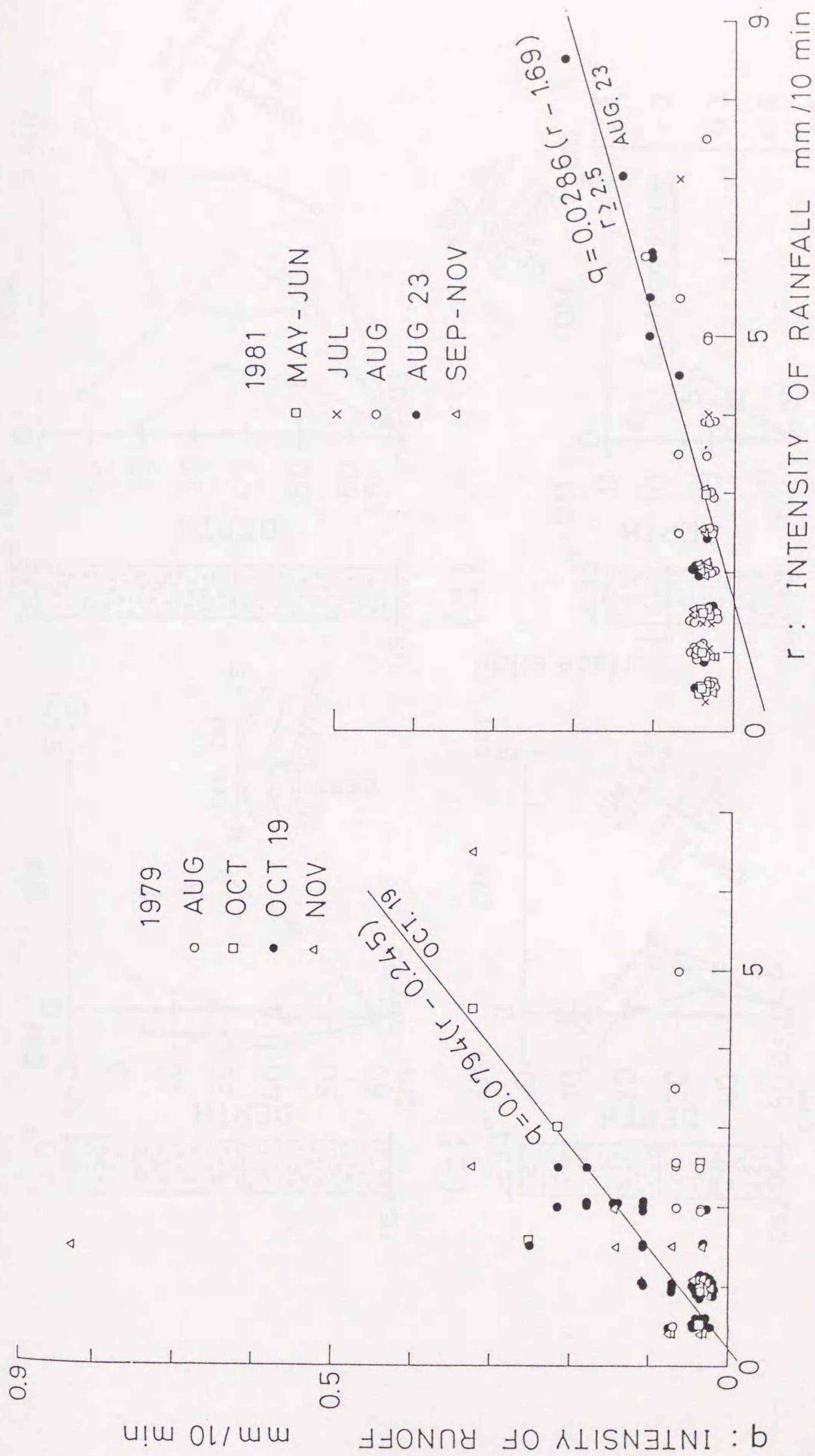


Figure 2-13 Relationships between the intensity of rainfall and the intensity of surface runoff.

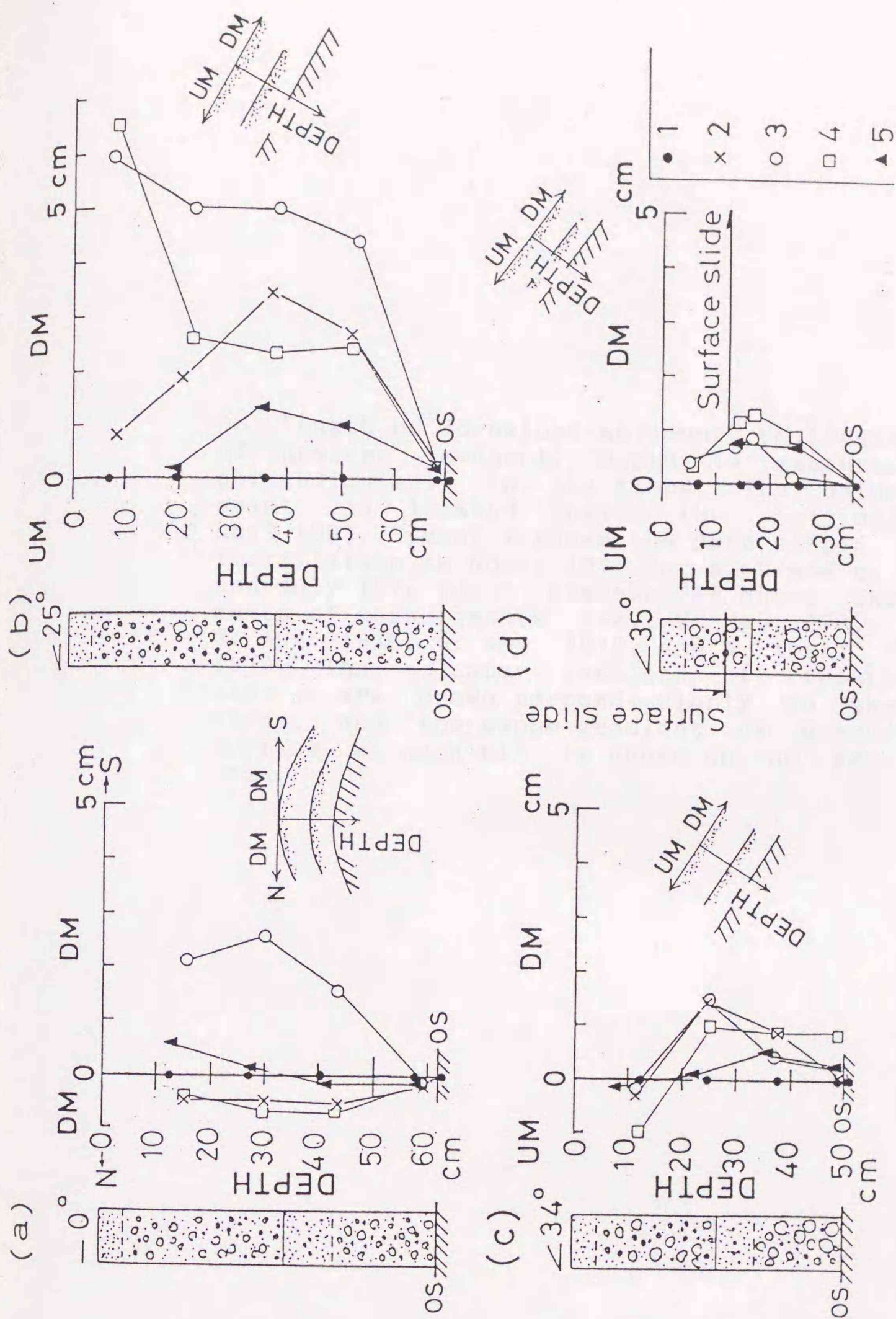


Figure 2-14 Subsurface creep movement of tephra layers at four test plots (a-d) on the experimental slope. (continued)

DM: Length of downslope movement, UM: Length of upslope movement. Depth is measured perpendicularly to the slope. The datum point is located inside the original soil (OS). Symbol 1 shows the date of pin installation in Nov., 1977 for a, b and c, and July 1978 for d. Symbols 2-5 shows the dates of measurements, i.e., 2: May 1978, 3: Aug. 1978, 4: Nov. 1978, and 5: April 1979. The columnar sections of tephra layers are drawn perpendicularly to the slope, and the slope gradient of ground surface at each plot is shown on the section.

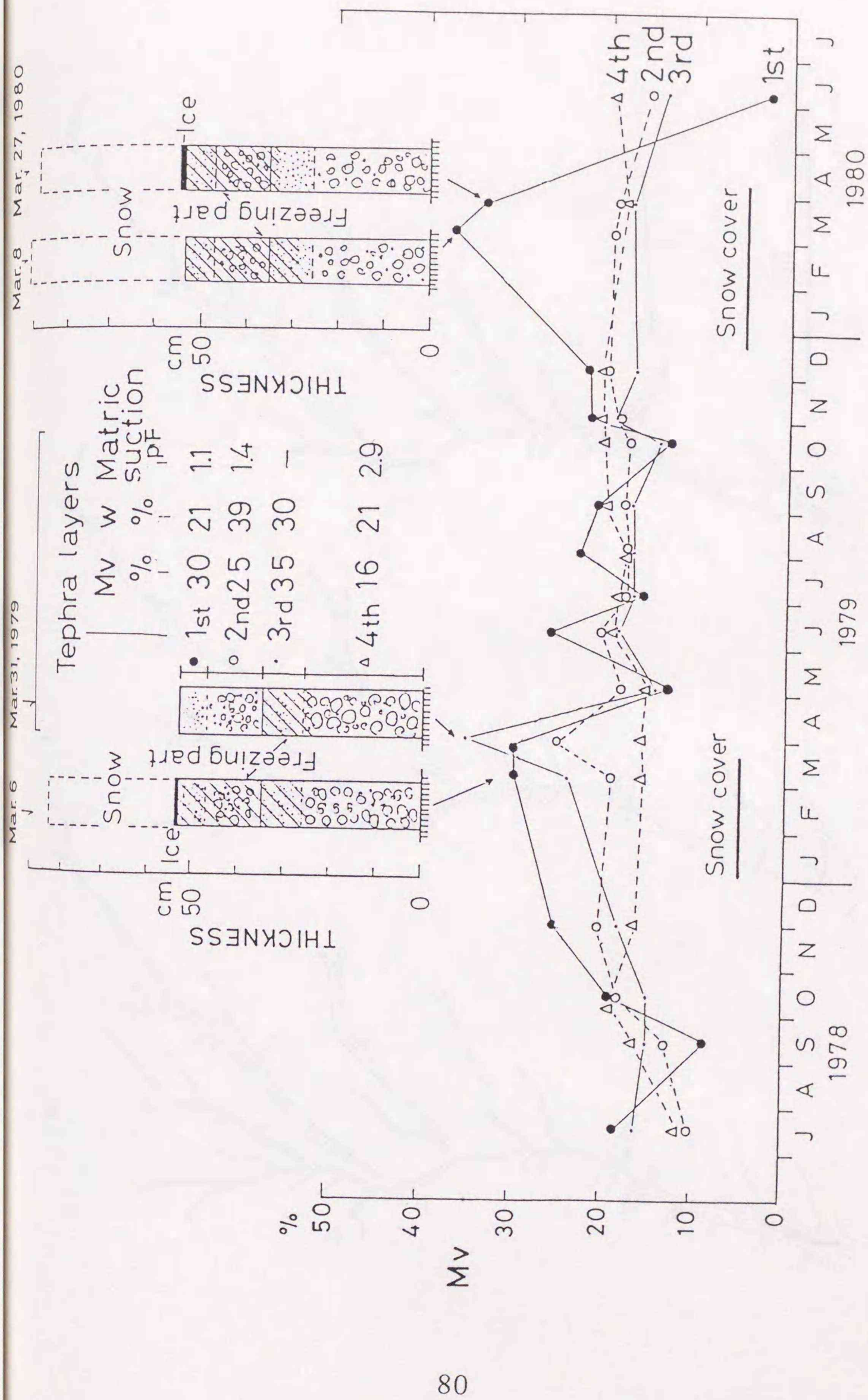


Figure 2-15 Temporal variations both of the volumetric water content (Mv) of the four tephra layers, and of the freezing part in the tephra layers on the main divide near U.
w: Water content by weight.

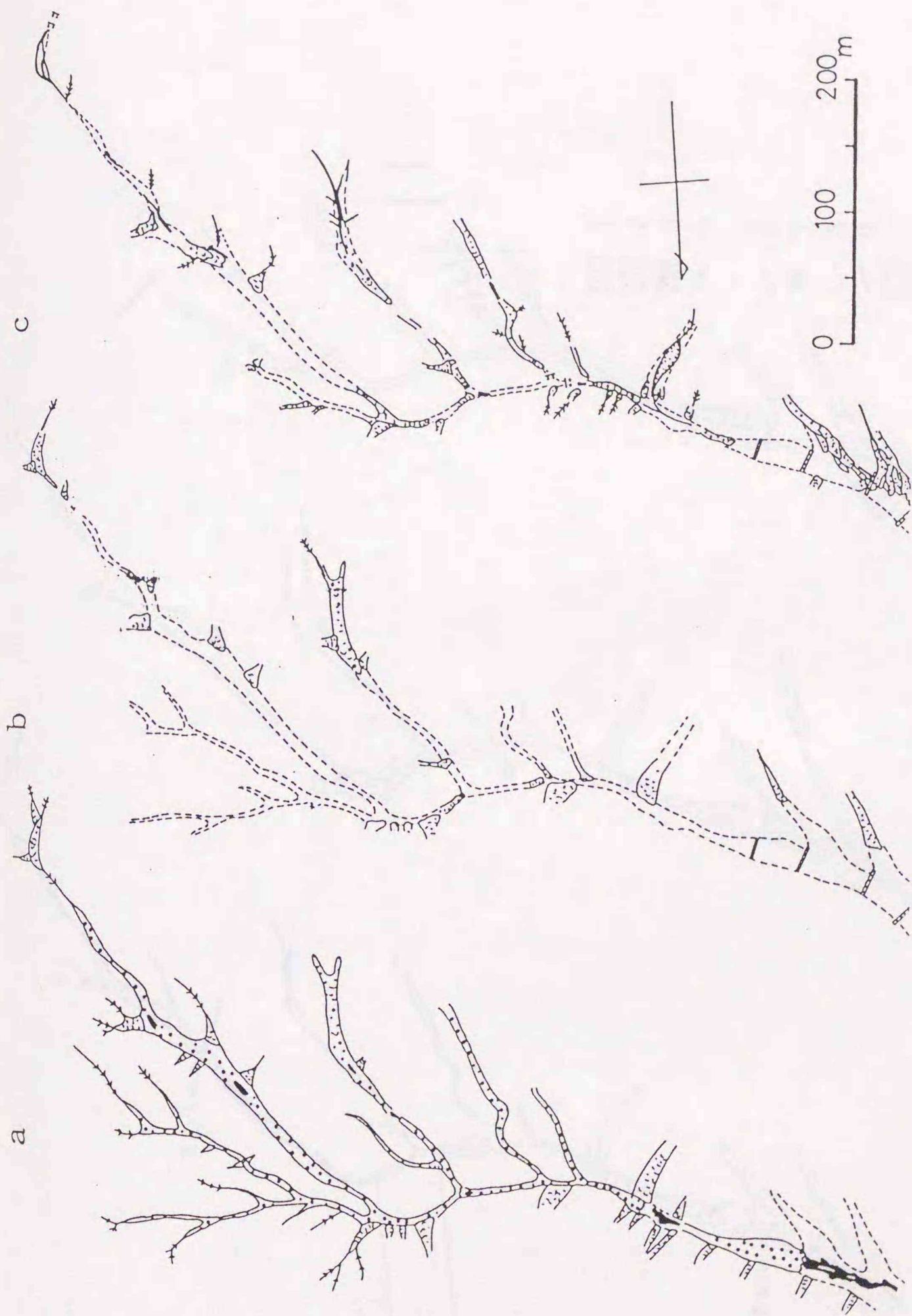


Figure 2-16 Geomorphic changes in the valley of Nishiyama river. August 1977-May 1979.
 Date of survey a: December 1, 1977, b: May 7, 1978, c: September 3, 1978, d: October 4, 1978, e: November 3, 1978, f: May 25, 1979, 1: pumiceous mudflow deposit, 2: Talus cone, 3: Water-laid deposit, 4: Scouring of valley floor, 5: Nick point, 6: Sabo-dam, 10: Slit-dam, 11: Road.

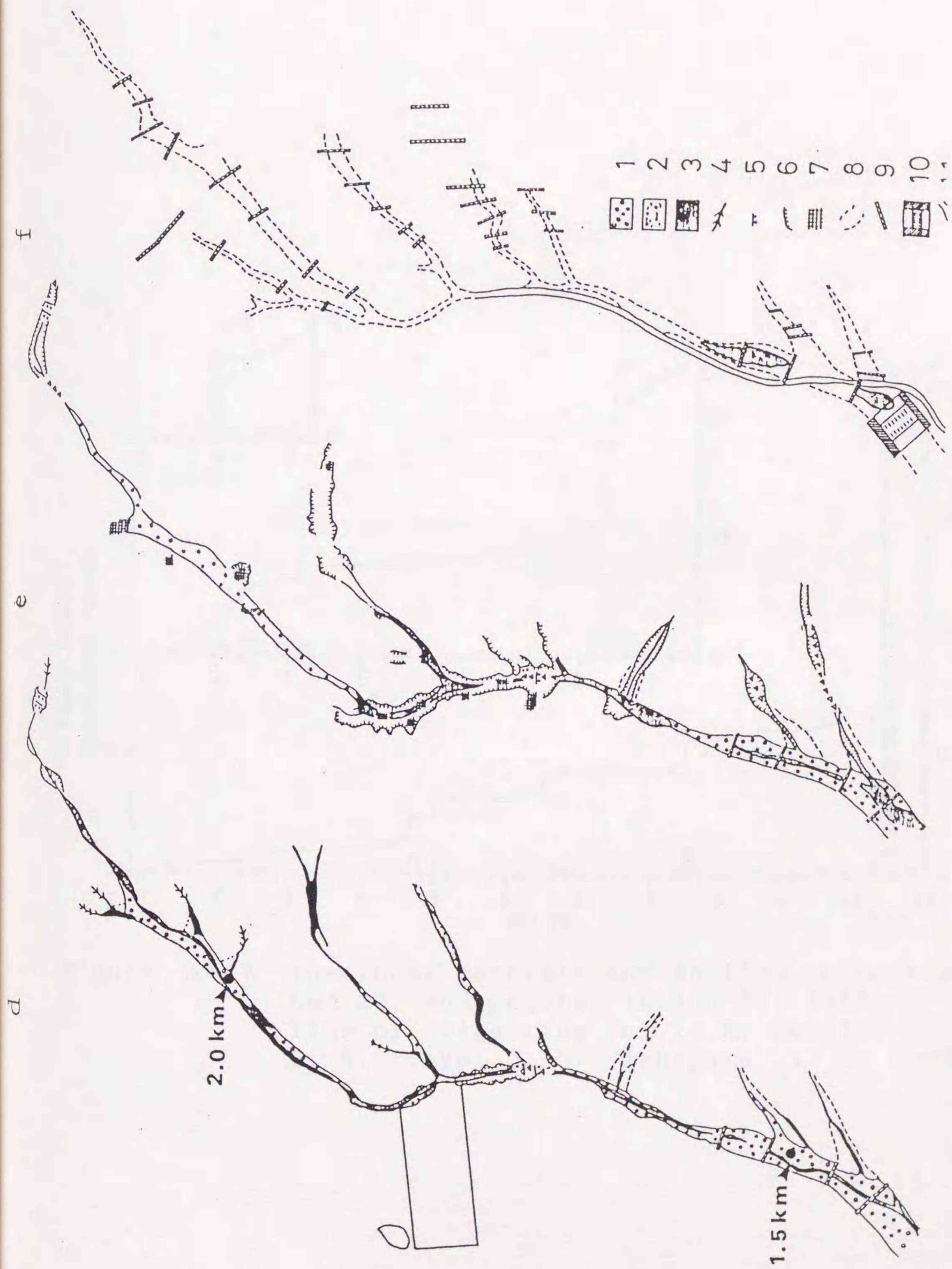


Figure 2-16 Geomorphic changes in the valley of Nishiyama river. August 1977-May 1979. (continued)

