Sediment Yield and Transport on a Mountainous Small Watershed

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Abstract

Observations on the runoff of rain, sediment yield and transport on a small mountainous watershed, called Hirudani, were carried out. Main sediment production sites were three landslide slopes and by use of particle size distribution analysis and petrographical classification of run off sediments the sources of sediments were identified. The majority of sediment was transported as contact load and sometimes the sediment reached the outlet of the watershed long after the arrival of the flood. The lag time varied case by case, depending on the antecedent sediment storage in the stream channel. A conceptual model of the sediment runoff was proposed and the channel process was analyzed using the bed load formula. A stair like channel configuration with many falls and pools could consume a great part of the energy by rollers at the bottom of the falls and the effective slope for transportation of sediment should much flatter than actual topographical inclination.

1. Introduction

The phenomena of sediment production and transport appear in very complex aspects in connection with the characteristics of runoff of precipitation. These phenomena are also subject to the sediment availability and characteristics, such as the location, quantity, state of accumulation, particle diameter, size distribution, etc.

Surface erosion of bare slopes, land slides, mud-debris flows and scouring of stream beds and banks would be the main causes of sediment yield on a mountainous watershed. Separation of flow components at each slope and stream channel section would be necessary, because the major factors controlling the sediment production and transport are different; the surface erosion is brought by overland flow, the land slide is brought mainly by subsurface runoff component, while the capacity of transportation should be decided by the discharge of each stream channel section before meeting any contributary or distributary channel. These circumstances suggest that it requires more detailed knowledge of hydrology than ordinary flood runoff analysis requires.

In the course of transportation of produced sediment, the effect of storage generally plays a very important role. But the quantity of storage and speed of transportation would be different for different particle size even though the sediment transporting capacity of the flow itself is assumed to be the same. This means that not only the quantity but also the quality of sediment production should be made clear. Unfortunately, nothing is known for the prediction of particle size distribution due to land slides.

Besides these difficulties, there is very little reliable information based on accurate observation, which might be another reason for the present state of uncertainty in respect to prediction of sediment yield on a mountainous watershed.

The authors and their colleagues have been doing observational study on the experimental watershed of Hodaka Sedimentation Observatory, Disaster Prevention Research Institute, Kyoto University, since 1966. This study aims at grasping the reality of the phenomena and then solving the mechanism of sediment yield by constructing some new physical models. The early stage of the study was spent for the design and construction of equipment and facilities. Since then, with the improvement of the facilities and owing to the accumulation of data, the qualitative characteristics of sediment yield on the Hirudani Experimental Watershed have been gradually made clear[1)-5)].

This paper describes the results of observations and discusses the qualitative characteristics of sediment yield and transportation. Although no land slide and mud-debris flow have occured, and the main sediment sources and their grain size distributions have been known, the phenomena have been quite complicated, making the quantitative discussion equally complex.

2. Description of watershed

Hodaka Sedimentation Observatory is located in the mountainous region of the North Japan Alps, where the rate of sediment yield is the largest in Japan. The whole experimental watershed is called Ashiaraidani, whose catchment area is 6.5

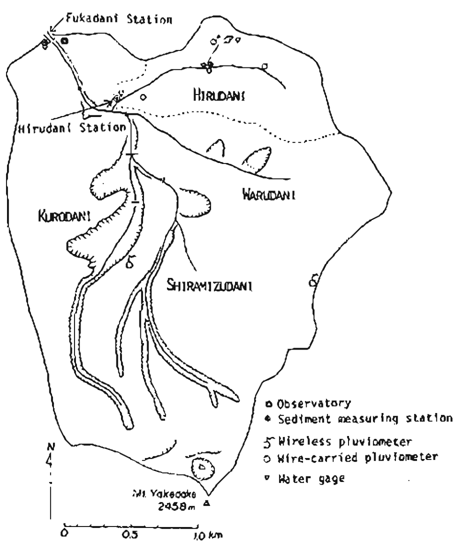

Fig. 1. Plan of watershed and arrangement of equipment for observation on the Ashiaraidani experimental watershed.

km^2. This watershed is composed of four smaller basins, Kuro-dani, Shiramizu-dani, Waru-dani and Hiru-dani (Fig. 1). The drainage network over Kuro-dani and Shiramizu-dani basins originate from the gullies on the active volcano, Mt. Yakedake. Waru-dani and Hirudani drain mainly the Paleozoic strata area. Kurodani, Shiramizu-dani and Warudani have many large landslides and in these basins mud-debris flows often occur. Hirudani is, on the other hand, now in a rather stable state and in this basin mud-debris flow has never occured since the beginning of the observation.

Hodaka Sedimentation Observatory is now carrying out their observation study by using two main observation stations. Fukadani Station, which is located on the main stream channel of the Ashiaraidani, and some subsidiary stations on the Kurodani, which measure the runoff and sediment yield of rather large scale including mud-debris flow. Recently, once or twice a year, mud-debris flows pass through Fukadani Station. Hirudani Station, which is located at the outlet of the Hirudani basin, aims at the measurement of small scale sediment process. This paper deals with the results of the observations on Hirudani Experimental Watershed.

The catchment area of Hirudani is 0.85 km^2. Its altitude is 1200 m at the outlet and over 2000 m at the heighest part. Geology of the watershed is, as shown in Fig. 2, Carboniferous or the Permian clay-slate in the upper part, granite-porphyry in the middle part and quartz-porphyry in the lower part. Terrace deposit of andesite gravel covers granite-porphyry and quartz-porphyry by some ten meters thickness. The main channel of Hirudani is incising the deposit layer whose infiltration capacity should be fairly good. The cover is shrub of broad-leaved trees and dense undergrowth of bamboo grass, except three very small bare slopes resulting from landslides.

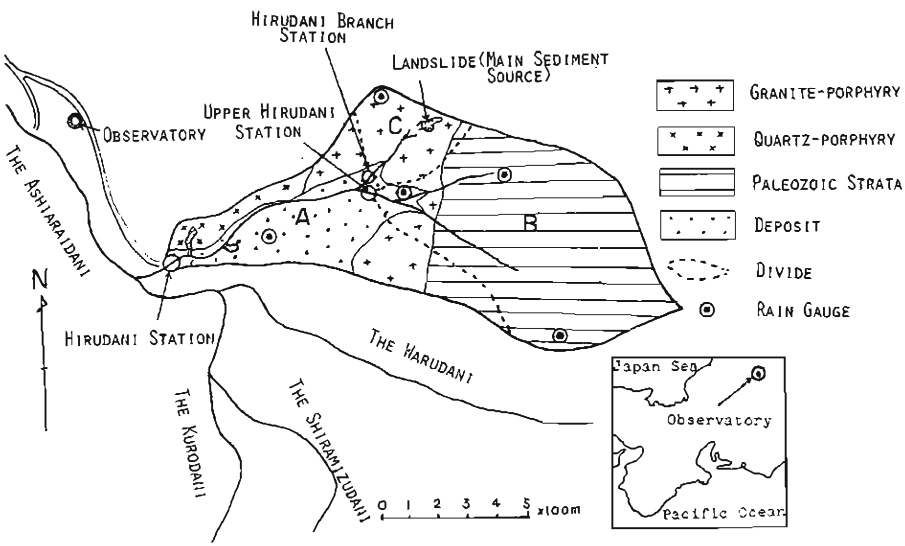

Fig. 2. Geology of Hirudani and its sub-watersheds (A, B, C).