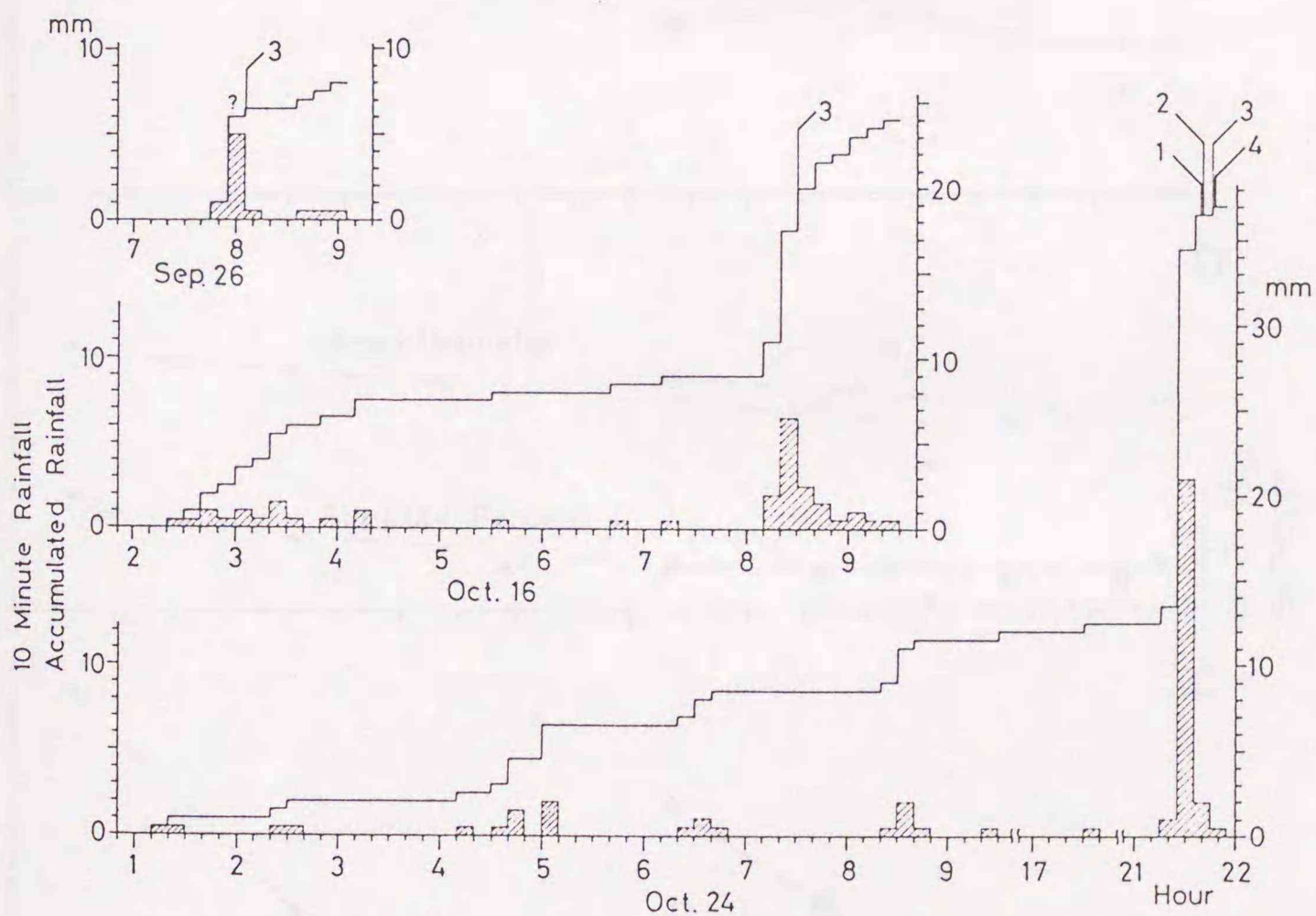


Figure 2-17 10-minute rainfall and mudflow on September 26, and October 16 and 24, 1978.
Time of triggering for 1: R. Sobetsu-onsen;
2: R. Itaya; 3: R. Nishiyama, 4: R. Ko-Uzu.

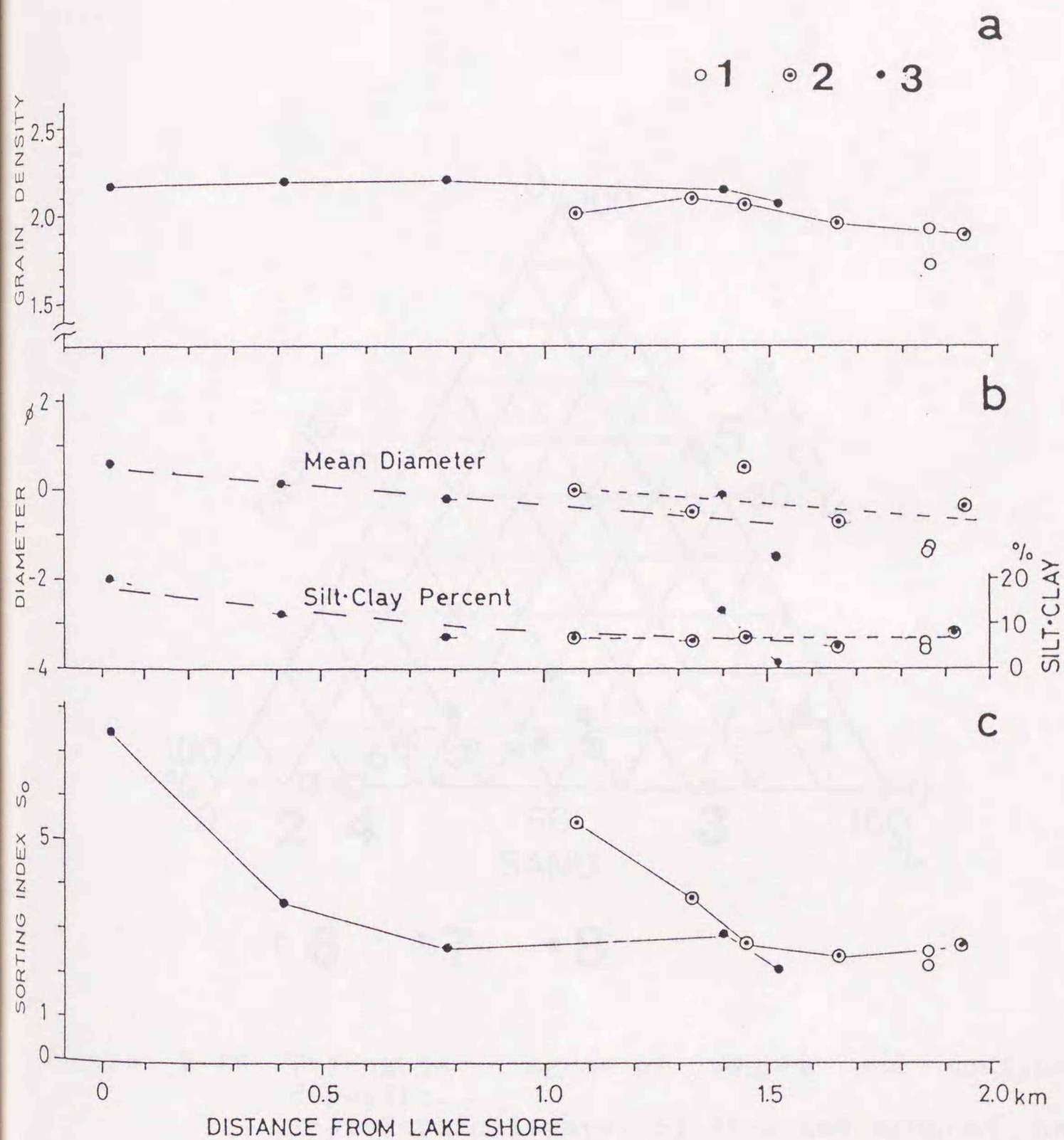


Figure 2-18 Longitudinal change of mudflow deposits on valley floor and alluvial fan.
a: Grain density, b: Mean diameter and silt-clay percent, c: Sorting index $S_o = (Q_{75}/Q_{25})^{1/2}$. Mudflows occurred on 1: August -early September, 2: September 26 and 3: October 24.

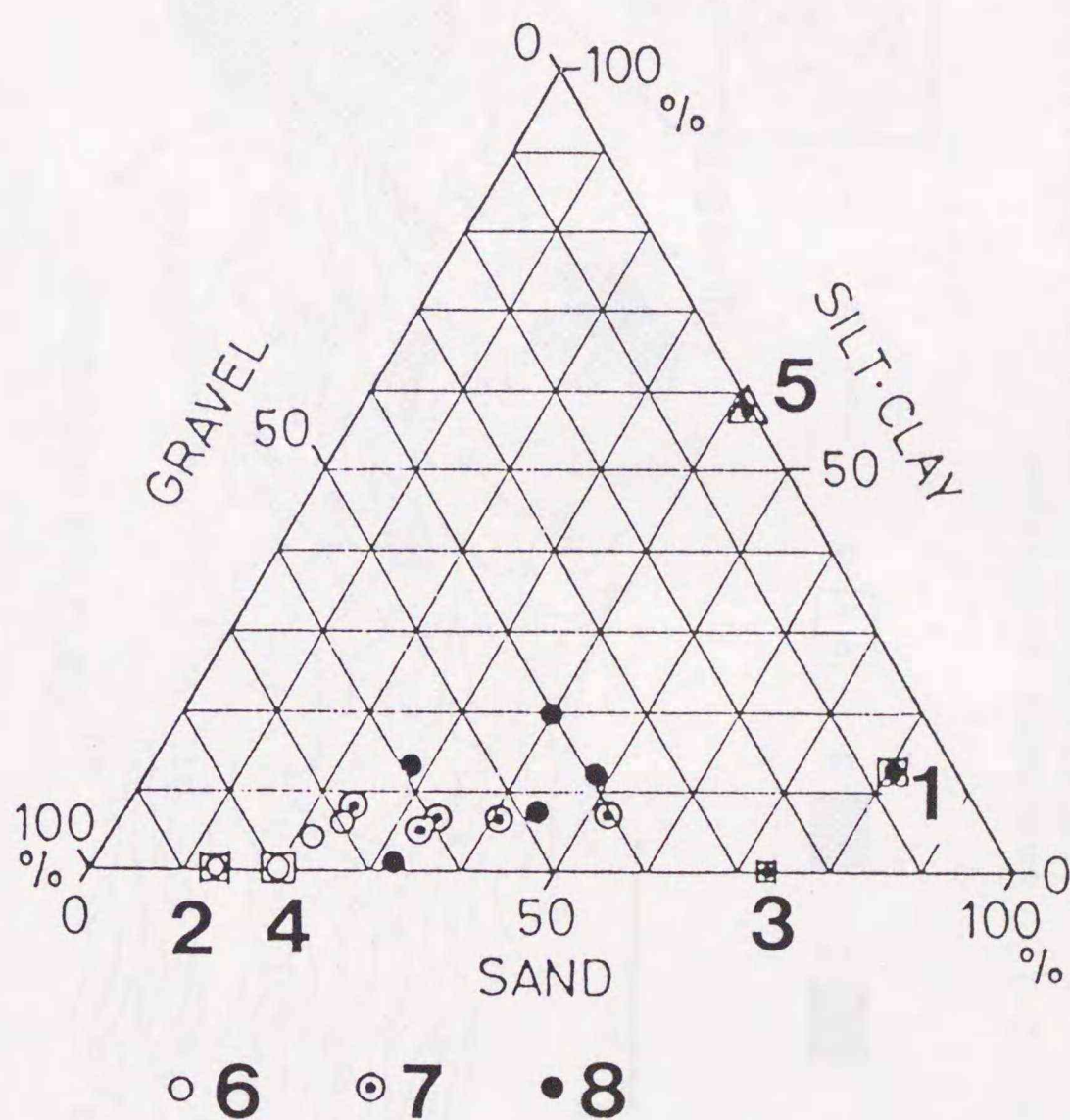


Figure 2-19 Triangular diagram of tephra and mudflow deposits.
 1-4: Tephra layers, 5: Fine ash erupted on September 12/13, 1978 6: Mudflow deposit of August - early September, 1978, 7: Mudflow deposit of September 26, 1978, 8: Mudflow deposit of October 24, 1978.

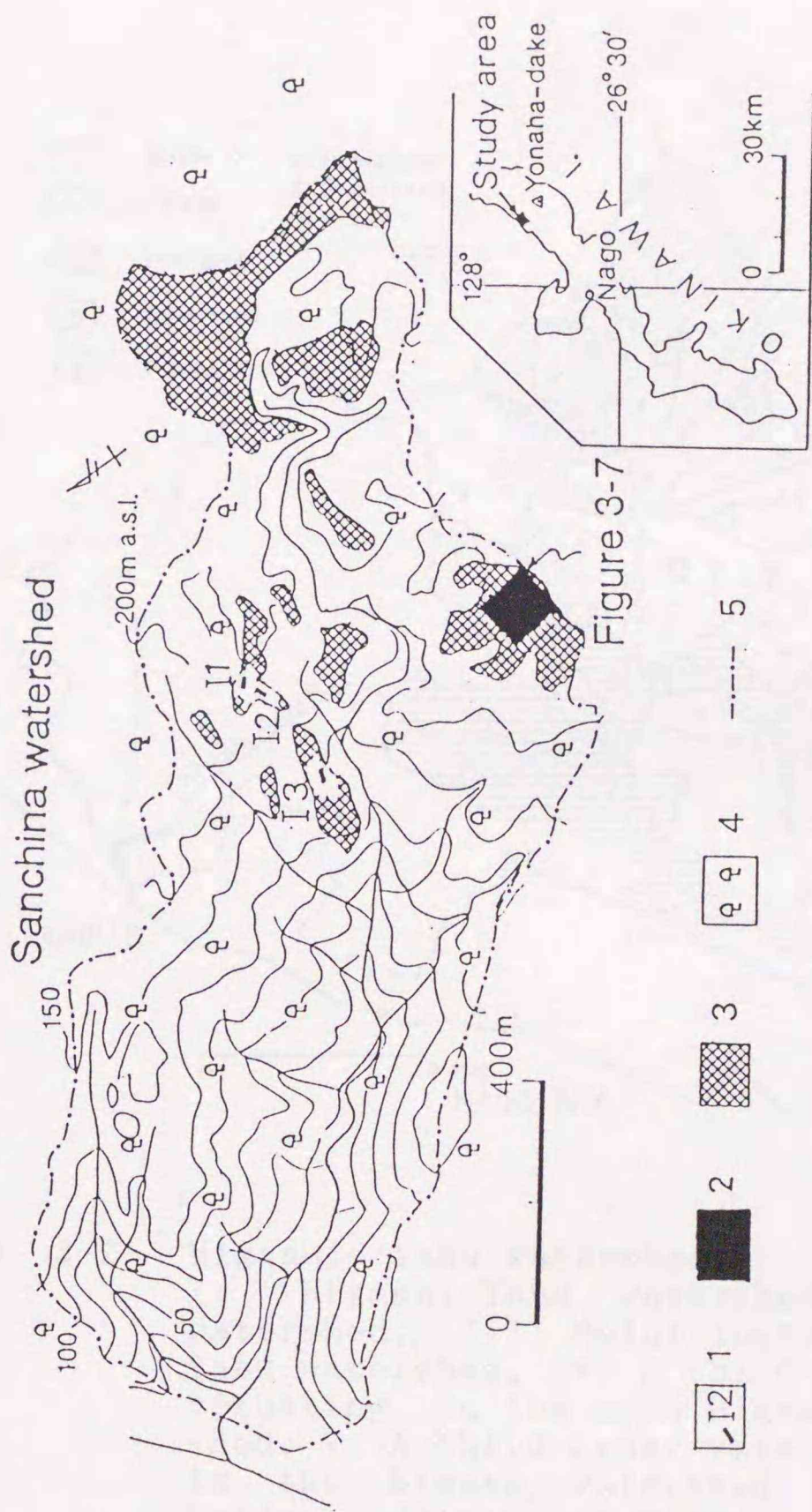


Figure 3-1 Sanchina watershed.
 1: measurement slope for inter-rill erosion (I1, I2 and I3), 2: measurement area for rill erosion, 3: bare land, 4: forest, 5: divide of Sanchina watershed.

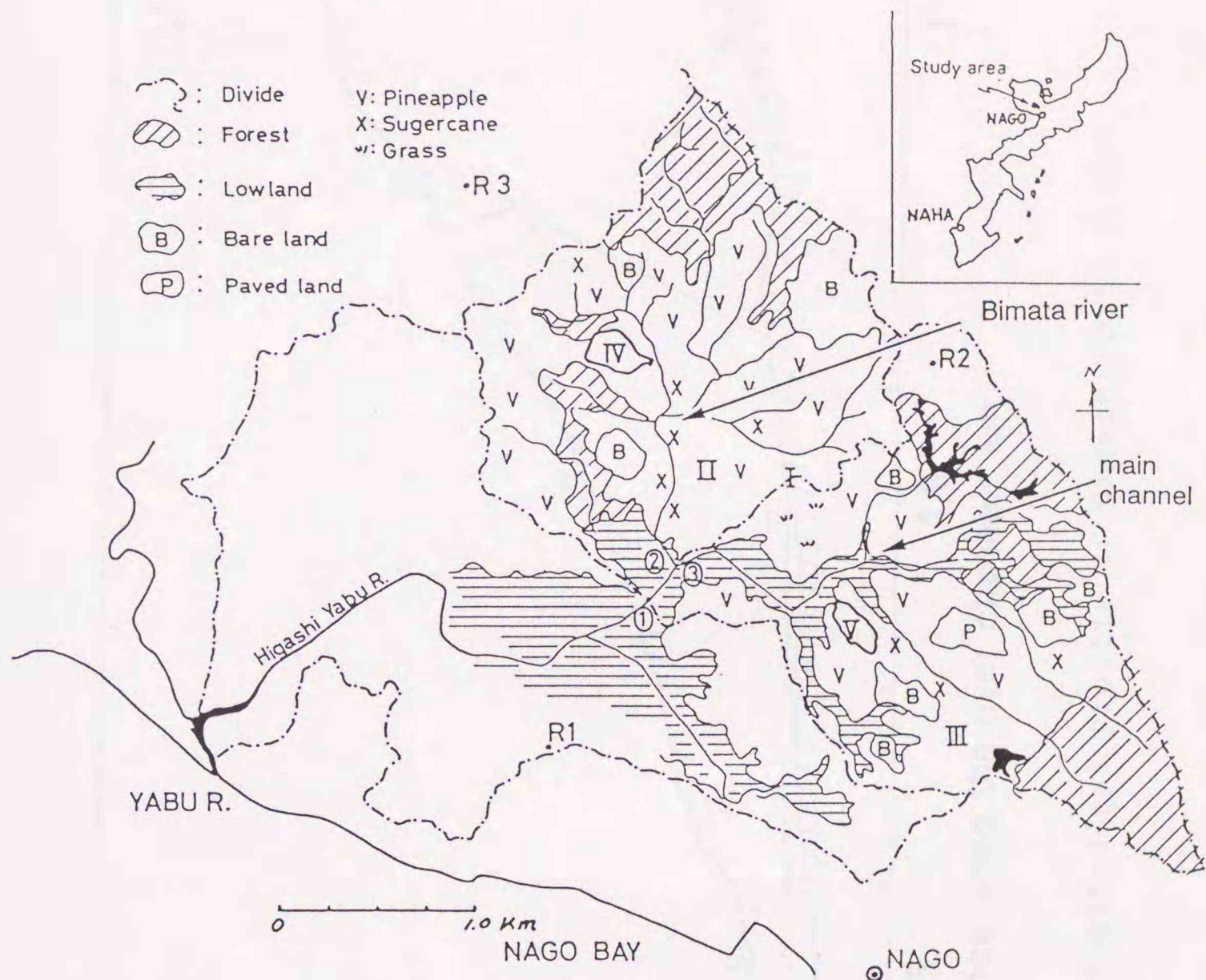


Figure 3-2 Higashi- Yabu watershed.
 I: Higashi-Yabu watershed, II: Bimata watershed, III: Maintributary of Higashi-Yabu watershed, IV: A third-order watershed situating in the main Higashi-Yabu watershed, V: A third-order watershed situating in the bimata watershed (1): Shirakane Bridge, (2): Suido Bridge, (3): Ashihara
 R1, R2 and R3: Rain gauge.