Photo. 1. Falls and pools on the Hirudani stream channel.

From the point of view of sediment yield, Hirudani watershed can be divided into three sub-watersheds, A-, B- and C-Watershed shown in Fig. 2. Sediment sources are mainly the landslides on C- and A- Watershed. Channel erosion along the stream in A-Watershed has produced negligible sediment since the beginning of observation. Petrographical classification of yielded sediment helps the identification of the location of source. Namely, the granite-porphyry particles come from C-Watershed, the andesite particles come from either the landslide on the terrace deposit or the channel bed downstream of the junction, and the quartz-porphyry particles are produced at the landslide on the right bank of the channel near the outlet. Although the topographical inclination of the main channel downstream of the junction is about 0.2, the effective slope for sediment transportation should be much flatter due to the linking of falls and pools as is shown in Photo. 1.

Precipitation in winter from November to March is usually snow. Flood due to the thawing of snow occurs in April and May. Discharge from snow-melting flood

Table 1. Water balance at Hiru-dani experimental watershed (1971).

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Monthly mean discharge (l/s)	8.0	10.0	15.0	30.0	37.3	57.8	65.0	40.8	93.5	38.3	37.6	10.8	
Run of depth (mm)	24.4	27.5	45.7	88.5	113.8	119.2	191.7	124.3	257.0	116.9	111.0	33.0	1,253.0
Precipitation (mm)	17.0	75.5	119.5	190.0	284.5	326.0	324.5	195.5	543.0	221.5	60.0	137.0	2,494.0
Loss (mm)	−7.4	48.0	73.8	101.5	170.7	206.8	132.8	71.2	286.0	104.6	−51.0	104.0	1,241.0
Runoff percentage (%)	143.5	36.4	38.2	46.6	39.8	36.6	59.2	63.5	47.3	52.8	185	24.1	50.3

is usually as high as the one due to rain fall, so that they are very important for the sediment process in the watershed. Water balance in 1971 is shown in Table 1. The loss is not necessarily due to evaporation and transpiration, because the measuring station is located on the deposit and some amount of ground-water can slip by the station. Moreover, a considerable number of springs exist outside the watershed, whose water sources are believed to be in the Hirudani watershed.

3. Items of observation and equipment for measurements

Following items of observation are now carried out after several improvements in measuring equipment.

(1) Temporal and spacial distribution of rainfall (Three rain gauges are available),
(2) Precipitation in winter at one representative place,
(3) Discharge at the outlet of the watershed; Hirudani Station,
(4) Discharge at the outlet of B-Watershed; Upper Hirudani Station,
(5) Discharge at the outlet of C-Watershed; Hirudani Branch Station,
(6) Discharge of a spring at the top of the land-slide on C-Watershed,
(7) Temperature and electric conductance in flowing water at Hirudani Station,
(8) Sediment discharge at Hirudani Branch Station,
(9) Sediment discharge, particle size distribution and petrographical classification of runoff sediment at Hirudani Station,
(10) Volume of deposited sediment after each flood in the reservoir at Hirudani Station,
(11) Volume of stored sediment along the river course,
(12) Other measurements.

Rain gauges tilt every 0.5 mm of rainfall into a bucket and one of those has a heater around the cylinder to be used for measurement of snow.

A concrete dam, 3.5 m in height and 13 m in width, was constructed at the outlet of the watershed. The dam is furnished with a rectangular discharge measuring weir, one meter wide. Water level in the reservoir is measured by a float type gauge. Water temperature and conductance are measured in the reservoir using electrical probes.

Here a sediment discharge measurement facility, as shown in Fig. 3, Photo. 2 and Photo. 3, is set up. This has an intake for water and sediment, whose opening is 20 cm square. This intake is fixed on a concrete flume of 1 m breadth, so that

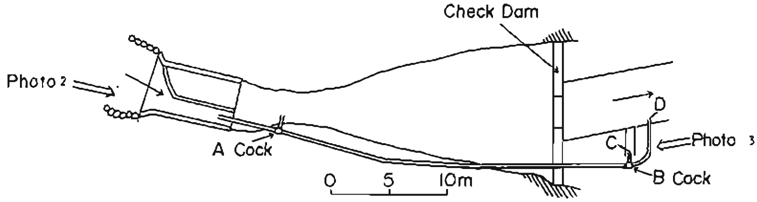

Fig. 3. Facility for the measurement of sediment discharge at Hirudani.

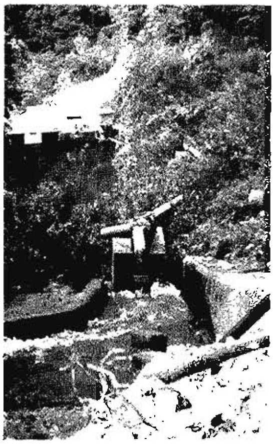

Photo. 2. A bird's-eye view of Hirudani Station.

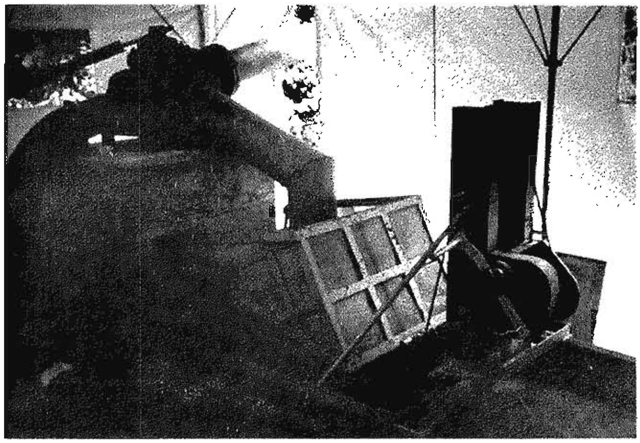

Photo. 3. Sediment sampler.

the sediment discharges are obtained by merely multplying the actually observed sediment discharge five times. The mixture of water and sediment, that is transported through the steel pipe from the intake comes down to cock B (Fig. 3), where the flow is switched at will to sediment trap C, a bucket made of stainless steel net, or to the by-pass D. Trapped sediment is weighed, sieved and petrographically classified by eye after drying. When the sediment discharge is low, cumulative weight variation in the sand trap is automatically measurable using a load cell. Flow rate through the trap is measured by a tank before draining.

Volume of deposition in the reservoir is surveyed after each flood. When the reservoir is filled up by sediment, two desilting gates are opened and all deposit is expelled.

Discharge at Upper Hirudani Station is measured by using a small reservoir with a rectangular knife edge weir and a float type water stage gauge. Since B-Watershed has produced no sediment, the reservoir has never met any trouble in measurement. Flow rates and sediment discharges at Hirudani Branch Station are measured

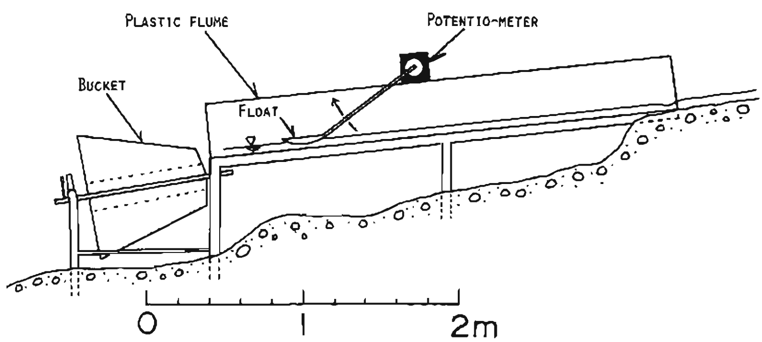

Fig. 4. Conceptual diagram of the equipment for the measurement of sediment discharge and flow rate at Hirudani Branch Station.

Photo. 4. The equipment at Hirudani Branch Station.

by using equipment shown in Fig. 4 and Photo. 4. The triangular smooth plastic flume deposits no sediment, and the water stage in it is measured by a float, which rotates the potentio-meter in proportion to the stage. The 60 mesh stainless steel net bucket downstream of the flume tilts and generates an electrical pulse with each 200 grams of sediment in it. Further improvement of the equipment would be necessary, because the weight for tilting varies a little depending on the manner of accumulation of sediment in the bucket or to the extent of clogging of the sieve.

Discharge of the spring at the top of the landslide in C-Watershed is measured by buckets tilting with every litre of water.

The equipment used for the observation items from 1 to 8 are all connected by cables to a recorder in the cabin at Hirudani Station, all data are recorded on one chart paper without any delay.

4. Some results of observations

(1) *1969.6 and 1969.7 Floods* (*Figs. 3 and 6*).

Characteristics of these floods are as follows:—

(a) Sediment discharges increase rapidly as soon as the flow rates begin to increase. After that, notwithstanding the flow rates still being large, the sediment discharge rapidly decreases.

(b) Sediment discharge and flow rate are not in very close relation.

(c) The calibrated electrical conductivity in flowing water decreases as the flow rate increases and recovers with the recession of the flow. It is presumably the case that the direct runoff component runs fast near the land surface and has not enough time to dissolve minerals in the ground. This characteristic might be one impor-

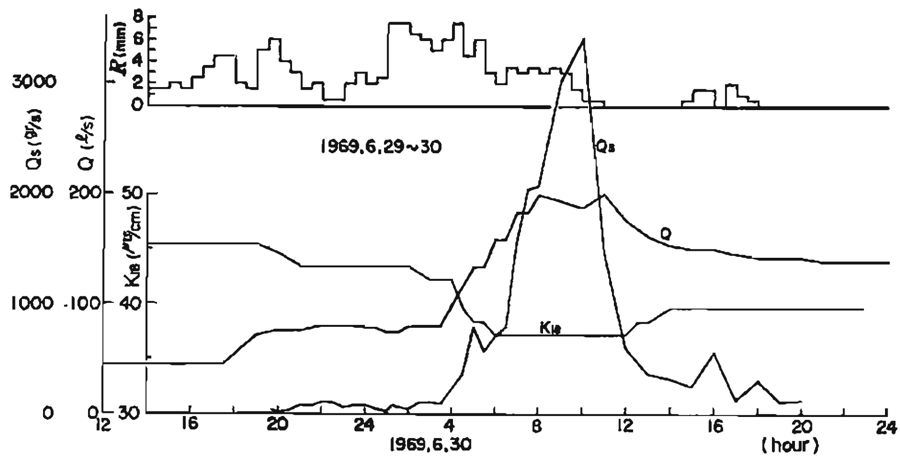

Fig. 5. 1969.6 Flood at Hirudani Station. R: rainfall (mm/30 min), Q: discharge, Q_S: sediment discharge, K_{18}: electric conductivity in water at 18°C.

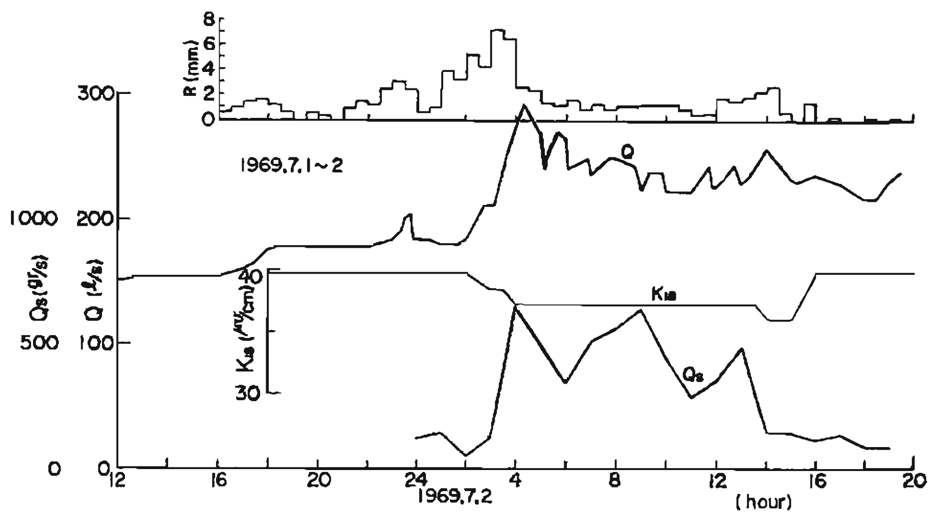

Fig. 6. 1969.7. Flood at Hirudani Station.

tant factor for the analysis of flow components. In each figure, only one rainfall record is shown, regardless that four other records were available at that time. As the analyses of spacial distributions of rainfall indicated that the rainfalls were close to uniform in respect to the total rainfall and hourly intensity, spacial uniformity has been assumed.

(2) *1971.6 and 1971.7 Floods (Figs. 7 and 8).*

As was noted for the cases above, sediment discharges are high in the rising phase, but in the recession or in the less variable flow phase, sediment discharges tend to decrease, notwithstanding that the flow rates are still high. Fig. 9 shows the particle size distributions in samples collected at Hirudani Station during 1971.6 Flood.