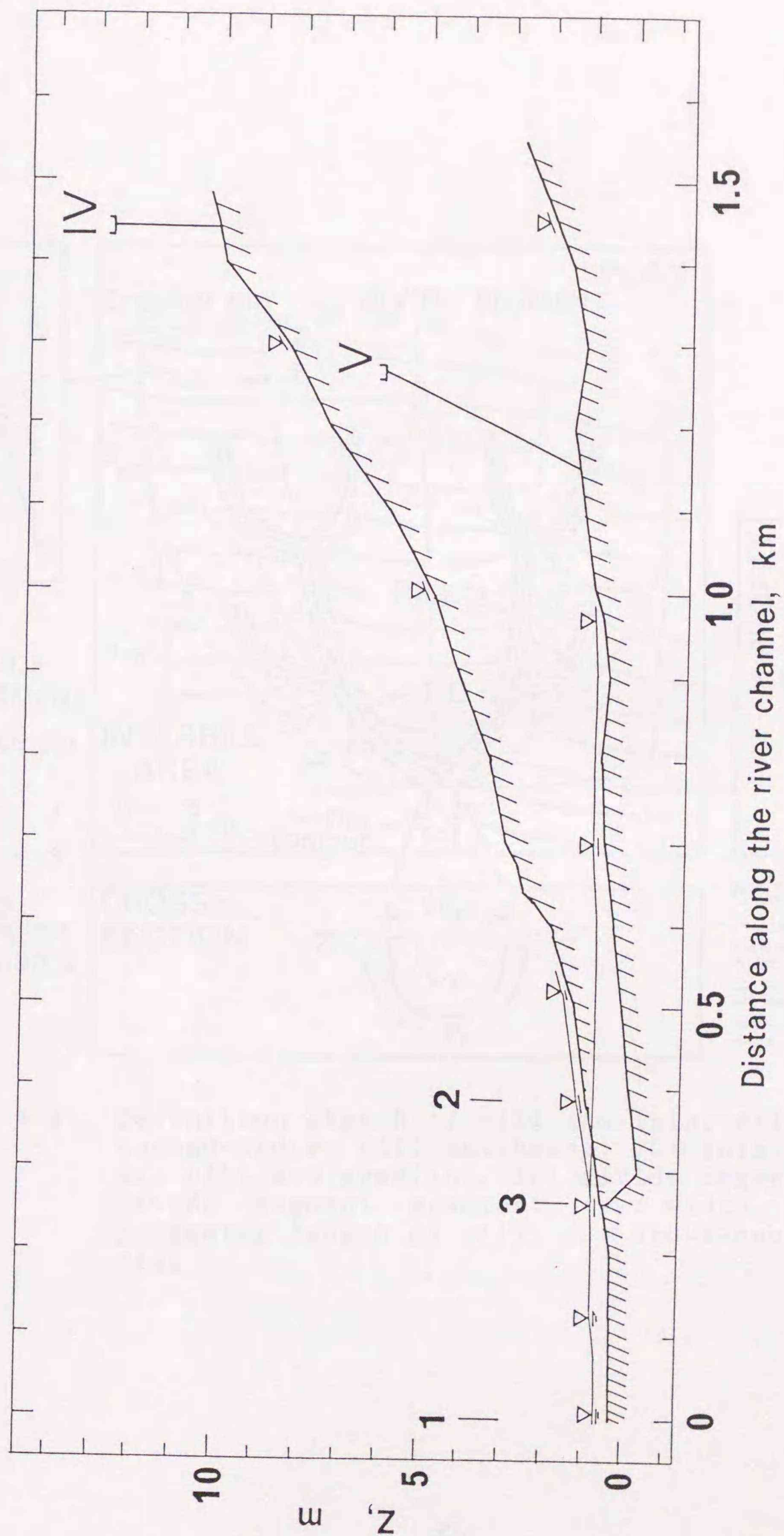


Figure 3-3 Longitudinal profile of Higashi-Yabu river.

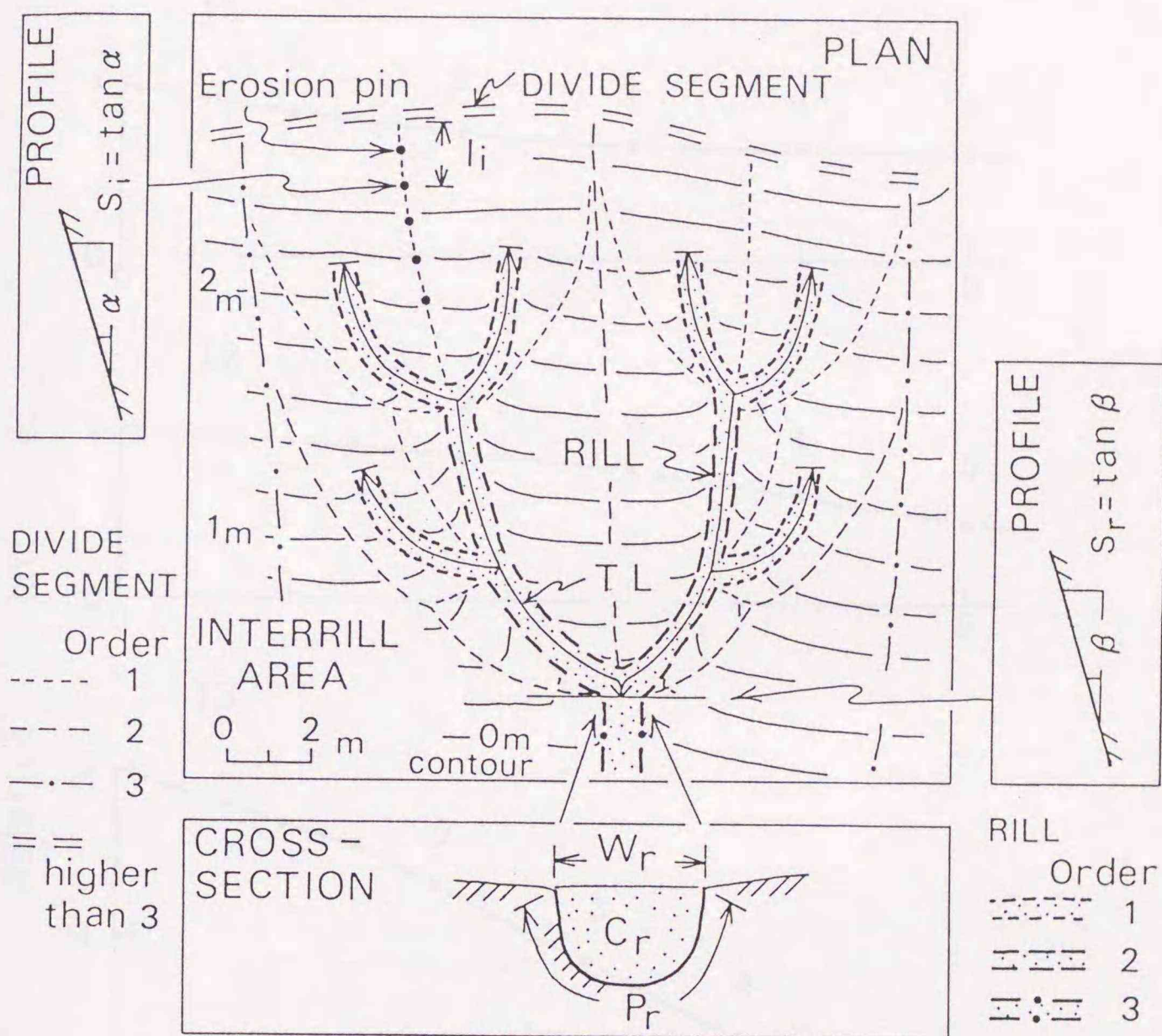


Figure 3-4 Definition sketch of rill and inter-rill area in a second-order rill catchment. TL: total rill length, s_r : rill bed gradient, l_i : divide segment length, s_i : divide segment gradient, w_r : width of rill, p_r : perimeter length of rill, c_r : cross-sectional area of rill.

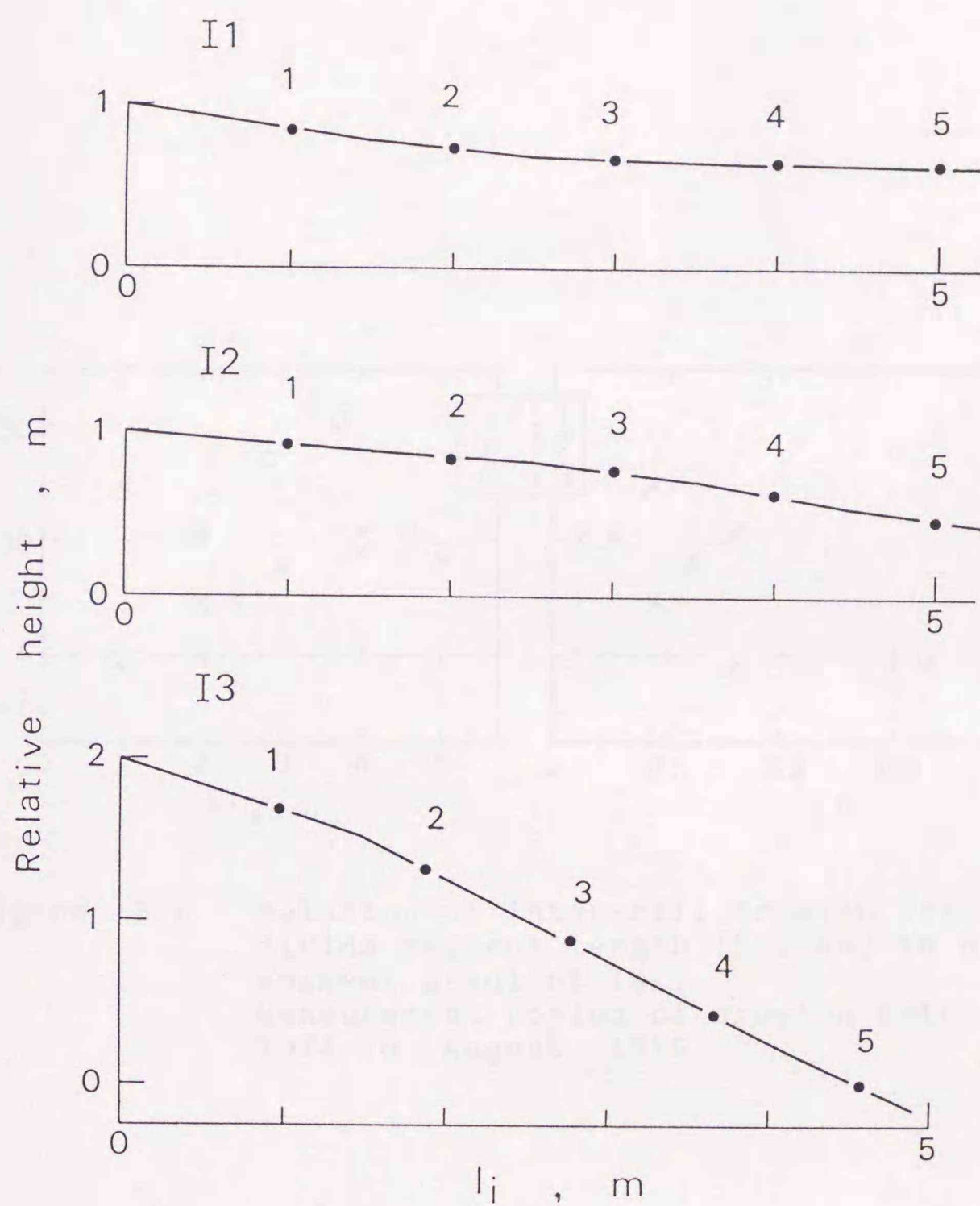


Figure 3-5 Profiles of first-order divide segment on inter-rill areas. Solid circles on profiles show location of erosion-pin sites.

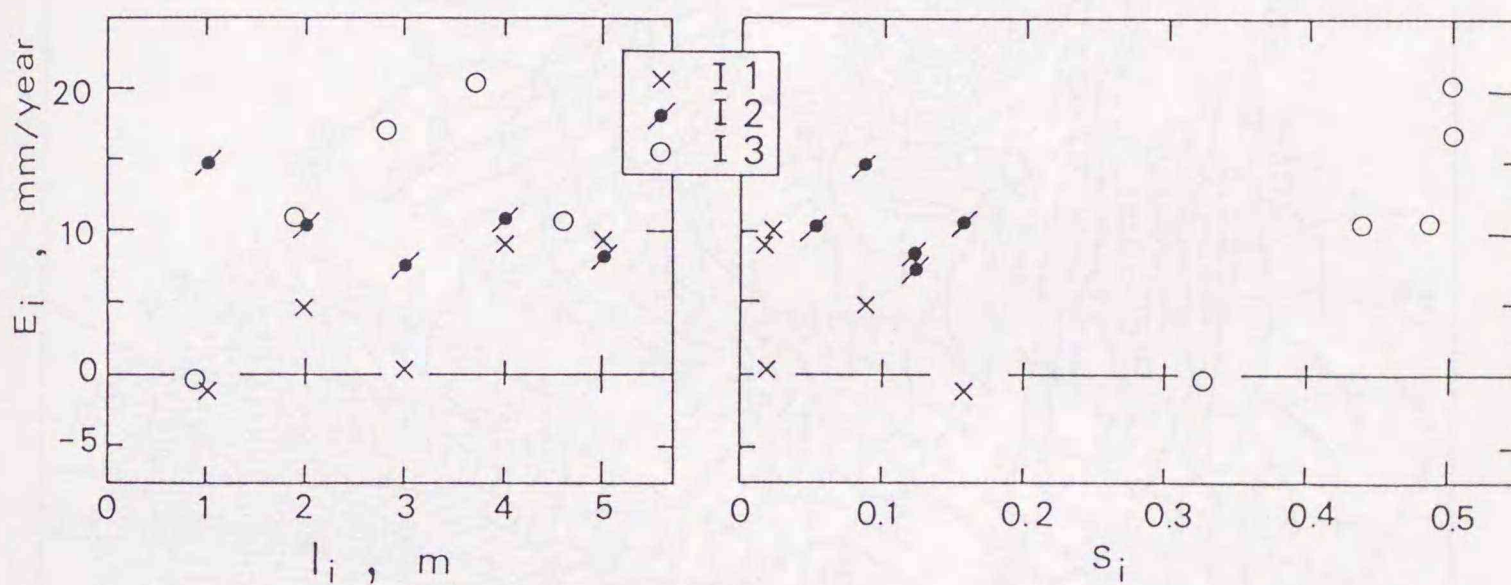


Figure 3-6 Relation of inter-rill erosion rate(E_i) to divide segment length (l_i) and to divide segment gradient (s_i). Measurement period of erosion rate: June 1974 to August 1976.

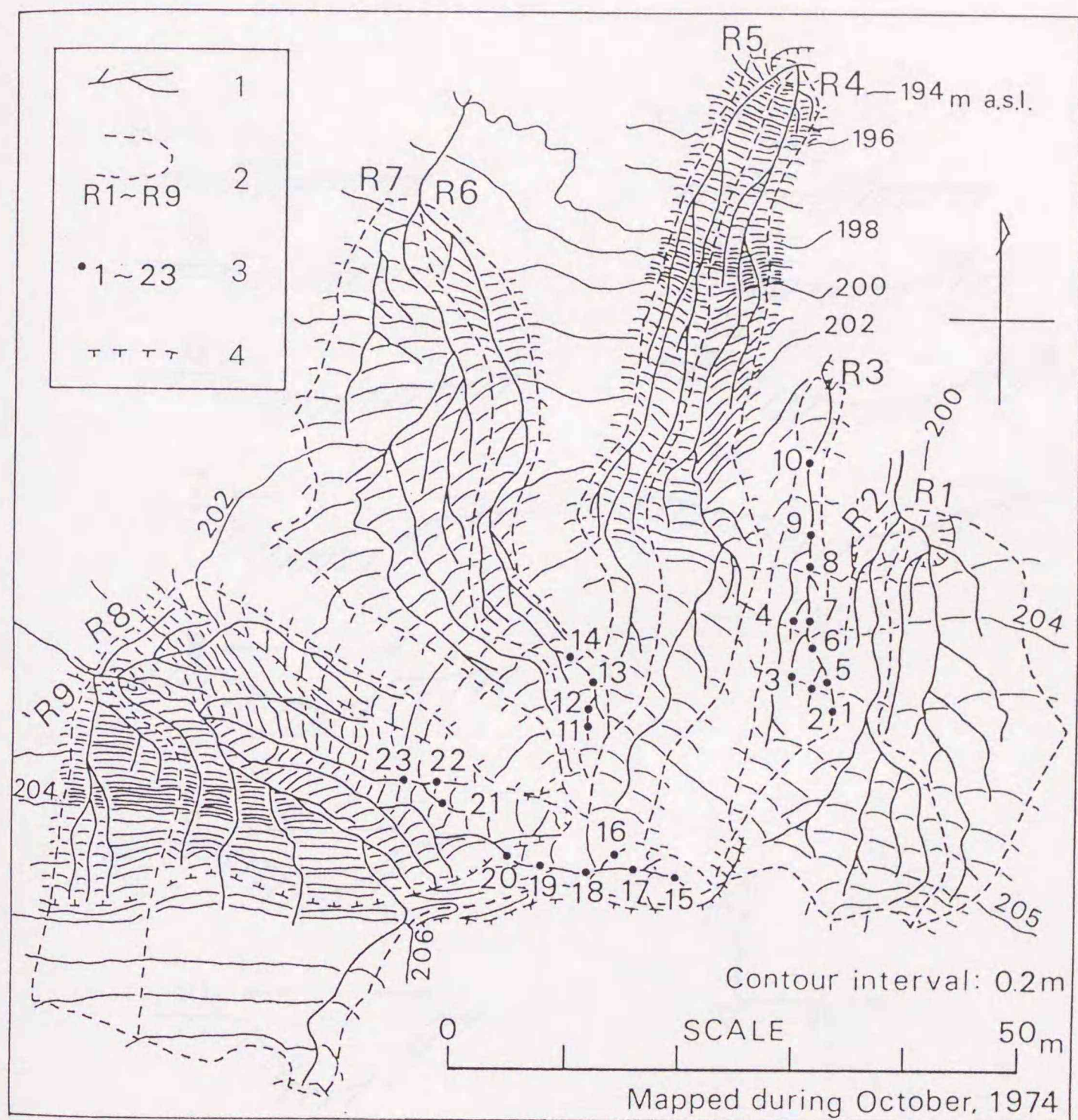


Figure 3-7 Topography of third-order rill catchment.
 1: rill, 2: divide and number of catchment,
 3: site and number of rill cross-section,
 4: steep slope.

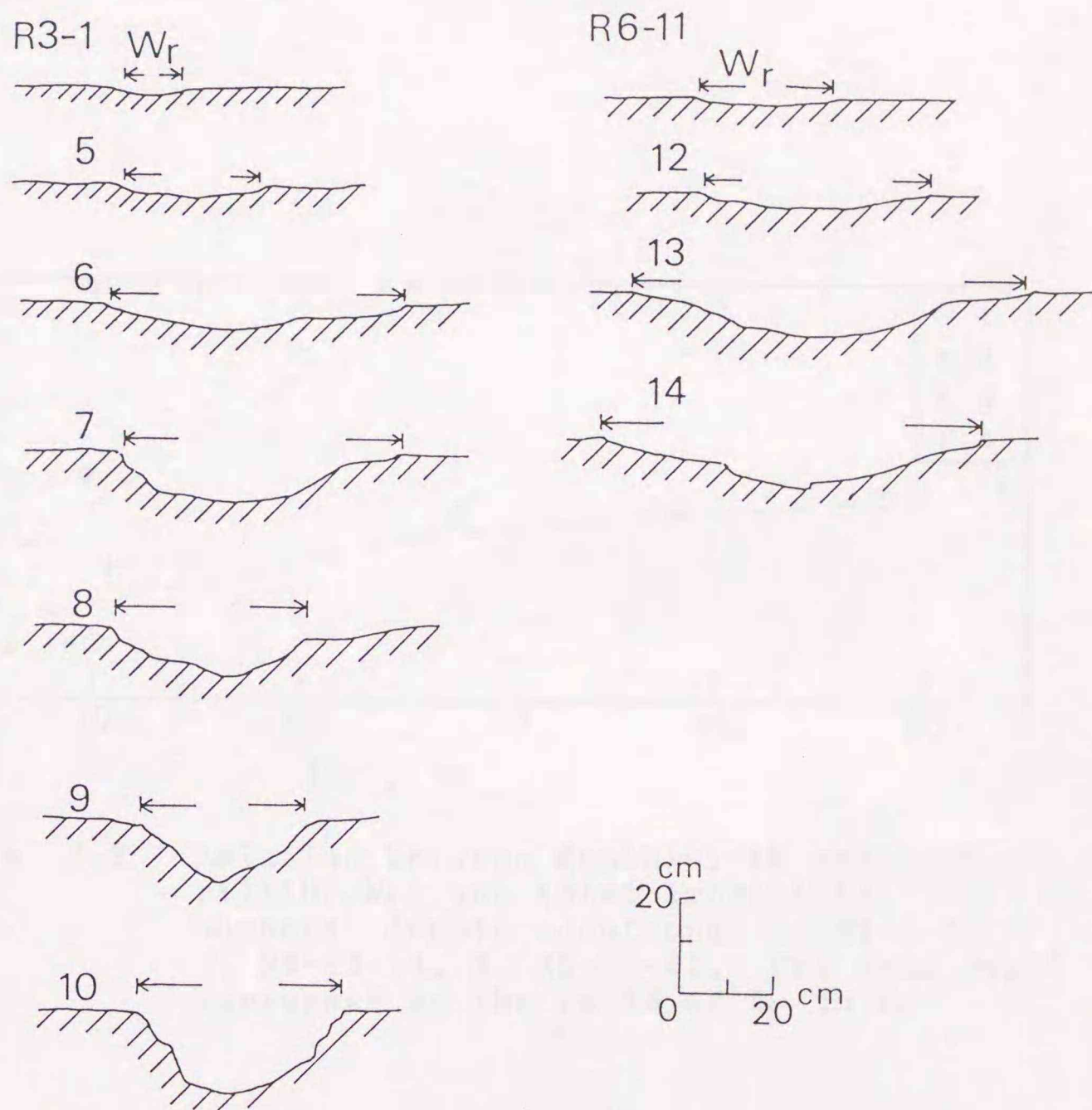


Figure 3-8 Some of rill cross-sections.

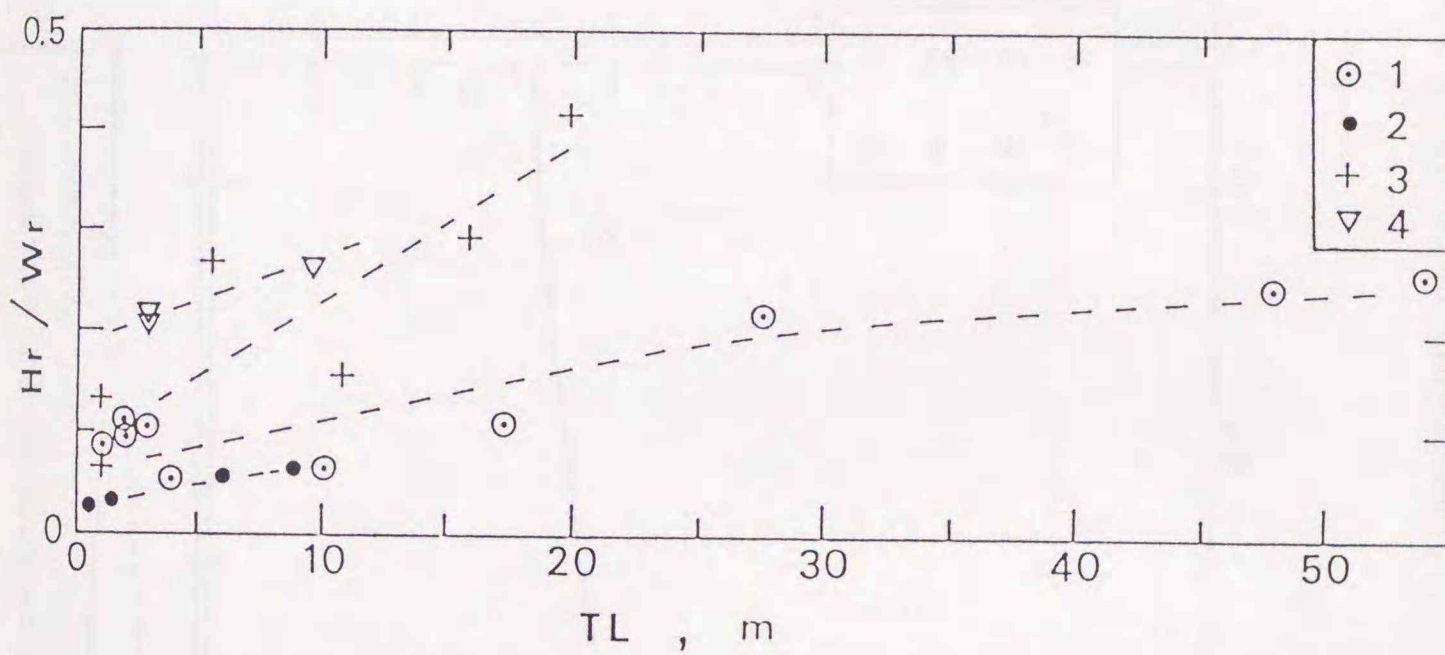


Figure 3-9 Relation between depth width ratio of rill(H_r/W_r) and total length(TL). Numbers denote locations: 1. R3-1-10, 2. R6-11-14, 3. R8-21-23, H_r : mean depth expressed by the ratio of C_r to W_r .

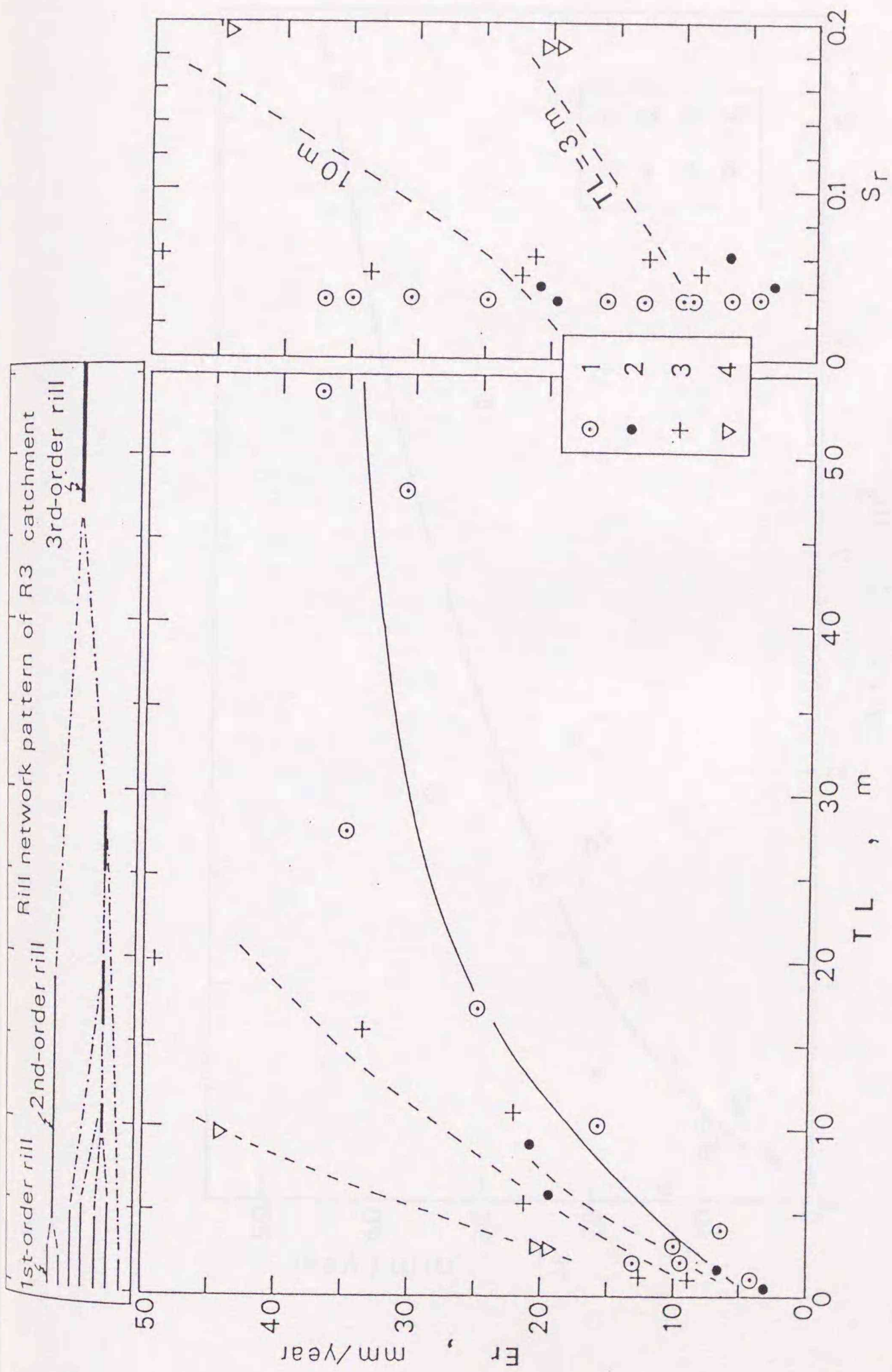


Figure 3-10 Relations of rill erosion rate (E_r) to total rill length (TL) and to bed gradient (S_r).
Legend is same as Figure 3-7.

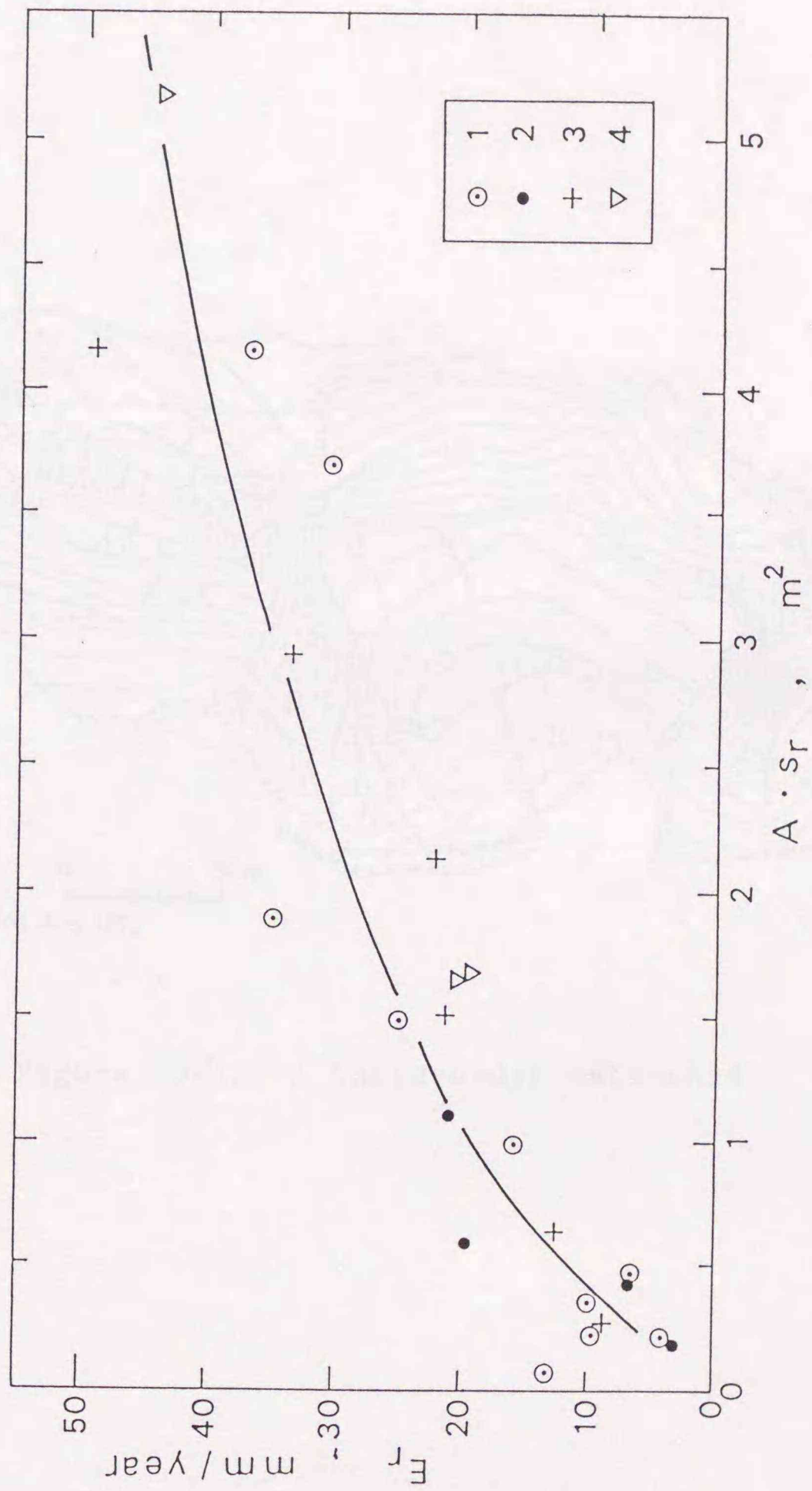


Figure 3-11 Relation of rill erosion rate (E_r) to the product of catchment area and rill bed gradient ($A \cdot s_r$). Legend is same as Figure 3-7.

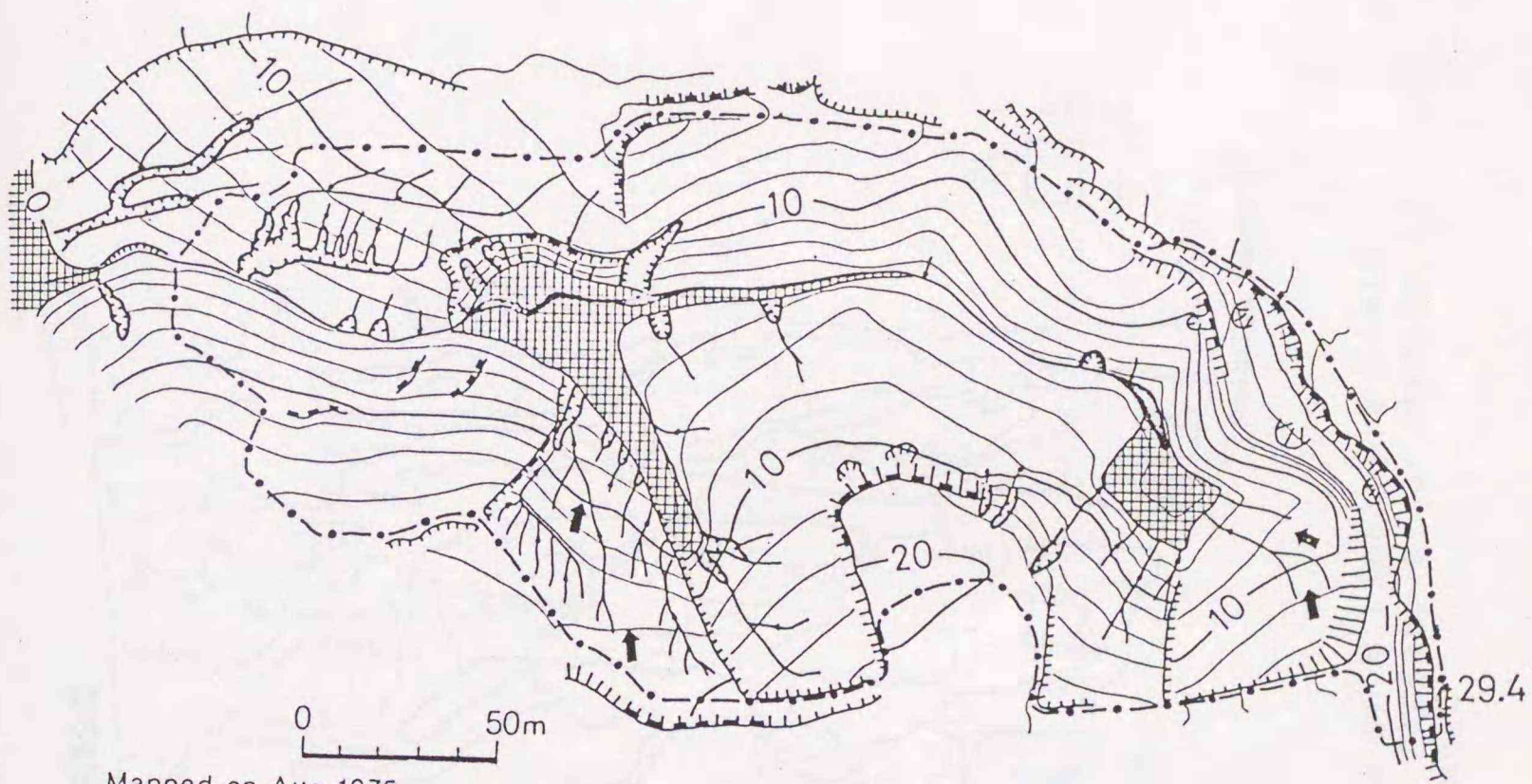


Figure 3-12 A third-order watershed.

Higashi-Yabu watershed

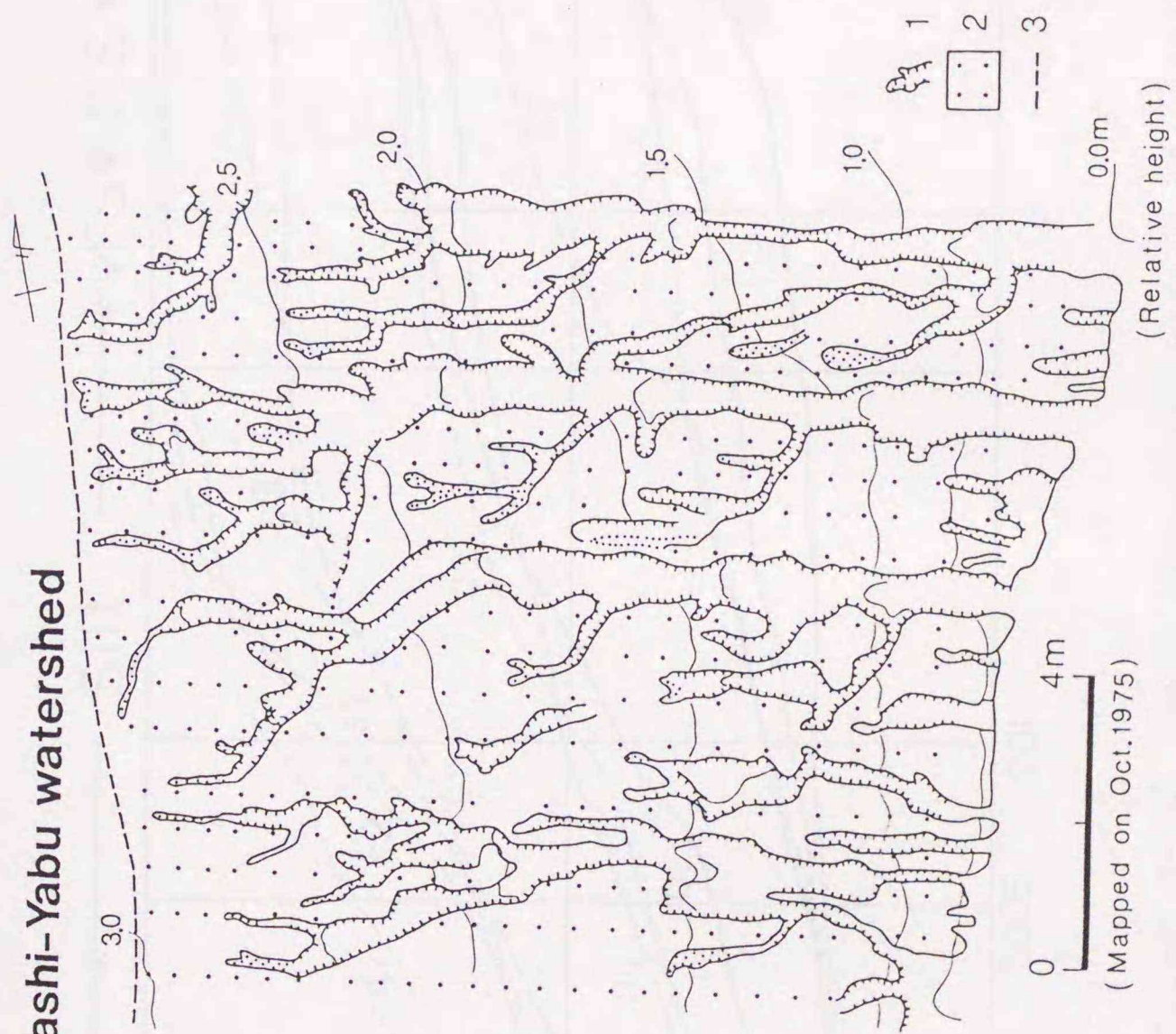


Figure 3-13 Rill erosion on a pineapple field.
1: Rill, 2: pineapple, 3: divide of third-order watershed.