Grain size distribution at the landslide in C-Watershed is also shown (Curve 1). Smaller size particles dominated at the early period of the rising stage (Curve 3), but afterward near the peak of flow rate, the particle size distribution (Curve 2) was very similar to the one at the source of the sediment.

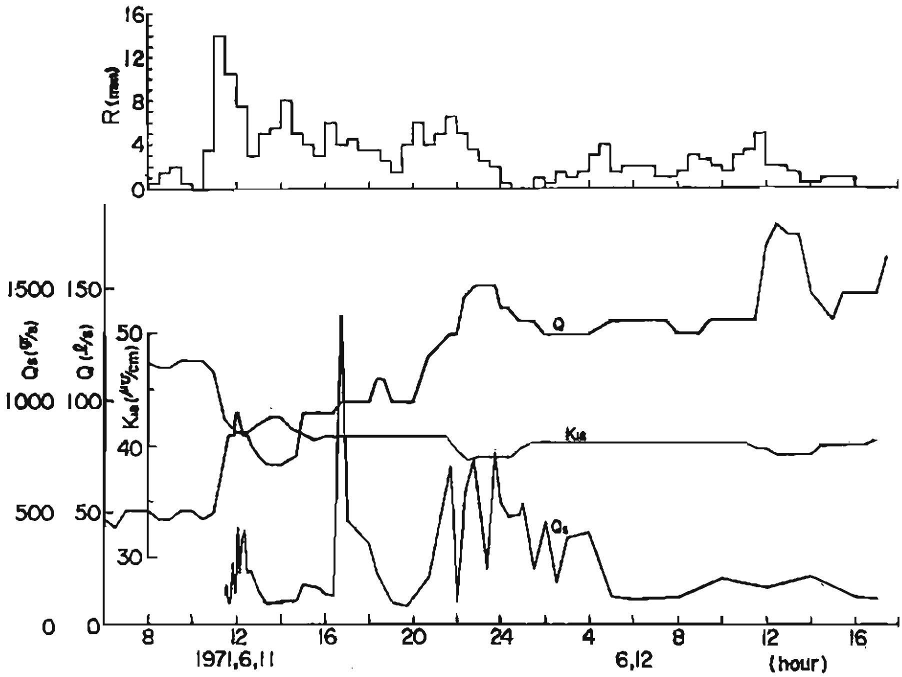

Fig. 7. 1971.6. Flood at Hirudani Station.

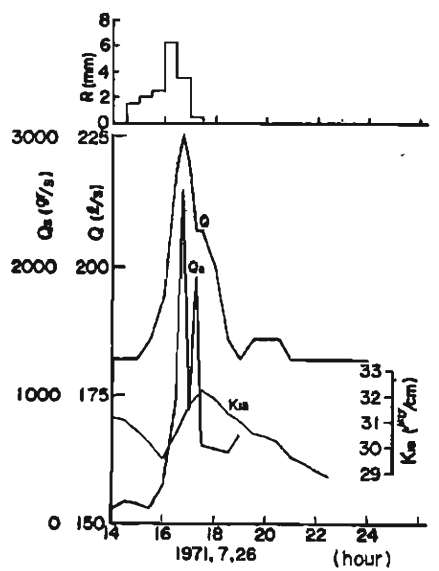

Fig. 8. 1971.7. Flood at Hirudani Station.

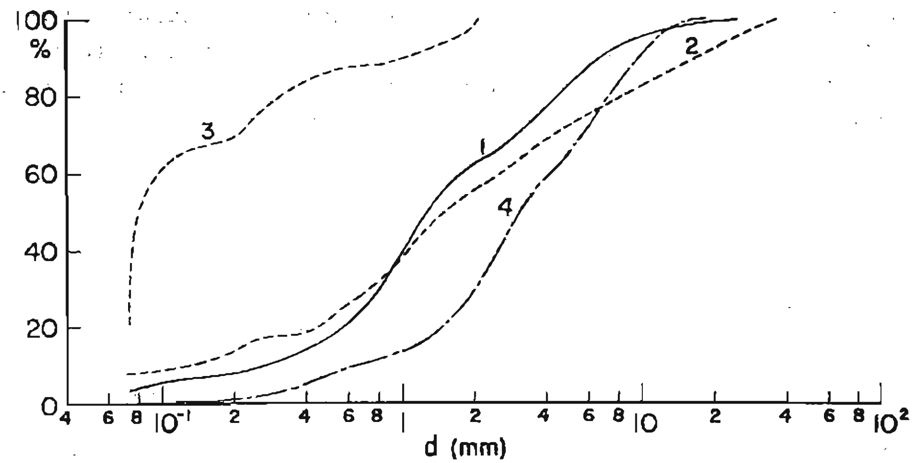

Fig. 9. Grain size distribution of the sediment:
1. Sampled at the landslide,
2. Sampled from flowing water at $Q=152$ l/s,
3. Sampled from flowing water at $Q=76$ l/s,
4. Sampled at the top-set bed in the reservoir.

(3) *1971.9 Flood (Fig. 10).*

Sediment runoff was not measured during this flood. The flow rate was the largest since the beginning of the observation. Long after the rainfall ceased the discharge did not decrease but even increased a little. This would suggest that in this watershed the sub-surface flow component, which runs off with a lag of one or two days is very important, and the hydrograph could be the result of a composition of sub-surface flows which come out through different routes with different lag times. This characteristic could never be analyzed without dividing the whole watershed into several sub-areas from the point of view of sub-surface runoff. This would be a theme for further investigation.

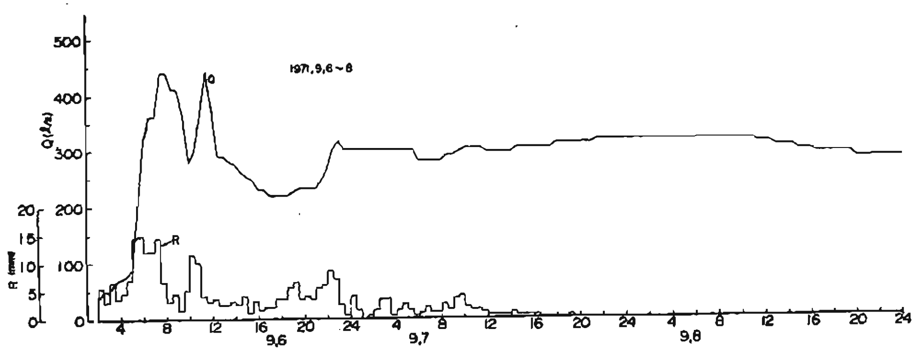

Fig. 10. 1971.9. Flood at Hirudani Station.

(4) *1972.2 Flood* (*Fig. 11*).

Two series of rainfalls caused the flood. The first one was on the 10th and the second one was from 17 o'clock of 11th July. The rainfall on the 10th was strong in intensity, but the duration was short and the flood due to this rainfall had a single peak. The hydrograph at Hirudani Station and that at Upper Hirudani Station had similar patterns.