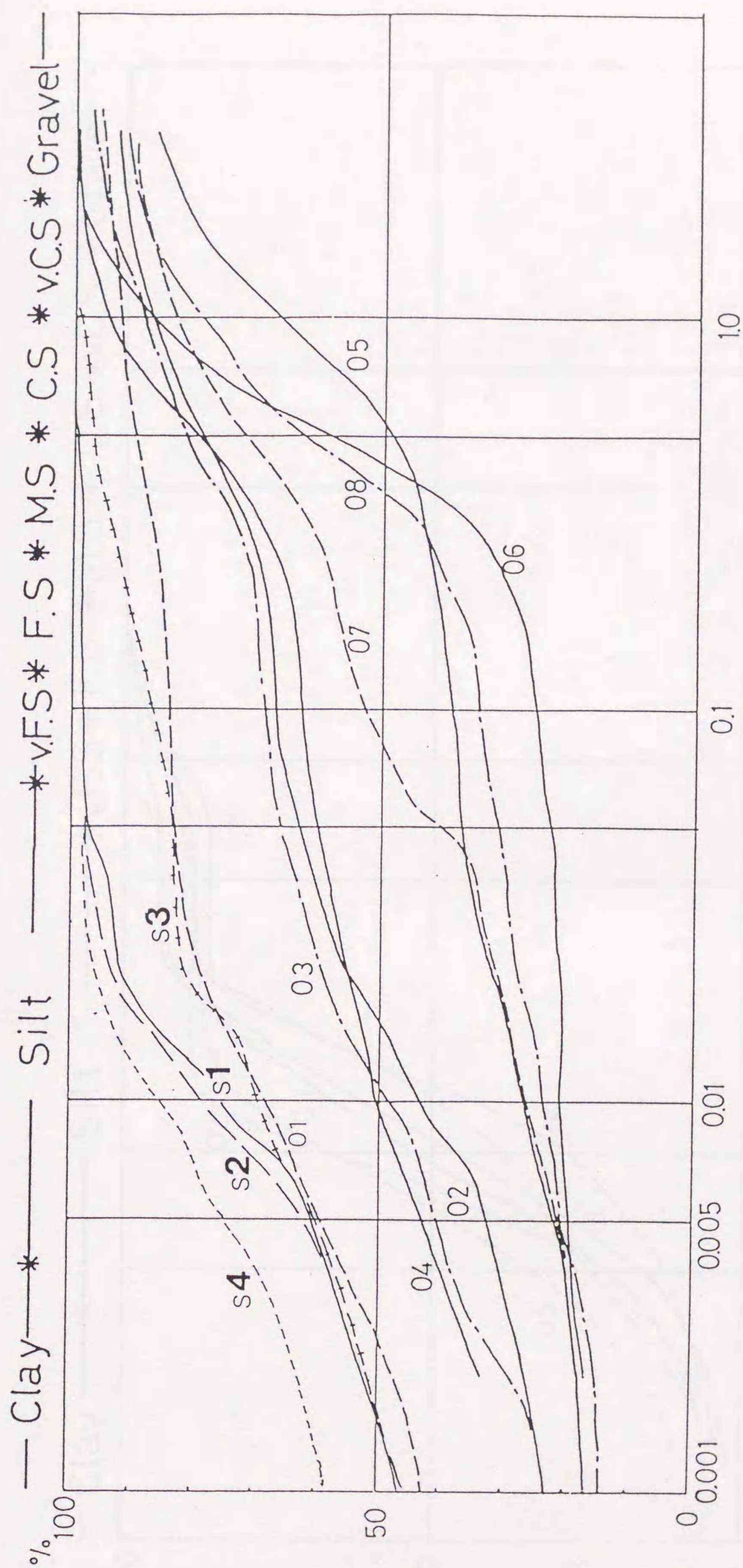


Figure 3-14 Grain size distribution of original forest soil, and bare land soil on inter-rill, rill and gully.

S1, S2, S3, S4 : Soil, 01, 02, 03 : Inter-rill slope
04, 05, : Rill head, 06, 07, 08 : Gully head.

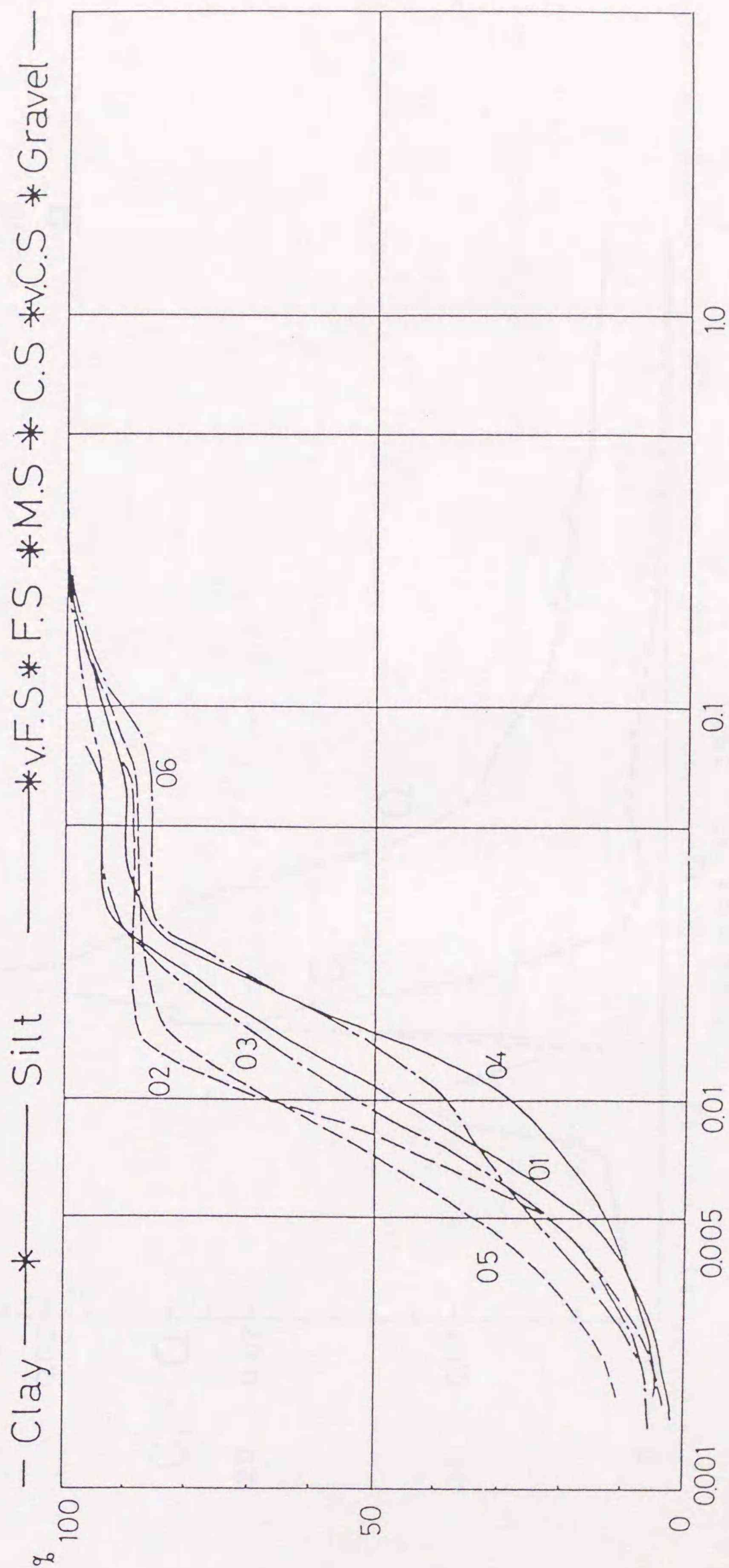


Figure 3-15 Grain size distribution of suspended-sediment.

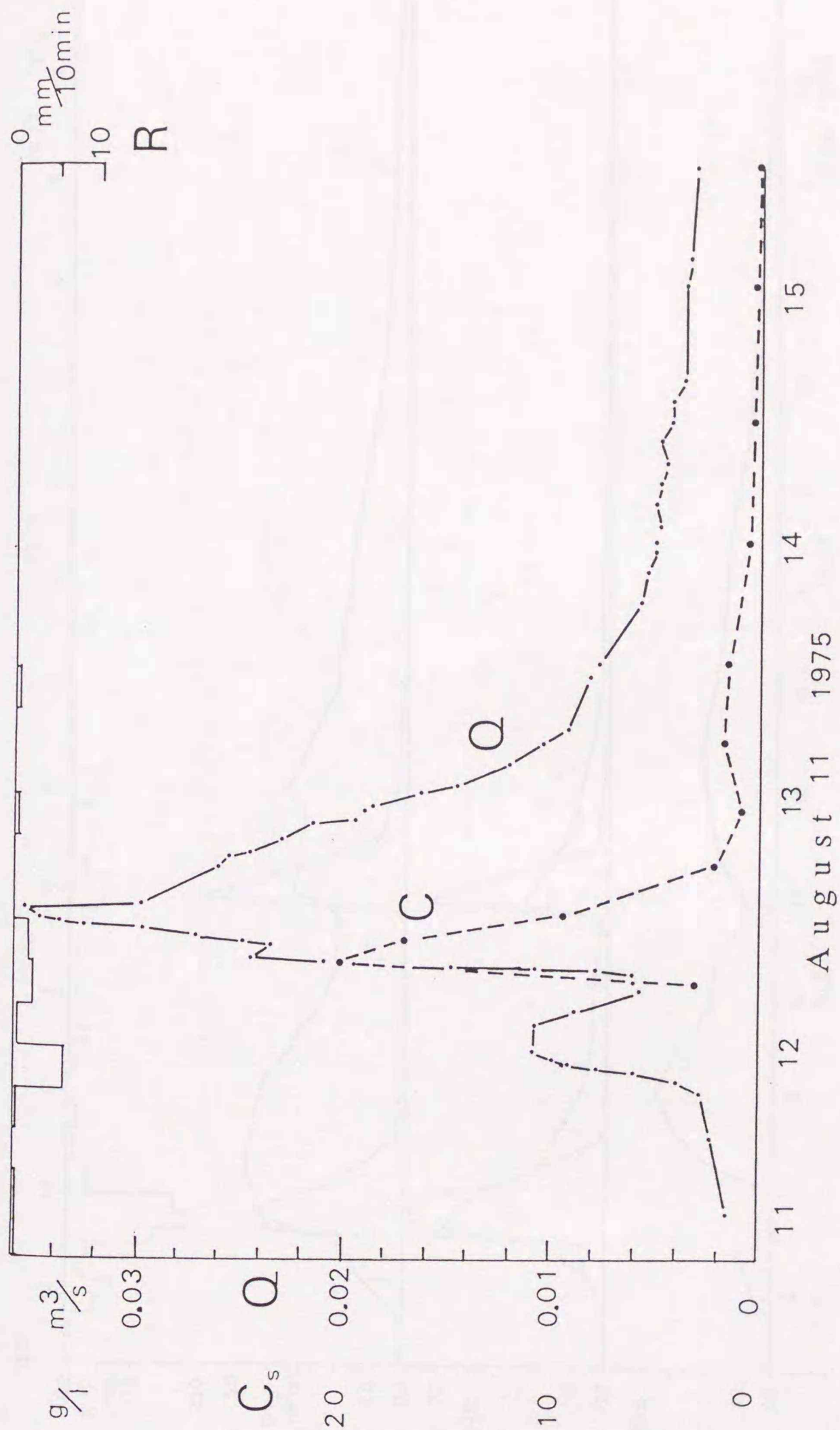


Figure 3-16 Rainfall (R), water discharge (Q) and suspended-sediment concentration (C_s) in the third-order watershed of V.

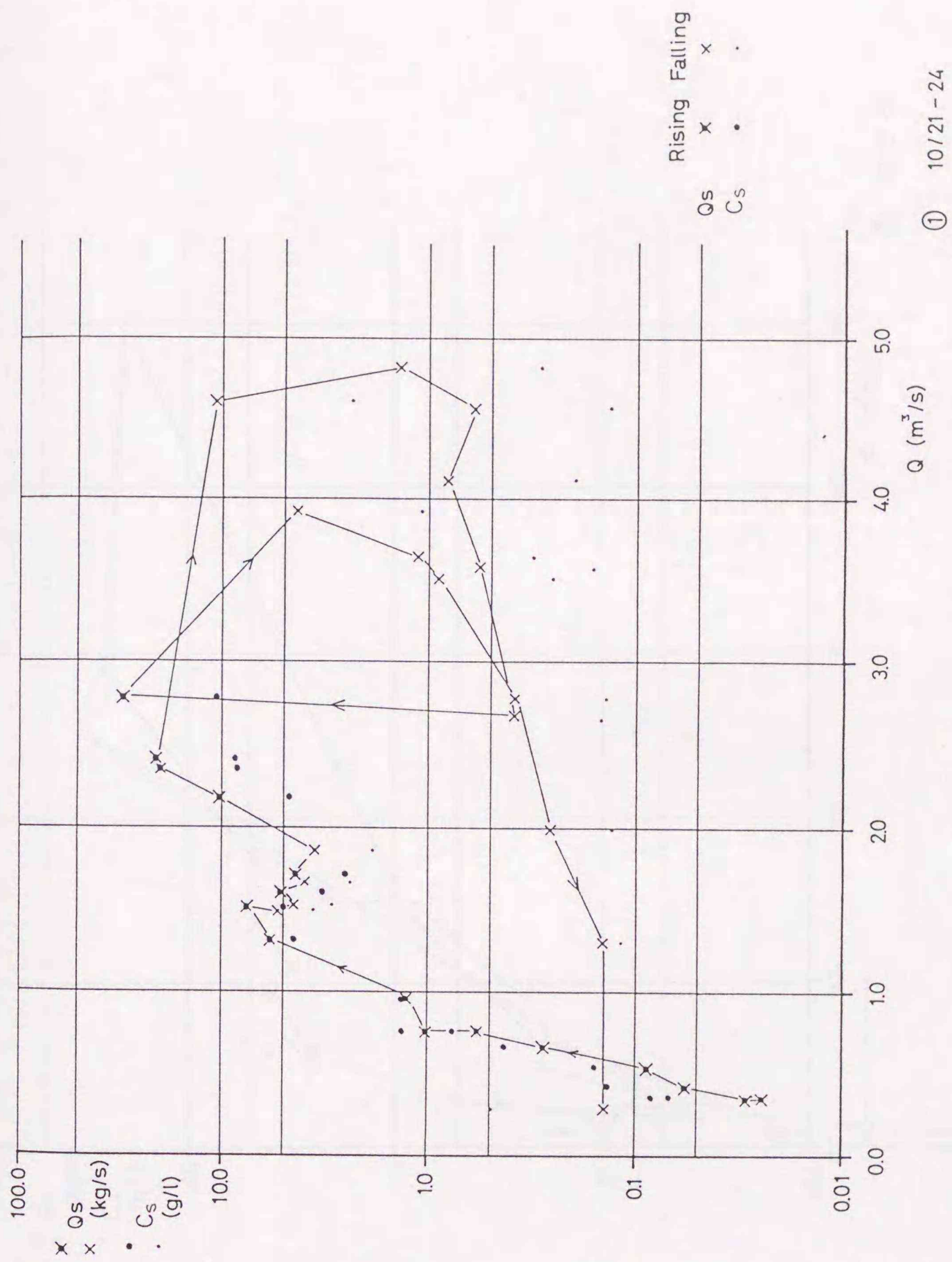
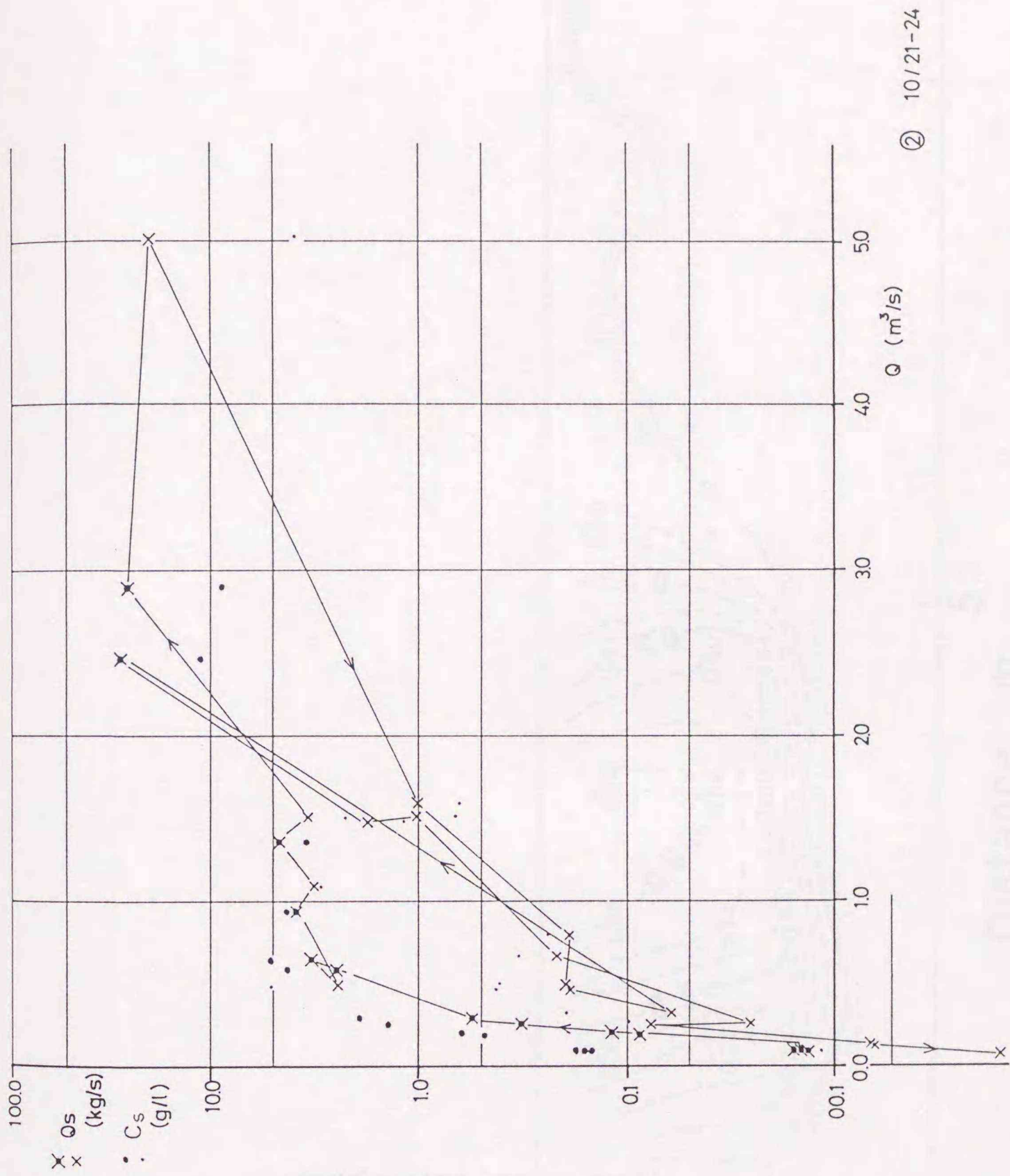


Figure 3-18 Relationship between water discharge and both suspended-sediment discharge and suspended-sediment concentration, measured at Shirokane Bridge.



② 10/21-24

Figure 3-19 Relationship between water discharge and both suspended-sediment discharge and suspended-sediment concentration, measured at Suido Bridge.

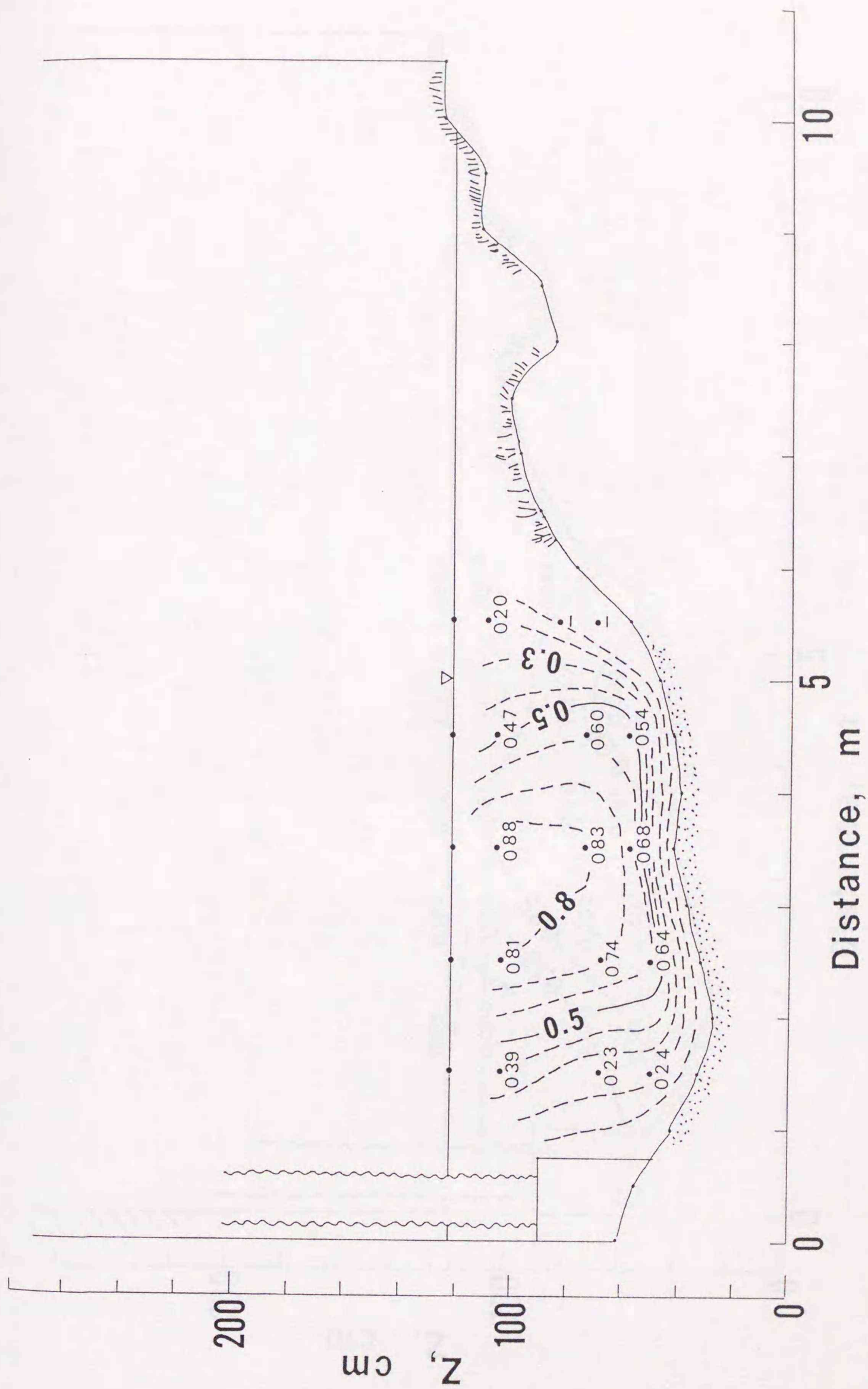


Figure 3-20 Cross-sectional distribution of flow velocity, measured at Shirokane Bridge. Unit of velocity is m/s.

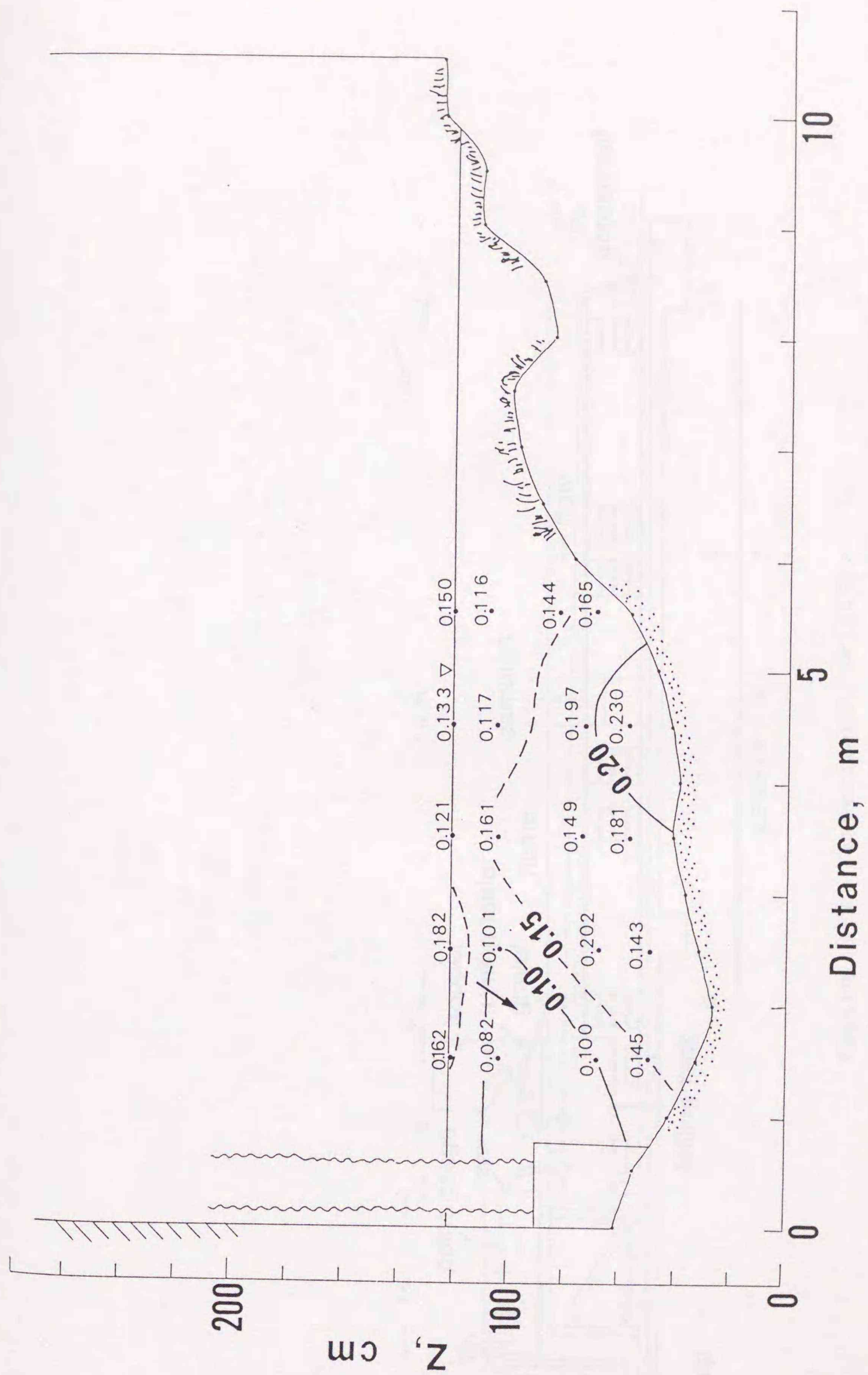


Figure 3-21 Cross-sectional distribution of suspended-sediment concentration measured at Shirokane Bridge.
Unit of concentration is g/l.

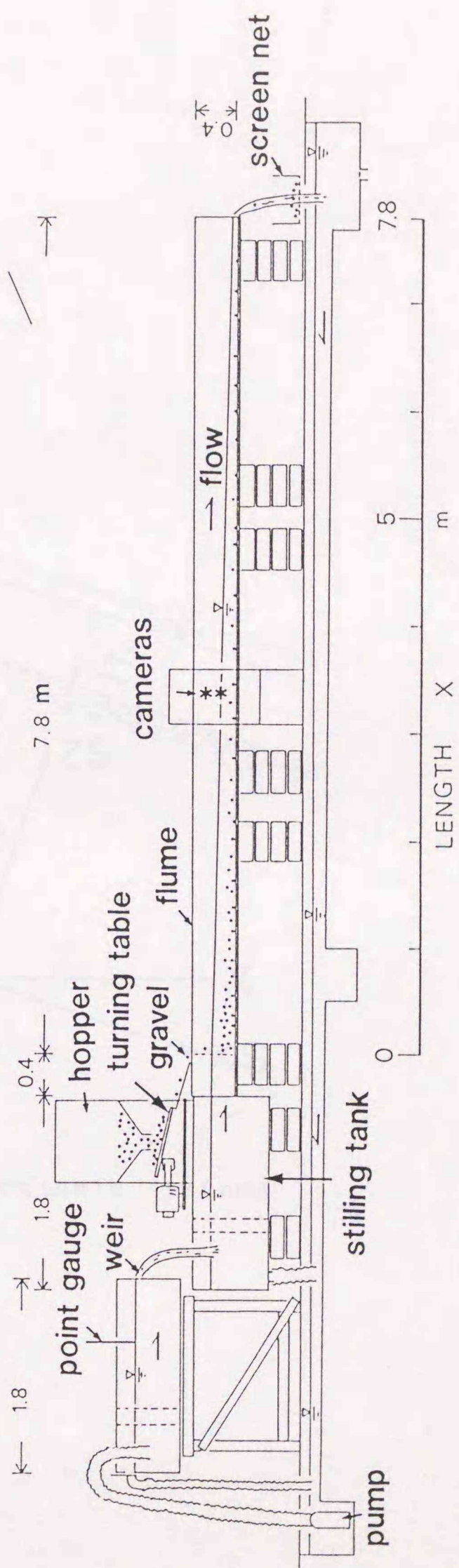


Figure 4-1 Experiment facility.

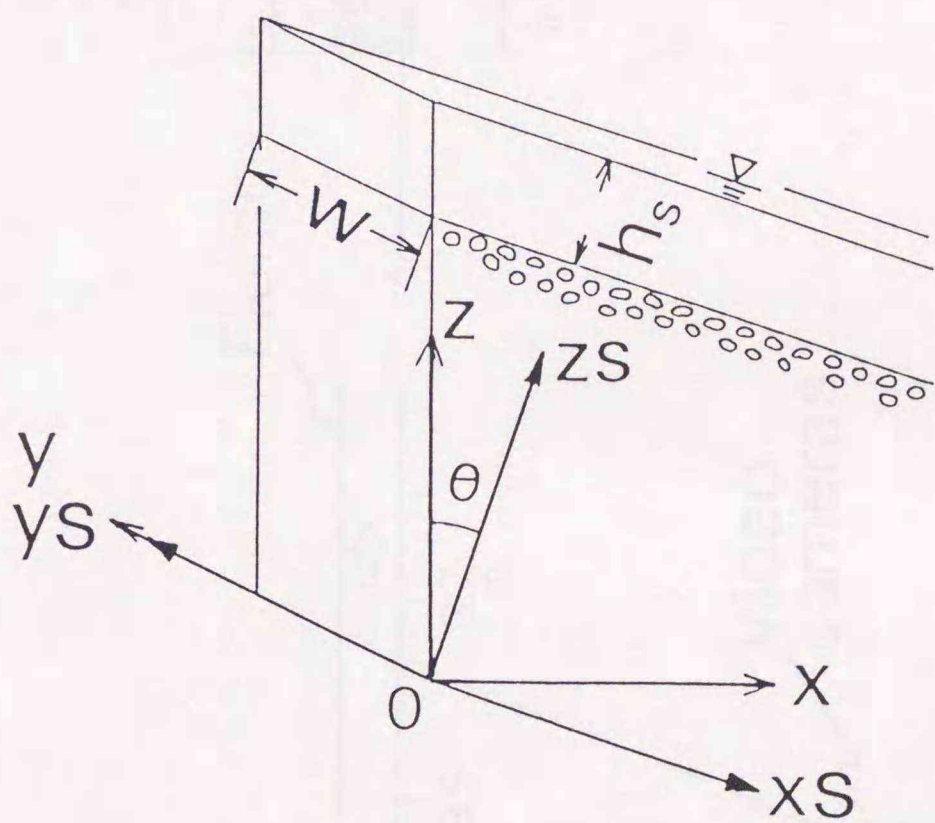


Figure 4-2 Coordinate systems.

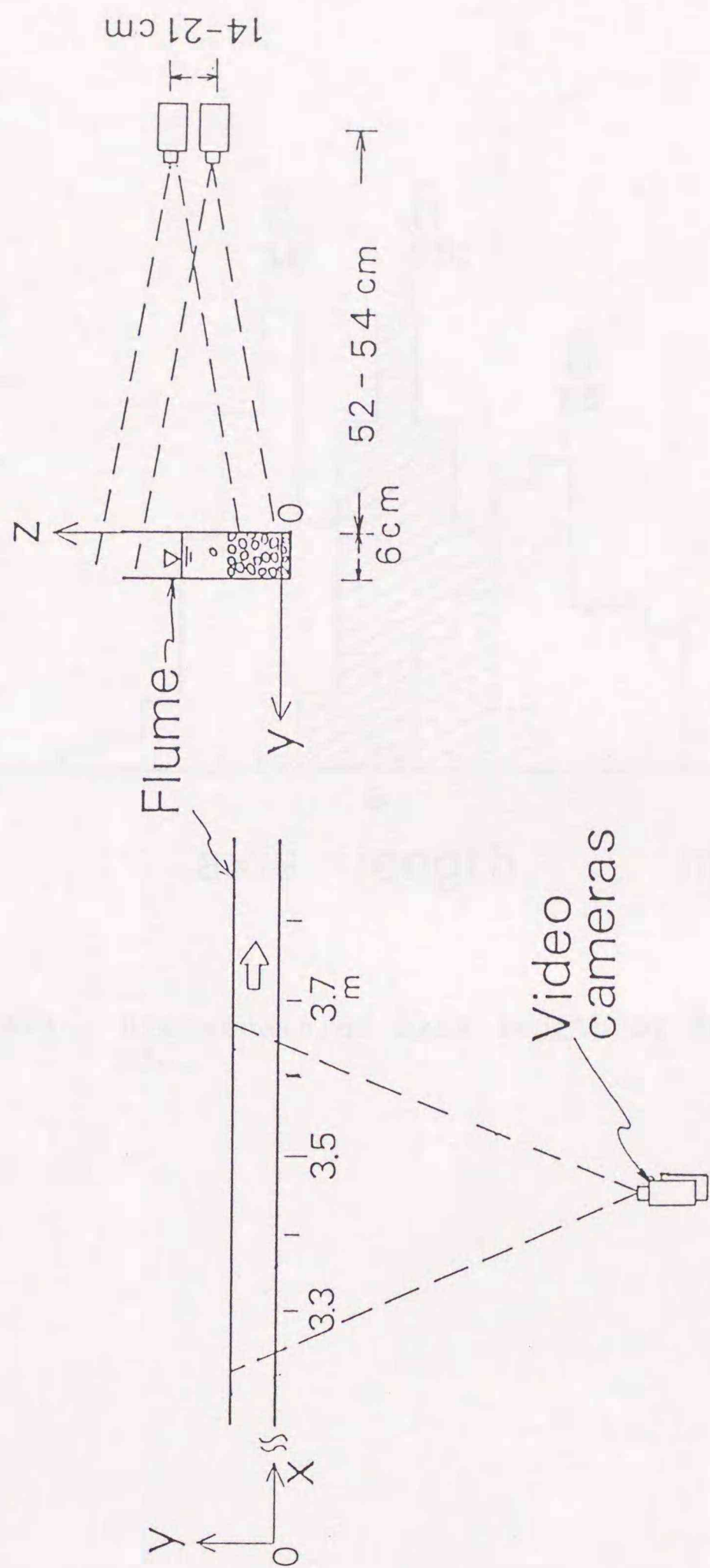


Figure 4-3 Video cameras set up.

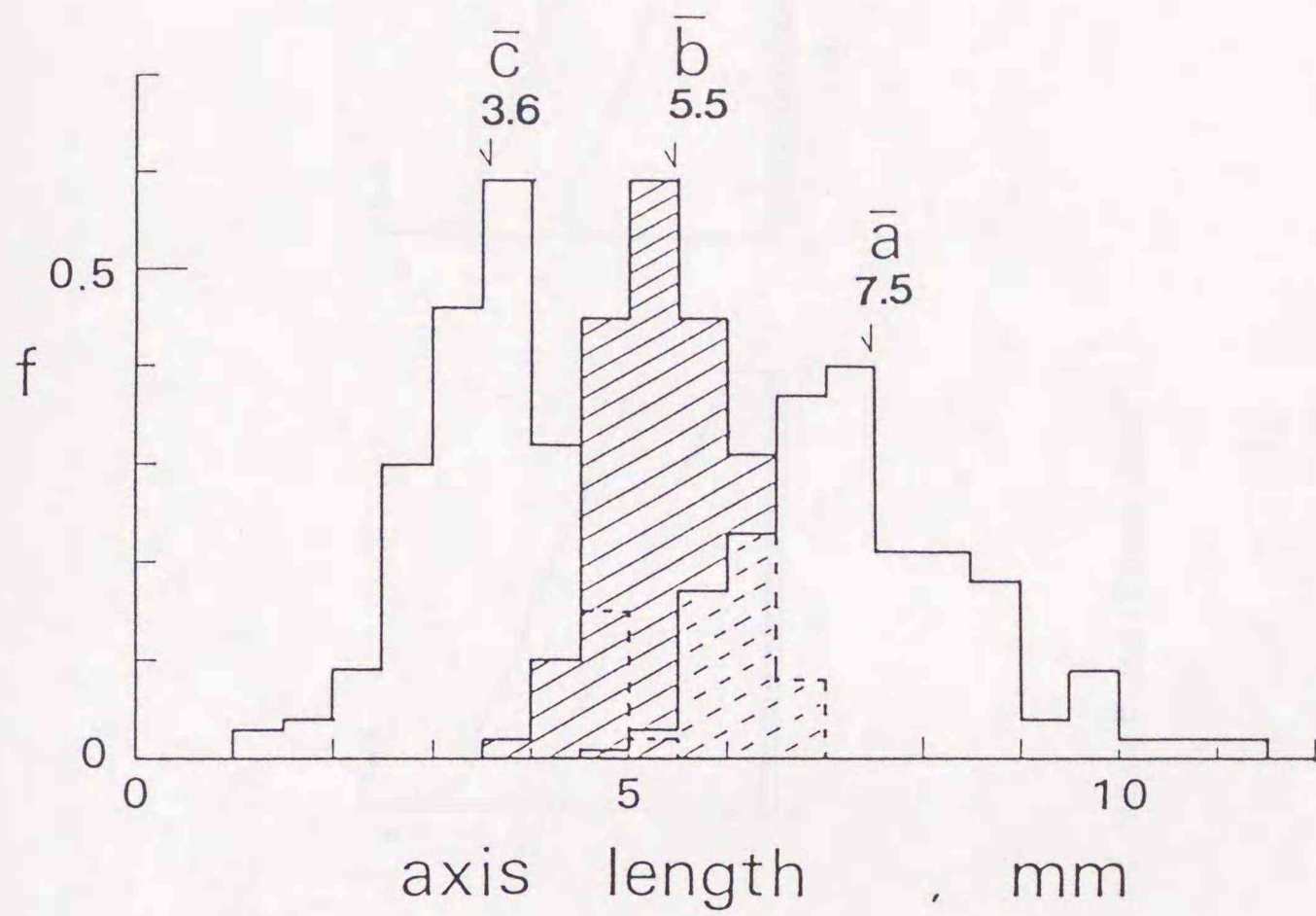


Figure 4-4 Histograms of axis length of gravel particle.