The flood, commenced in the evening of 11th, had a maximum rainfall intensity less than that of the 10th's, but the duration was long and the peak discharge was much larger. The maximum discharge at Hirudani Station occured during the morning of the 13th, while the maximum rainfall intensity occured in the evening of the 11th. At Upper Hirudani Station, however, the peak discharge occured in the early morning of the 12th. This would imply the runoff pattern of subsurface flow of A-Watershed and that of B-Watershed is different. In order to recognize the circumstances more precisely, the runoff heights from both watersheds were compared. The runoff height from A-Watershed was 253 mm and that from B-Watershed was 201 mm, whereas the total rainfall from 9th to 23rd was 438.5 mm. As was shown in Fig. 2, Upper Hirudani Station is located on the deposit, and a part of the subsurface runoff component in B-Watershed is likely to escape from measurement at the station and come out as valley springs into the stream channel of A-Watershed. This component might have come out later than the 12th and caused a delayed peak discharge at Hirudani Station.

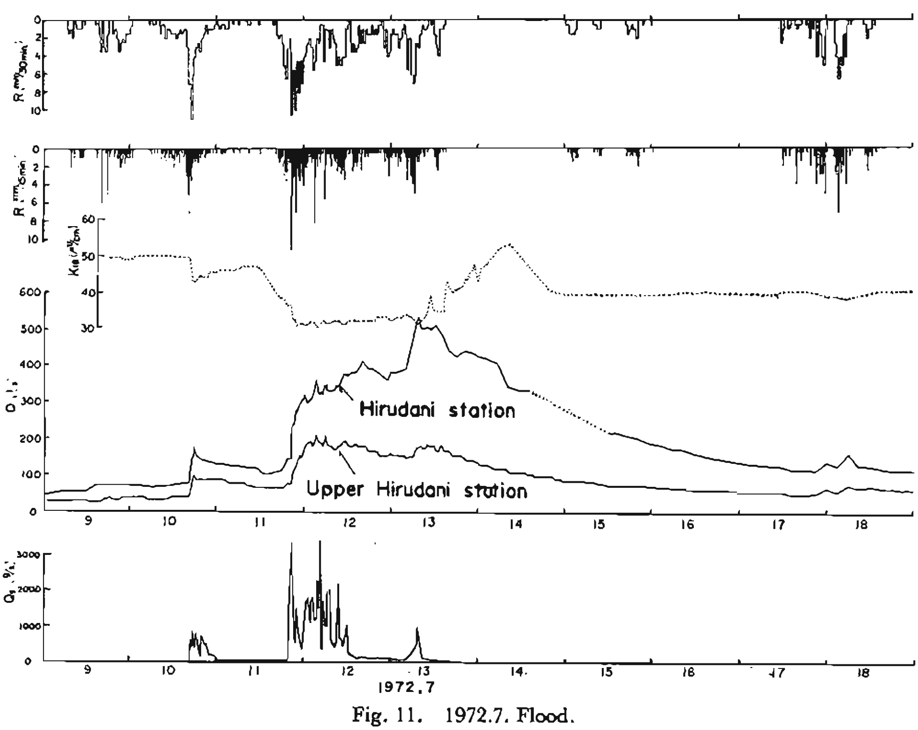

Fig. 11. 1972.7. Flood.

As was noted for the cases above, sediment runoff commenced as soon as the flow rate rapidly increased, but after a while, even though the flow rate was still high, it ceased. Seeing the pattern of sediment runoff from 10th to 13th July, one might conclude that there are some close relations between sediment runoff and rainfall. The rainfall from 17th to 18th July, however, produced no sediment runoff.

More detailed aspects of the phenomena were as follows:—Sediment runoff during 10th July corresponded to either rainfall or flow discharge. The majority of grain size of sediment at that time was less than 2 mm and the median diameter was 1.2 mm. Materials which run off were mostly soil and pieces of wood and grass. This is probably due to the fact that this was the first flood of the year by rainfall. The first peak of rainfall intensity for the second flood occured between 20:30 and 21:00, 11th, July. Coinciding with the rain, the flood occured and sediment discharge increased. Flow materials at that time were again mostly soil and pieces of wood and grass. The sediment discharge at 21:00 was up to 3300 grams per second under a flow rate of 240 *l/s*. Then the flow rate increased up to 300 *l/s*, but the high concentration did not last long, namely, at 23:30 the sediment discharge damped to 300 grams per second. It was when the coler of water changed from dark brown to red brown and the percentage of particles larger than 2 mm increased. This should imply that the bed load had reached the station. From that time on, the sediment discharge again increased and fluctuated making a few peaks, but these peaks had no correlation with peaks in flow rates or rainfalls. After 12 o'clock of 12th, July, sediment discharge decreased to 250 grams per second, without any reduction in size of run off sediment, while the flow rate at Hirudani Station was still rising. Particle size distribution in the samples during the flood is shown in Fig. 12.

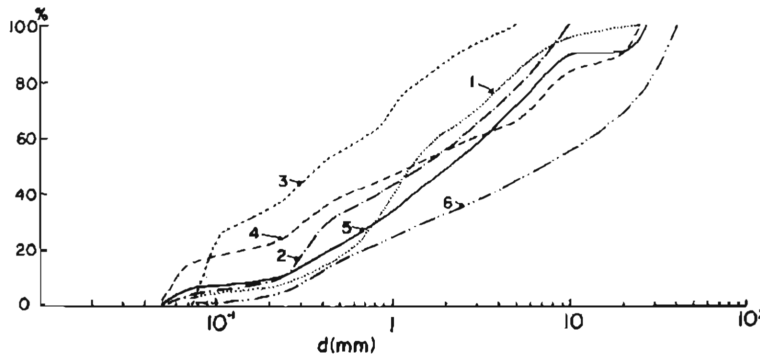

Fig. 12. Particle size distribution in the samples during the flood. 1; Sampled from the surface of landslide, 2; 11:00, 11th, July, 3; 21:00, 11th, July, 4; 21:10, 11th, July, 5; 6:10, 12th, July, 6; 22:00, 13th, July.

Fig. 13 shows the petrographical classification of sediment discharge for various grain-size diameters. Fig. 12 and Fig. 13 indicate that the run off sediment was mostly granite-porphyry originating from the landslide on C-Watershed.