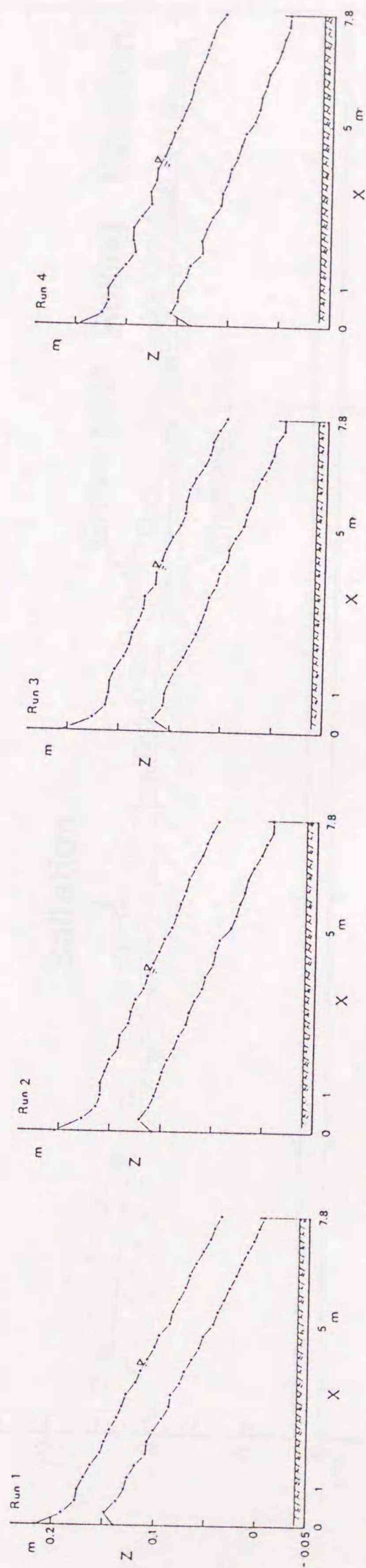


Figure 4-5 Longitudinal profiles of water surface and channel bed.

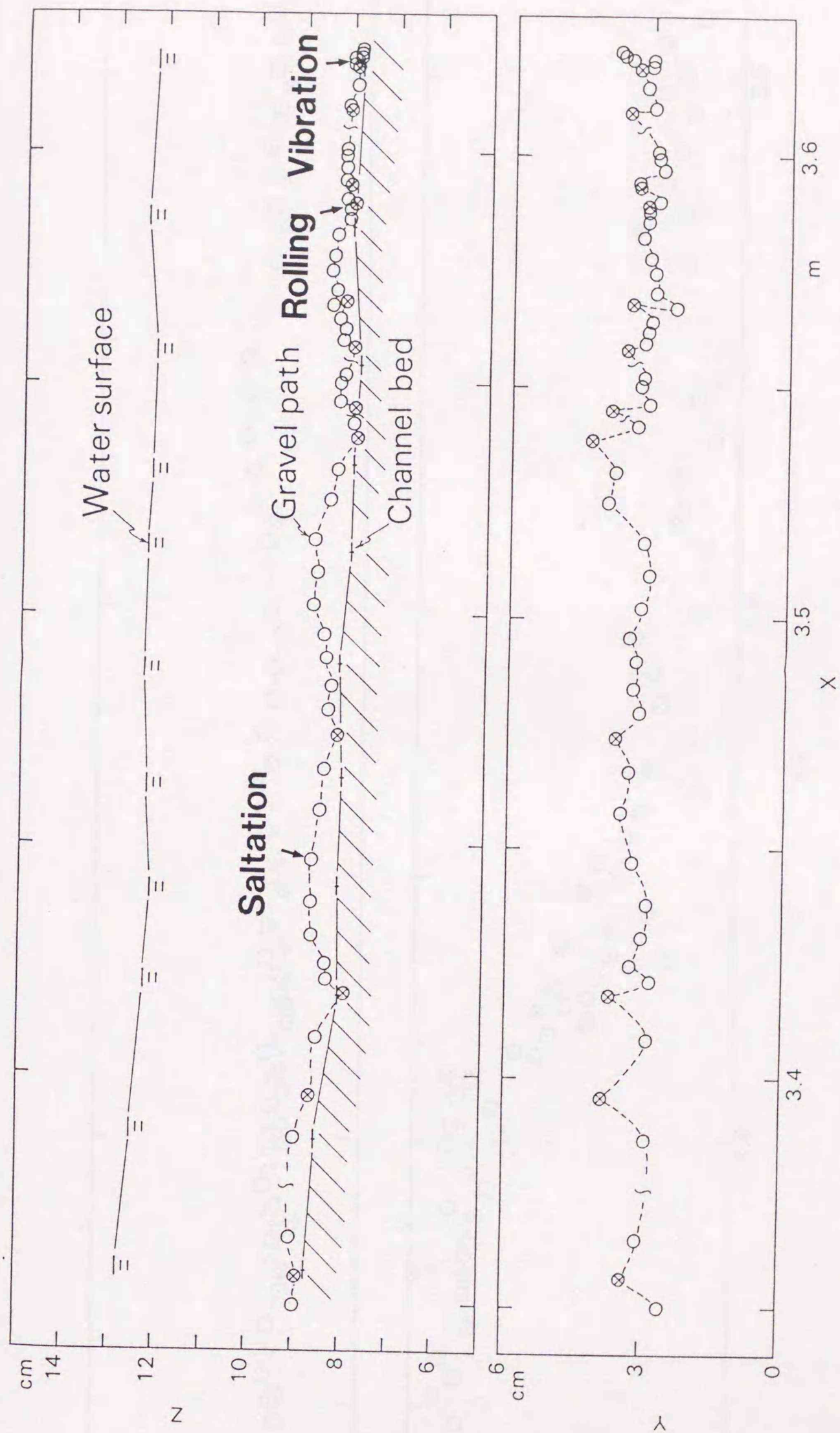


Figure 4-6 Example of gravel path; saltation movement parallel to stream.

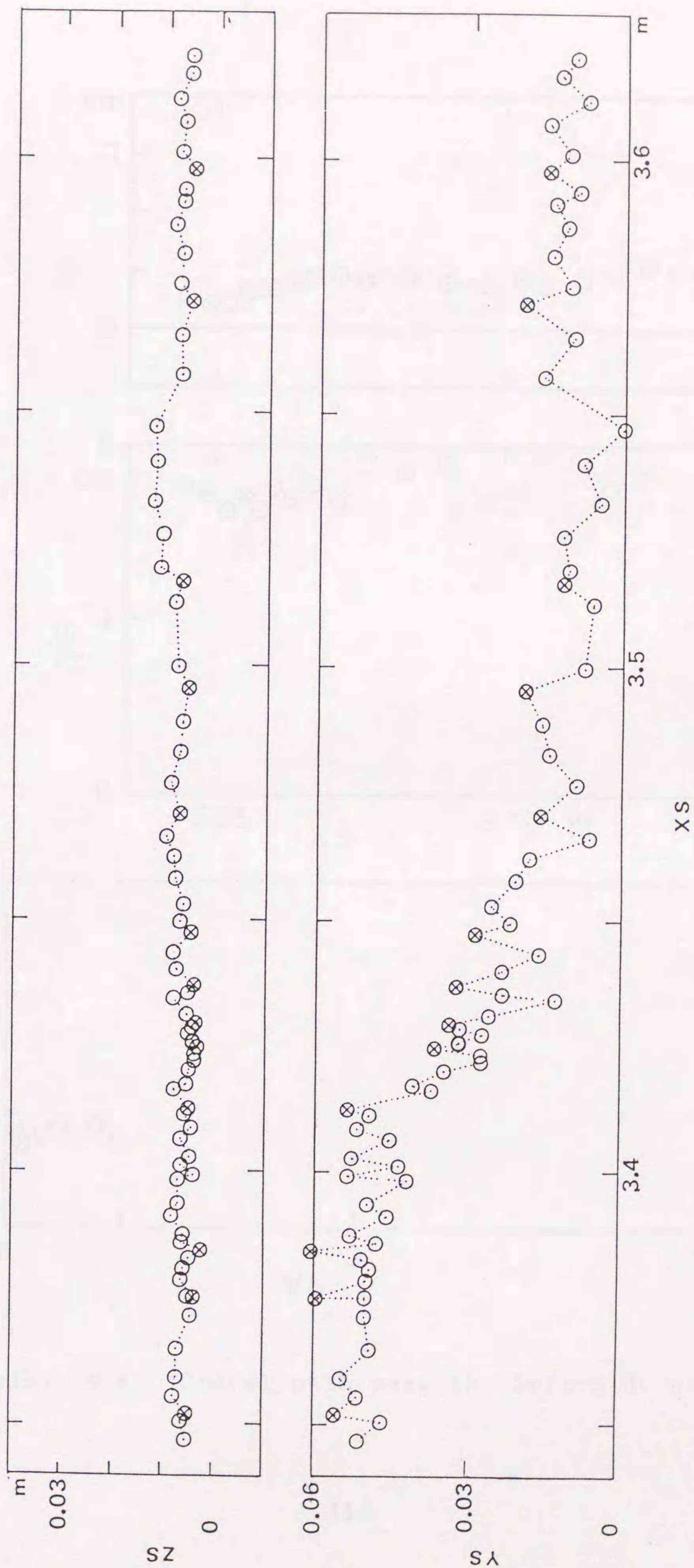


Figure 4-7 Saltation movement oblique to stream.

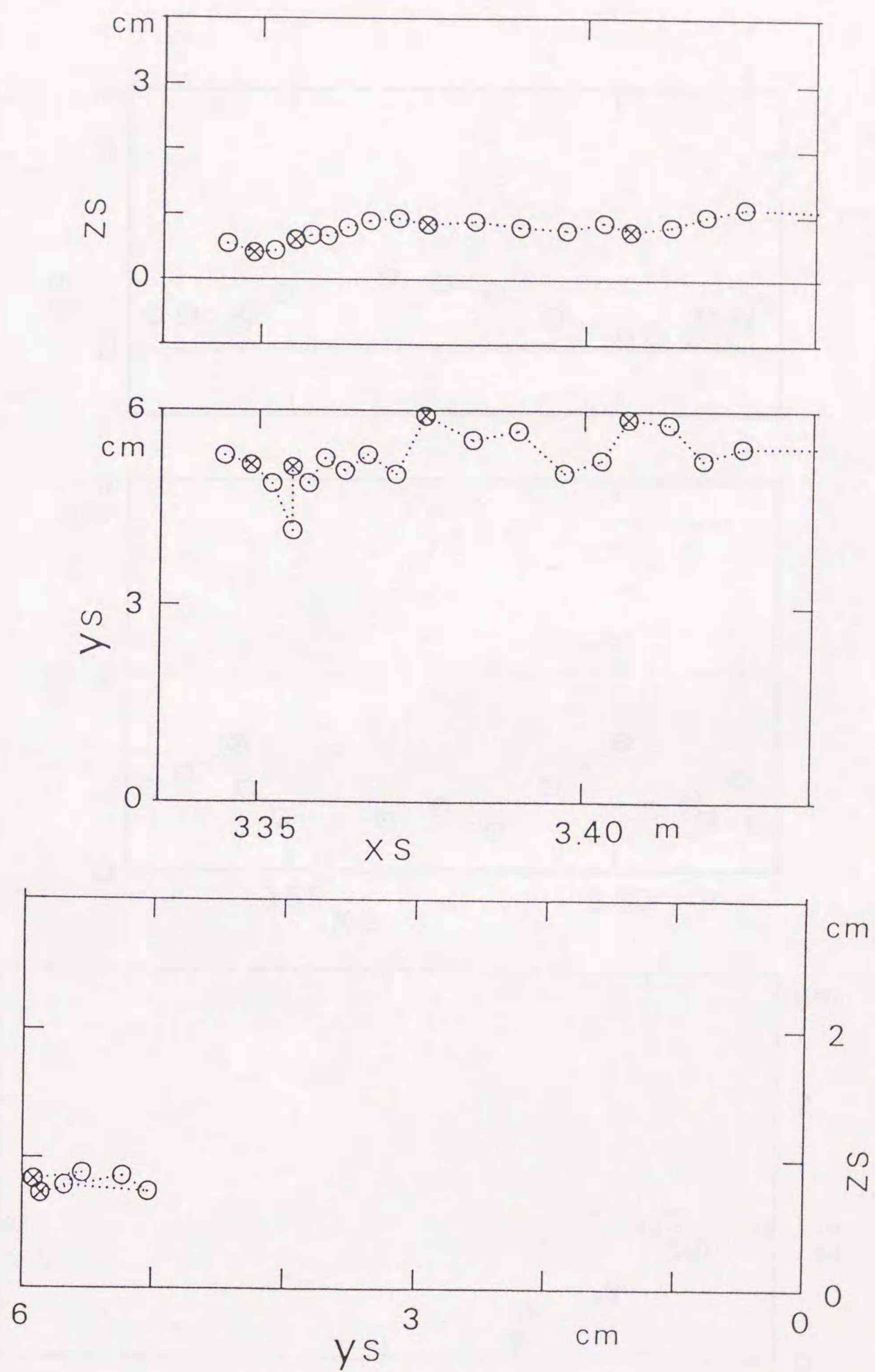


Figure 4-8 Gravel path near the left-side wall.

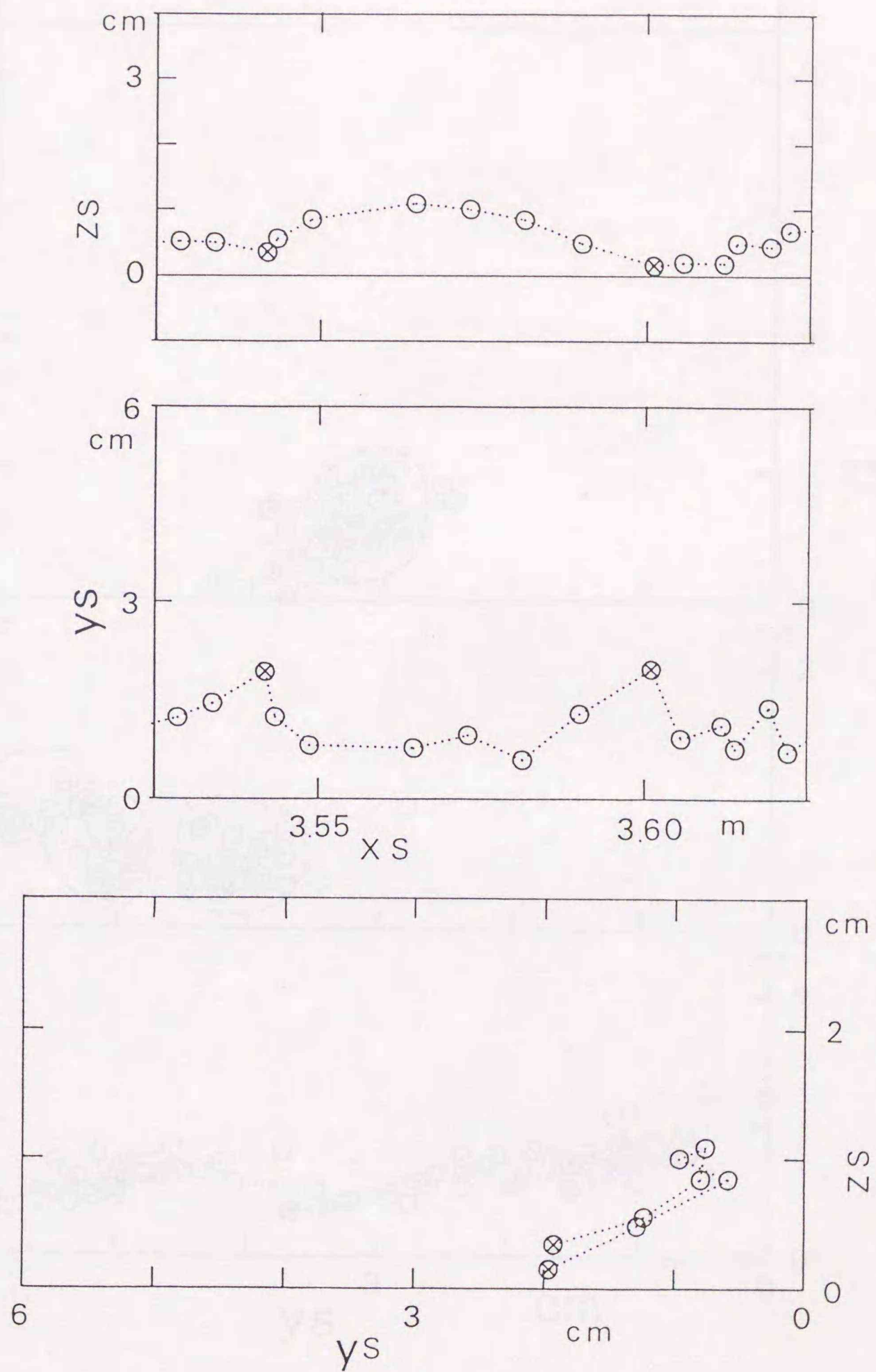


Figure 4-9 Gravel path near the right-side wall.

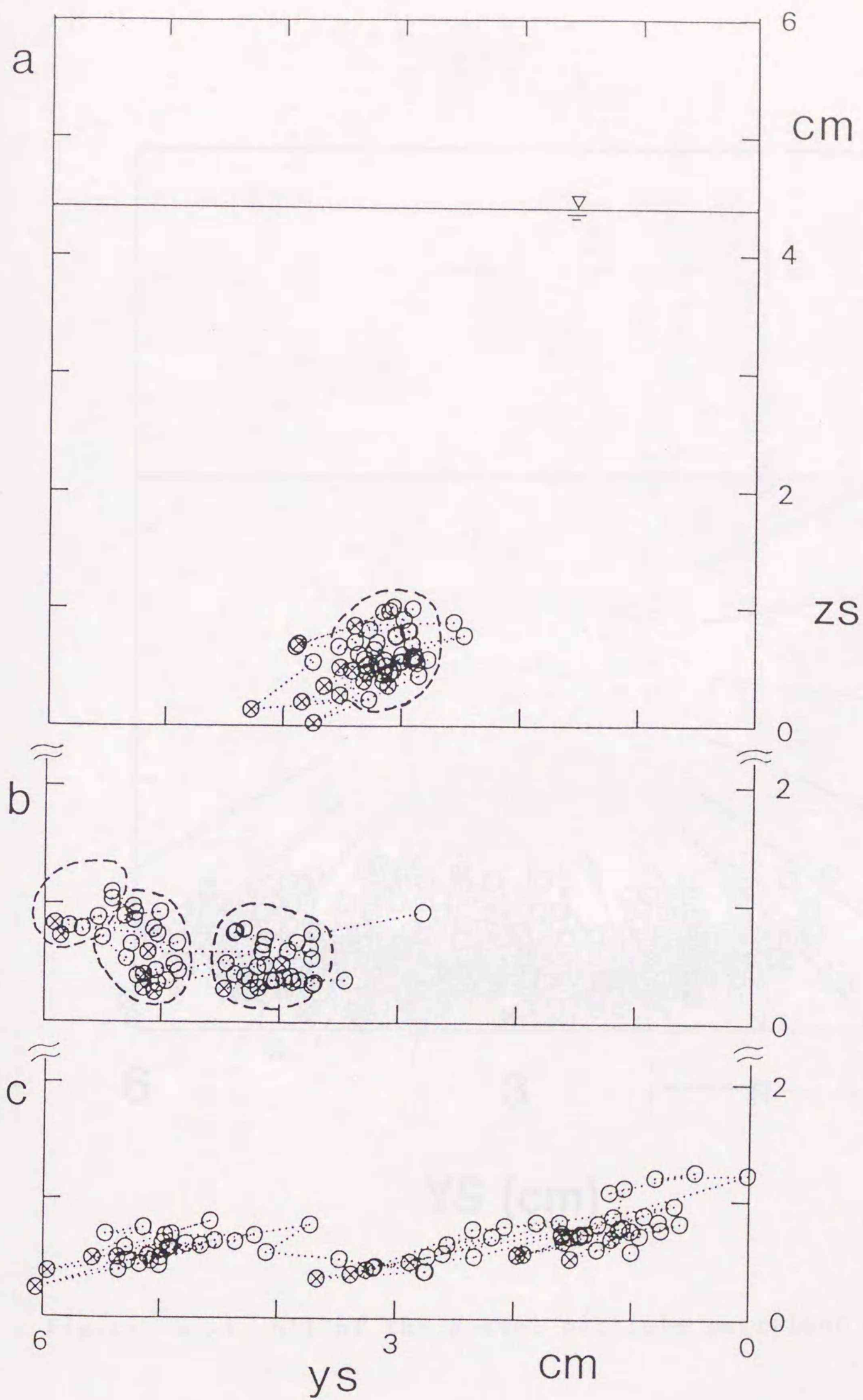


Figure 4-10 All of gravel particle positions.

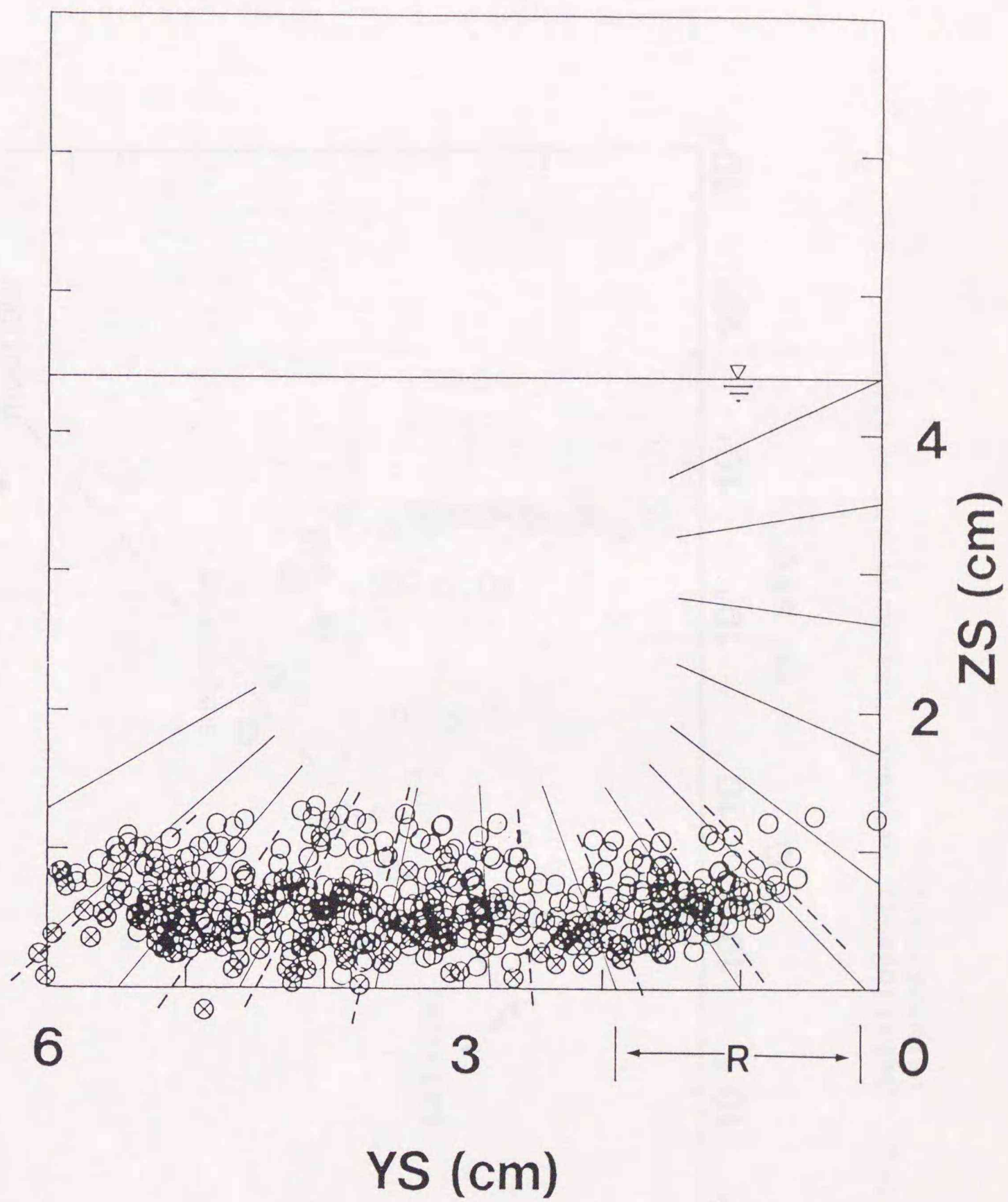


Figure 4-11 All of the gravel particle positions of Run 1.

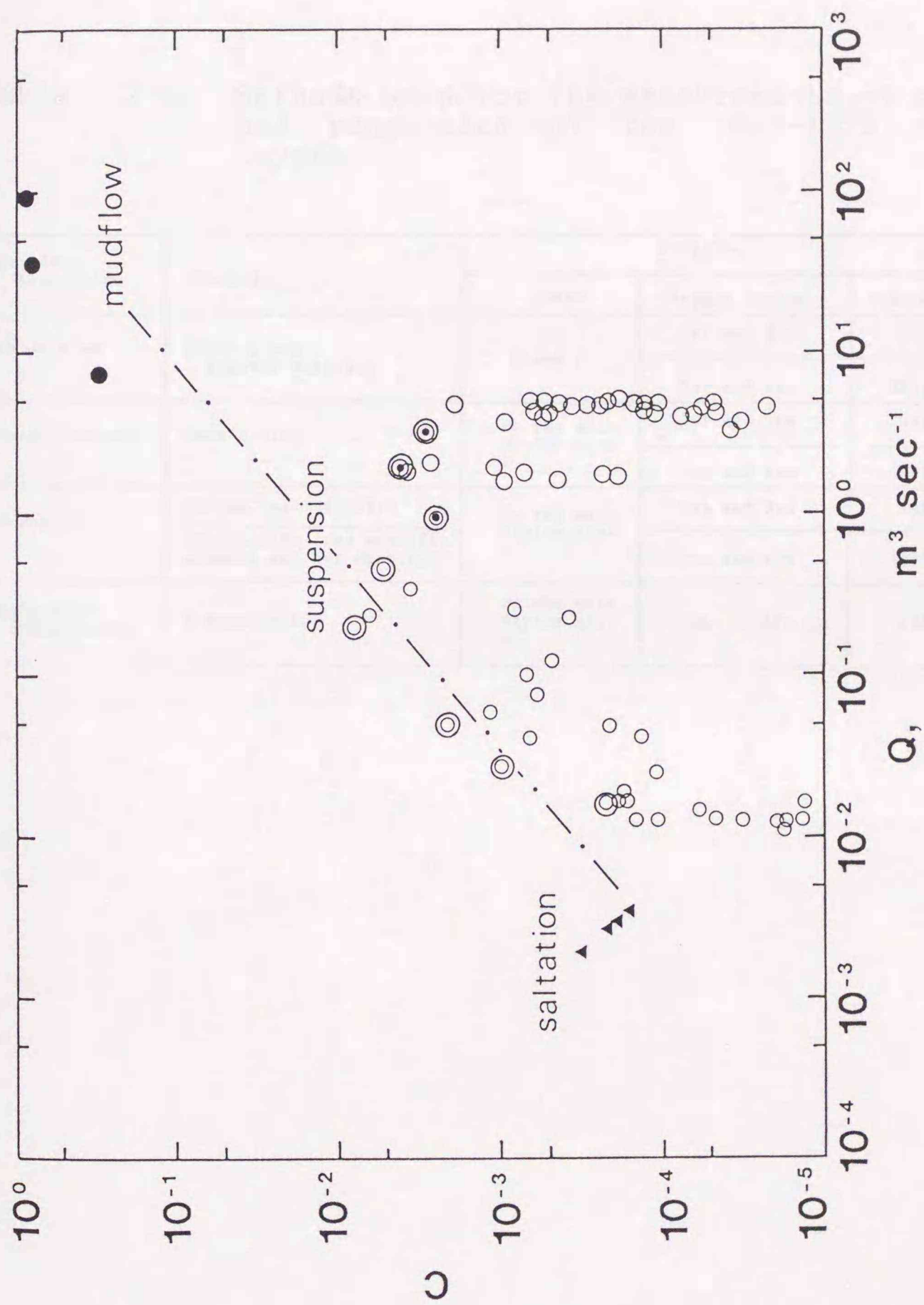


Figure 5-1 Relationship between discharge and sediment concentration.

Table 2-1 Methods used for the measurements of physical properties of the 1977-1978 tephra layers.

Physical properties	Method	Sampling		
		Sites	Tephra layers	Volume in cm ³
Grain size	Sieving and pipette analysis	U and L	1st and 3rd	100
			2nd and 4th	1070
Water content	Oven drying	On the main divide near U	1st and 3rd	100
			2nd and 4th	1070
Porosity	Actual volumetry	On the main divide near U	1st and 3rd	100
	Calculation from specific gravity and dry density		2nd and 4th	1070
Hydraulic conductivity	A permeameter	On the main divide near U	1st - 4th	100

Table 2-2 Physical properties of 1977-1978 tephra.

Layer	Mean grain size (mm)	Hydraulic conductivity (cm/sec)	Porosity (%)	Specific gravity
I	0.5	$1.1-2.7 \times 10^{-5} *$	47.0	2.50
II	3.4	> 0.6	63.2	1.96
III	1.1	2.56×10^{-2}	47.8	2.42
IV	3.2	> 0.6	63.3	2.06
Buried original soil		1.37×10^{-2}	72.8	2.53

Sampled on September-October 1978, *: after Kono and Tohma (1979).

Table 2-3 Sediment budget in the Nishiyama watershed,
September - October 1978.

Geomorphic type	Erosion m ³	Deposition m ³
Crest and inter-rill	21,000	0
Rill	18,000	0
Gully	39,000	?
Vally side	2,800	0
Main vally floor	3,300	11,800
Tributary vally floor	45,000*	?
Total	129,100	11,800 <

* After Yamaoka *et al.* (1979).

Table 2-4 Mudflows down to the alluvial fan.

Date	Max. 10min. rainfall P10 mm/10min	Water volume Rp m ³	Runoff duration td min	Sediment volume Rs m ³	Mudflow discharge Q m ³ /s = (Rp+Rs)/td	Sediment concentration C = Rs/(Rp+Rs)
Sep.26	5.0	3000	10	1200	7	0.29
Oct.16	6.5	3900	10	17200	35	0.82
Oct.24	21.0	12600	20	103000	96	0.89

Table 3-1 Measurement results for inter-rill erosion.
 (1): number of inter-rill slope, (2):
 number of erosion pin sit, M: mean, S:
 standard deviation, C: coefficient of
 variation, l_i : divide segment length, s_i :
 divide segment gradient, E_i : inter-rill
 erosion rate (period: June 1974-August
 1976)

(1)(2)	l_i (m)	s_i	E_i (mm/year)				
			Total period	Subdivided I	II	period III	
I1-	1	1.0	0.16	-1.0	23.1	-1.5	-6.7
	2	2.0	0.087	4.7	19.5	1.5	2.7
	3	3.0	0.017	0.3	-16.3	0.0	4.6
	4	4.0	0.017	9.2	3.3	9.0	10.7
	5	5.0	0.017	9.3	26.1	9.0	5.3
I2-	1	1.0	0.087	14.7	9.8	15.1	15.8
	2	2.0	0.052	10.4	26.1	9.0	7.2
	3	3.0	0.12	7.5	29.6	-7.7	10.2
	4	4.0	0.16	10.8	19.9	10.7	8.5
	5	5.0	0.12	8.4	29.6	9.0	2.7
I3-	1	0.9	0.33	-0.4	13.7	4.8	-6.7
	2	1.9	0.49	10.9	-33.6	15.5	19.4
	3	2.8	0.50	17.0	26.4	15.7	15.3
	4	3.7	0.50	20.4	33.9	8.7	23.3
	5	4.6	0.44	10.6	29.0	13.4	4.6
		M	8.9	16.0	7.5	7.8	
		S	6.1	18.8	6.8	8.5	
		C=S/M	0.69	1.18	0.91	1.09	

Table 3-2 Measurement results for rill erosion.
 (1): number of rill catchment, (2): number of rill cross-section site, TL: total rill length, s_r : rill bed gradient, A: area of rill catchment, W_r : width of rill, P_r : perimeter length of rill, C_r : cross-sectional area of rill, E_r : rill-erosion rate (period: August 1972-October 1974)

(1)(2)	TL (m)	s_r	A (m ²)	W_r (cm)	P_r (cm)	C_r (cm ²)	E_r (mm/year)
R3- 1	1.0	0.035	6.4	12	13	12	4.2
2	3.0	0.035	10.0	22	23	50	10.0
3	2.0	0.035	5.9	20	21	44	9.6
4	2.0	0.035	2.1	32	35	100	13.1
5	4.0	0.035	13.4	29	31	44	6.5
6	10.2	0.035	28.4	60	65	225	15.9
7	17.2	0.035	42.3	59	69	375	24.9
8	27.6	0.035	53.5	40	46	350	34.9
9	47.9	0.035	105.5	35	45	300	30.6
10	53.9	0.035	118.5	43	59	475	36.9
R6-11	0.5	0.044	4.3	28	30	21	3.2
12	1.5	0.061	6.8	49	51	74	6.7
13	6.0	0.035	16.8	83	88	374	19.5
14	9.0	0.044	25.1	80	88	400	20.9
R8-15	1.0	0.061	10.4	22	23	63	12.6
16	1.0	0.052	4.9	33	35	68	8.9
17	5.5	0.061	24.8	22	28	130	21.3
18	10.8	0.052	41.0	35	39	188	22.1
19	15.8	0.052	56.5	36	52	380	33.5
20	19.8	0.061	68.2	38	56	600	49.1
21	2.9	0.185	9.1	22	25	106	19.4
22	3.0	0.135	8.9	24	27	120	20.4
23	9.6	0.194	26.7	41	46	442	44.1

Table 4-1 Properties of gravel.

Sieve opening	Axis length			Mass *	Grain density	Grain Volume
mm	mm			ms,g	σ	$V=ms/\sigma, \text{cm}^3$
	a	b	c			
4.5 - 5.4	7.5 ± 1.2	5.5 ± 0.6	3.6 ± 0.7	0.19 ± 0.06	2.63	0.072 ± 0.023

Table 4-2 Experiment condition.

Run	W , cm	L , m	Q , $10^{-3} \text{m}^3/\text{s}$	Fs , g/s
1	6	7.8	1.9	1.7
2	6	7.8	2.7	1.5
3	6	7.8	3.0	1.6
4	6	7.8	3.5	1.4

W : Width of flume, L : Length of flume
 Q : Discharge, Fs : Gravel feed.

Table 4-3 Channel form, flow and sediment discharge.

Run	Slope	Flow depth	Hydraulic radius	Wetting perimeter	Mean flow velocity	Temperature	Coef. kinetic viscosity	Reynolds number	Shear velocity	Roughness Reynolds number	Froude number	Sediment discharge	Sediment concentration
Sb	Sw	hs	R	P	vs	T	ν	Re	v^*	Rr	Fr	Qs	C
cm	cm	cm	cm	cm	cm/s	degree	cm ² /s		cm/s			g/s	
1	0.0203	0.0204	4.4	14.8	73.5	18.3	0.01038	12600	6.0	320	1.8	1.6	0.000315
2	0.0176	0.0174	5.7	17.5	78.0	18.6	0.01030	14900	5.8	310	1.8	1.5	0.000218
3	0.0159	0.0155	6.2	18.5	80.3	19.5	0.01003	16100	5.6	310	1.8	1.5	0.000188
4	0.0155	0.0152	7.1	20.2	82.5	21.0	0.00972	17900	5.7	320	1.8	1.5	0.000158

Table 5-1 Debris transport modes and their relating meteorological, hydrological and geomorphological conditions on slope.

Transport mode	Multi-phase flow	Suspension	Saltation
Rainfall intensity	5mm/10min	2-3mm/10min	
Material	Pyroclastic materials (pumice and ash)	Pyllite and unconsolidated sediment	Sandstone and shale
Grain density	1.9-2.0g/cm ³	2.6g/cm ³	2.6g/cm ³
Particle size	0.095-4.6mm	0.002-0.02mm	5.5mm
Weathering	Fresh, but easily leached	Deep weathering	
Hardness	< 10mm	21-25mm	
Porosity	47→43→58%	54-60%	
Hydraulic conductivity	10 ⁻⁵ →10 ⁻¹ cm/s	10 ⁻⁵ -10 ⁻⁷ cm/s	
Land form	Inter-rill erosion Rill erosion	Inter-rill erosion Rill erosion	Landslide
Erosion rate	32 - 34 mm/year 56 mm/year	10 mm/year 15 mm/year	

Table 5-2 Debris transport modes and condition of flow and debris.

Transport mode	Multi-phase flow	Suspension	Saltation
Flow velocity	3-4m/s 8-10m/s	0.5-0.8m/s	0.7-0.8m/s
Discharge	7-96m ³ /s	0.7-2m ³ /s	1.9-3.5*10 ⁻³ m ³ /s
Particle size	1.2-1.9mm	0.007-0.02mm	5.5mm
Critical velocity	0.3-0.4m/s	0.4-0.8m/s	0.6m/s
Sorting index	2.3-7.4	~ 2	1.1
Movement of sigle particle or clustre particles	whole	bottom to	near bottom
Volumetric concentration	1< - 1/10	1/100-1/1000	1/1000-1/10000
Movement of single particle or cluster of particles	Fluidization	Diffusion	Spiral motion



Photo 2-1 1977-1978 tephra layers of Usu Volcano.



Photo 2-2 Rills and gullies formed on the experiment slope.



Photo 2-3 Mudflow in the valley of Nishiyama river (September 26, 1978).



Photo 3-1 Rills formed on the bare land of Sanchina watershed.



Photo 3-2 Suspended-sediment transport in the third-order watershed.

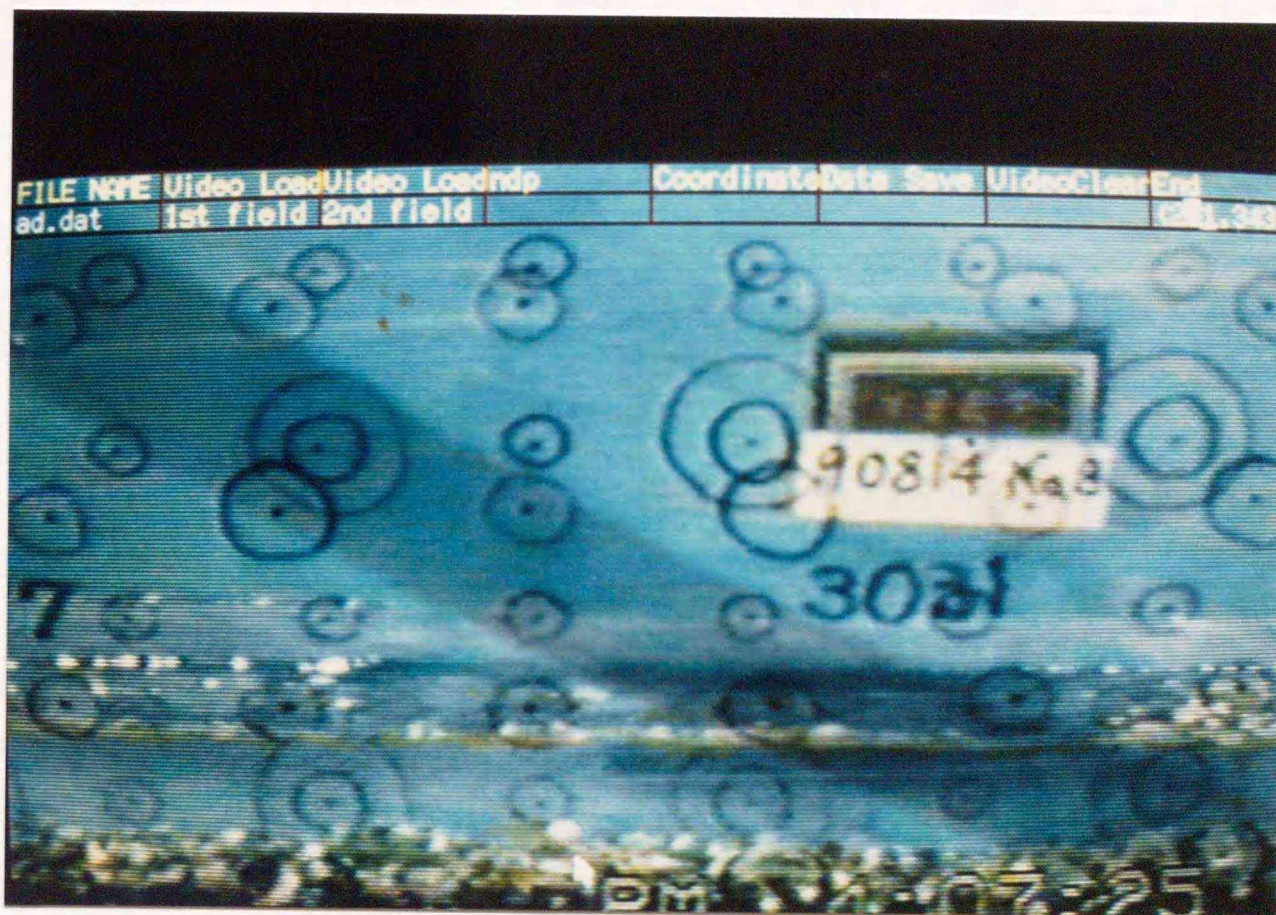


Photo 4-1 Gravel movement in a transferred video picture.
An arrow indicates a saltation gravel.