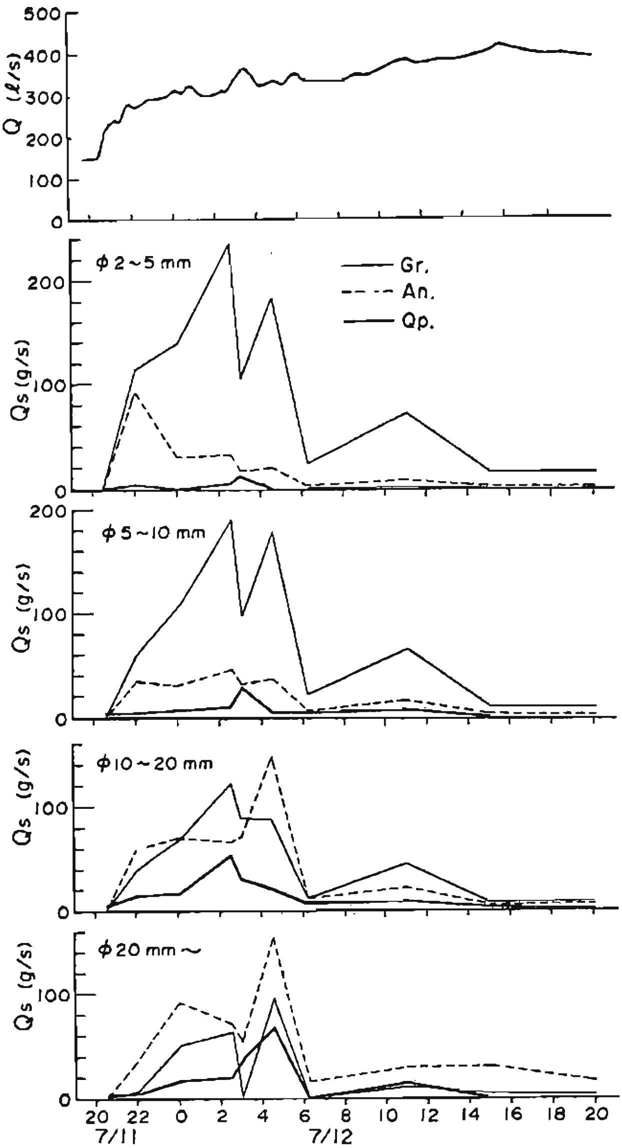

Fig. 13. Sediment discharge classified by grain size diameter and petrology.

(5) *1973.8 Flood* (*Fig. 14*).

Rain in 1973 was very scarce. The small scale flood on the first of August was the only one occasion for observation. Measurement of the discharge from the spring at the top of the landslide on C-Watershed commenced from this year. Q_0 in Fig. 14 indicates this discharge. The runoff pattern of Q_0 corresponds rather well to that of rainfall, with half or one hour lag, and also resembles the hydrograph at Hirudani Station.

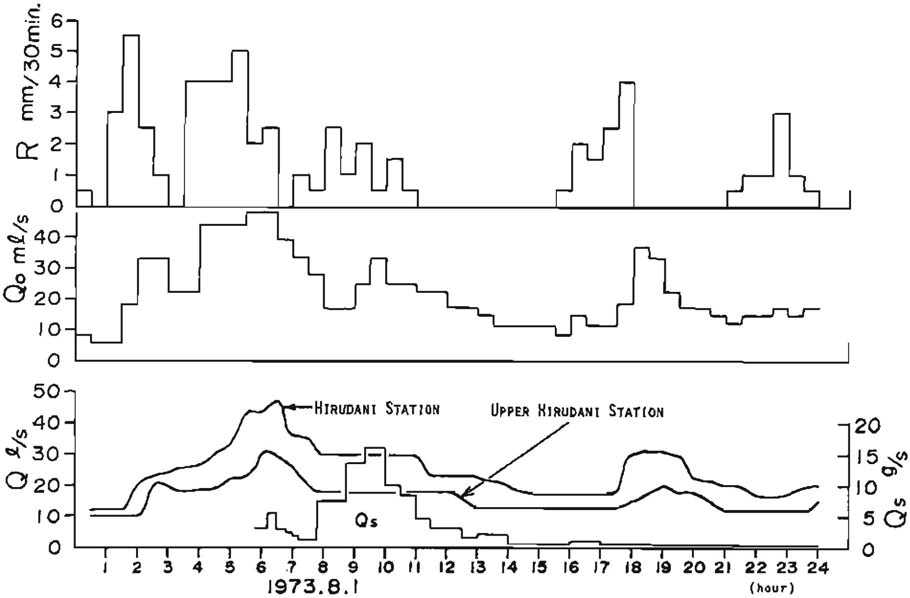

Fig. 14. 1973.8. Flood. Q_0: Spring discharge.

Turbidity in river flow began 5:30 of 1st, August. From that time on, although the volume was small, the sediment runoff occured in correspondence to the hydrograph until 7:50 a.m.. Abruptly from 7:50 a.m., sediment discharge increased, forming a peak and then decreased, meanwhile the flow rate was almost constant. From 17:30, the flow rate again increased, but the sediment runoff no longer in-

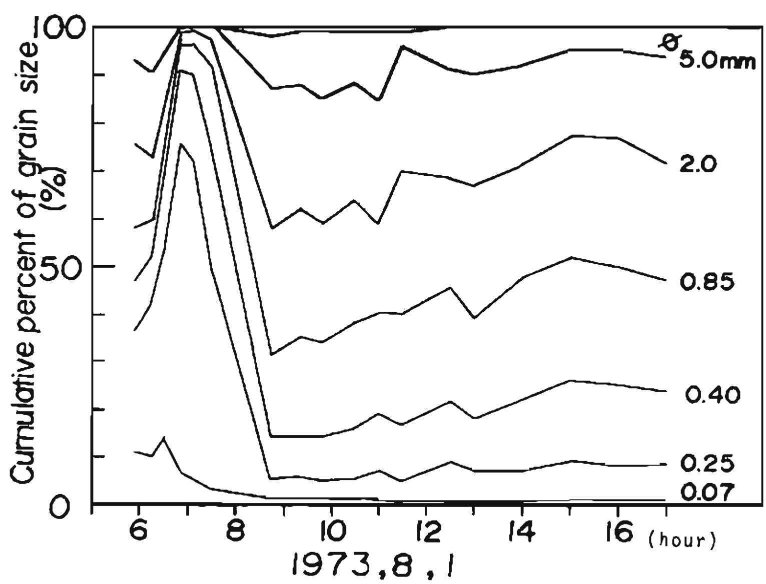

Fig. 15. Variations in grain size distribution of the sediment during the flood.

creased. Sediment particle size distribution varied during the flood as shown in Fig. 15. Sediments sampled from 6 to 8 o'clock had far smaller size than that at the place of production, which is 2 mm in median size. After 9 o'clock, however, the sediment particle size distribution resembled that at the place of production. This fact would imply that the manner of transportation of sediment between the early stage and later had been different; as suspension in the former and as bed load in the latter. Although the sediment size distribution is similar to the one at the landslide of granite-porphyry, petrographical classification of sediment revealed the majority of run off sediment was andesite.

(6) *1974.7 Floods (Fig. 16).*

For the case of the first flood, turbidity in the flowing water began to be observed with the beginning of rise in flow rate, but the measurable amount of sediment reached the station about ten hours later. On the other hand, for the case of the second flood, the peak of sediment discharge well corresponded to the peak of flow rate. This was the first time such a long lag between hydrograph and sediment runoff had been observed. Eighty to ninety percent of the run off sediment was granite-porphyry and the andesite, which was very scarcely distributed along the stream channel. This would mean that the sediment was mostly transported from C-Watershed. In this flood sediment particle sizes were rather large and about 80 percent of them were larger than 3 mm. Remarkable fluctuation in sediment discharge under constant flow rate is another characteristic of this flood.

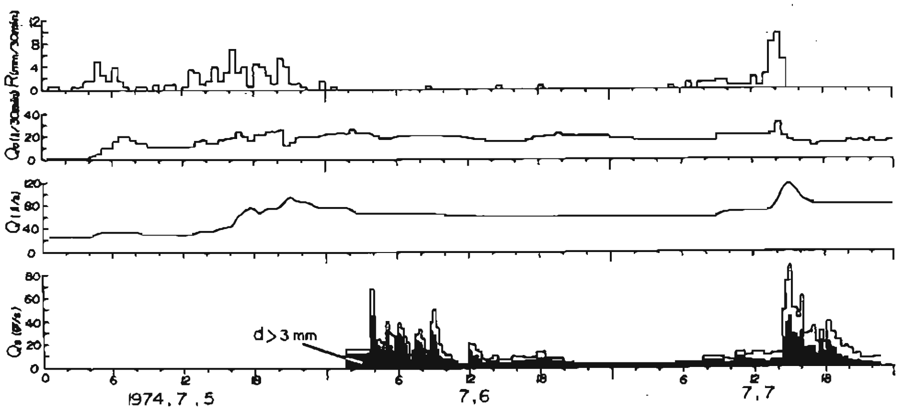

Fig. 16. 1974.7. Floods.

(7) *1974.9 Floods (Fig. 17).*

These flood happened following the flood described above. Sediment runoff in these floods well corresponded to the flow rate. Petrologically, the sediment was, as the previous floods, mostly granite-porphyry, but its size was finer than previously.

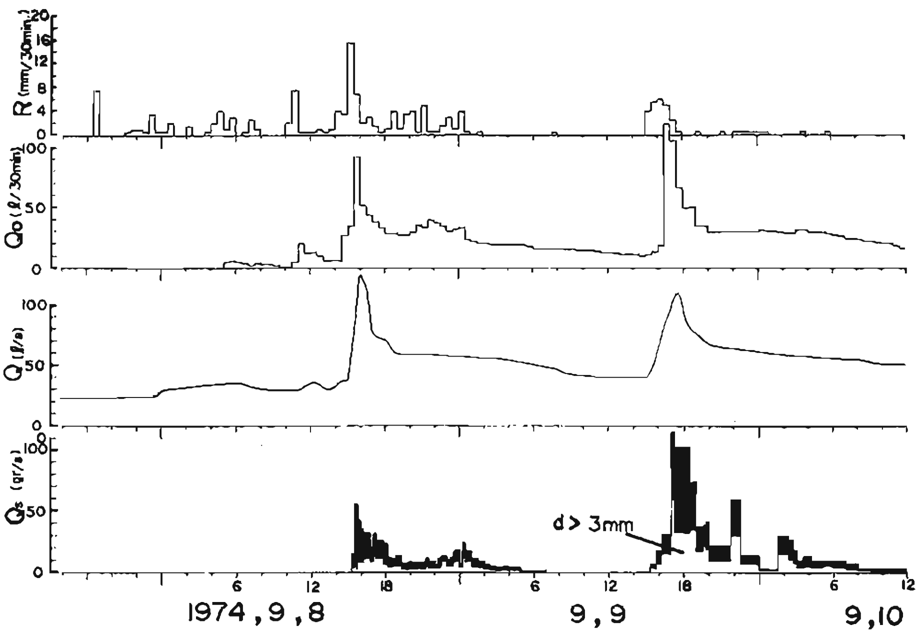

Fig. 17. 1974.9. Floods.

(8) *0975.4 Flood (Fig. 18).*

Flow rate due to snow melting is large in this watershed. Since the duration time of snow melting flood is long, it plays a very important role in sediment runoff phenomena. Fig. 18 shows one example of snow melting flood. Similar to the flood due to heavy rainfall, sediment runoff concentrated in the first stage of the flood

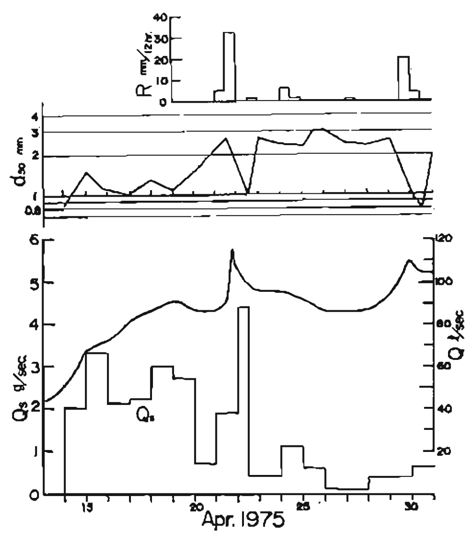

Fig. 18. 1795.4. Flood due to snow melting.

and then gradually tapered. Rain fell on 21st April and the flow rate increased a short while later. The peak of sediment runoff appeared twelve hours after the occurence of the flow rate's peak. These circumstances resembled those of the 1974.7.6 Flood.

(9) *1975.7 Flood* (*Fig. 19*).

In the cases of 1975.4 Flood, 1974.7 Flood and 1974.9 Flood, sediment runoff occured when the flow rate exceeded 50 *l/s*. Although the flow rate reached 81 *l/s* on 4th, July, 1975, no sediment runoff was observed. From 8th July small amount of sediment discharge was being observed when, suddently, on 12th July considerable sediment runoff appeared. A series of sediment runoffs which had a peak of 230 grams per second, of which occurence time was coinciding to that of flow peak of 160 *l/s*, damped out to 20 grams per second before 17 o'clock on the 12th. After that, the sediment discharge, which had a similar runoff pattern and was equivalent in peak sediment discharge to the former one, was again observed under nearly constant flow rate. Sediment discharge at Hirudani Branch Station has been observed since this year. At this station, as is shown in Fig. 19, the sediment discharge hydrograph corresponded well to the hyetograph or spring discharge hydrograph, having only one peak during 12 to 24 o'clock of 12th July. So the double peaked sediment runoff at Hirudani Station should have its cause in the process of stream channel downstream of the junction. It might be due to the stream channel variation. On the 13th July, the sediment discharge hydrograph seemed to correspond to the flow rate variation, but unfortunately, after 6 o'clock, sediment discharge measurement became impossible due to clogging of the intake of the sampler.

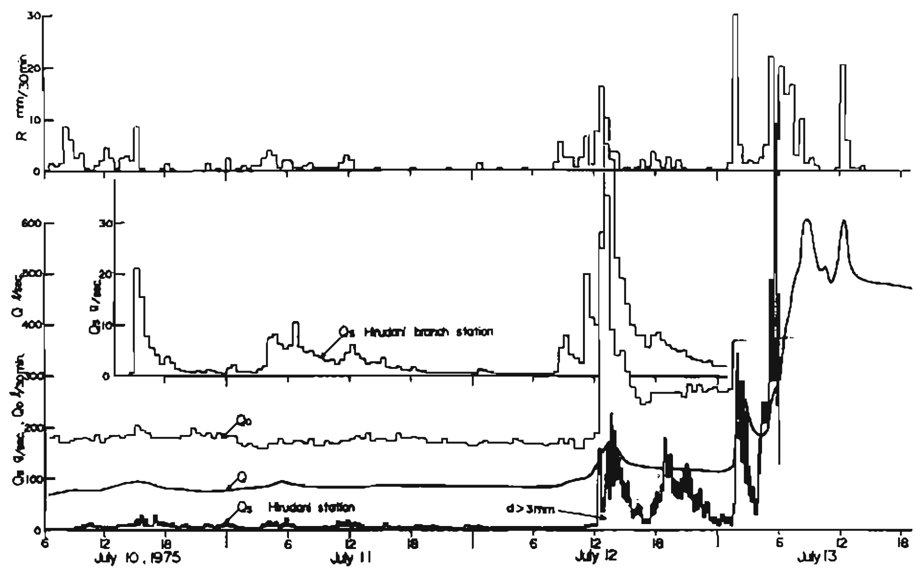

Fig. 19. 1975.7. Flood.

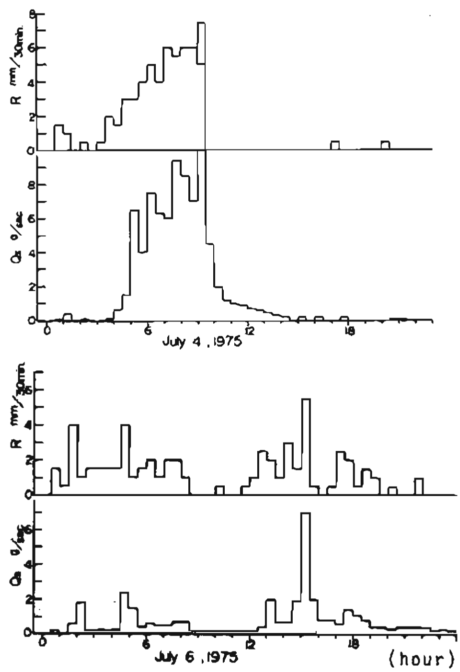

Fig. 20. Rainfall and sediment discharge at Hirudani Branch Station.

Other examples of sediment runoff measurement at Hirudani Branch Station are shown in Fig. 20. Here, it seems to be close relation between sediment discharge and rainfall. This implies that as soon as rain stops, sediment supply from C-Watershed would also stop. On the other hand, discharge from B-Watershed would continue long after that and would able to transport the sediment sweeping, occasionally scouring the channel bed and banks downstream of the junction.

(10) *1975.8 Flood (Fig. 21).*

Since the flood in July was very high, there was severe scouring of stream channels. The flood shown in Fig. 21 was the first to occur after the July flood. Sediment

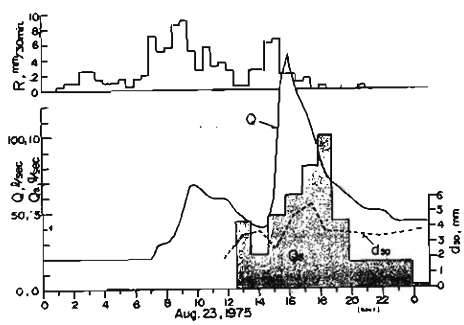

Fig. 21. 1975.8. Flood.

runoff was observed at Hirudani Station from 5.5 hours after the beginning of rise of flow or 3 hours later than the time of flow peak. The transported sediment during this flood was mostly andesite gravel whose median diameter was 3 to 5 mm. The source of supply of andesite gravels is located at about 150 m upstream of Hirudani Station. This is a land slide on the margin of the terrace deposit. Fig. 21 shows that the andesite gravels were transported for a length of 150 m in three hours, corresponding to the average velocity of 1.4 cm/s.

Survey of the channel after this flood revealed that the granite-porphyry gravel had reached 50 m downstream of the junction and practically no granite-porphyry gravel was discovered further downstream.

5. Discussion

As is obvious from the results of observations, sediment runoff phenomena are very complicated: at one time sediment runoff occurs as soon as a flood begins, while at another time it occurs very long after. Limiting the discussion to the above cases, the sediment discharge much varies even under constant flow rates. These circumstances would have been enough to discourage a motivation to solve the phenomena chasing the processes in runoff by use of physical theories on transportation. This might be one reason why many sediment runoff predicting formulae so far have considered the watershed as a black box from which sediment has, any way, been produced, depending on rather macroscopic factors in climate, topography, geology, etc. In these attempts, the only one reliable tool has been multiple regression analysis.

An alternative approach to a more universal prediction would need a conceptual modeling of the phenomena on the watershed. In developing the structure of the model, the component processes would be identified and linked as a flow chart. Theories representing the component processes do not exist yet in forms ready to be used. The authors believe that investigations on the mechanism of transportation and deposition along the stream channel should be as important as the investigations on the producing mechanism on the surfaces of slopes. This should be especially so, if the produced sediment particle sizes are large and they are mostly

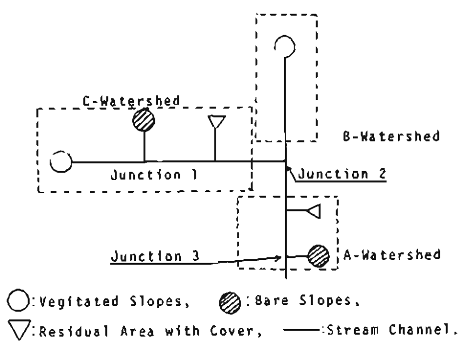

Fig. 22. Schematic representation of Hirudani watershed.

transported as bed load just as is the case in the Hirudani watershed.

A schematic representation of the Hirudani watershed could be shown as Fig. 22, in which the landslide of quartz-porphyry is not considered.

Fig. 23 shows a flow chart of related processes in Hirudani. Since no new landslide has happened and no sediment from B-Watershed has been produced, sediment runoff due to the occurence of landslides or that due to the surface erosion of the covered area are omitted from the flow chart. Of course, this does not necessarily

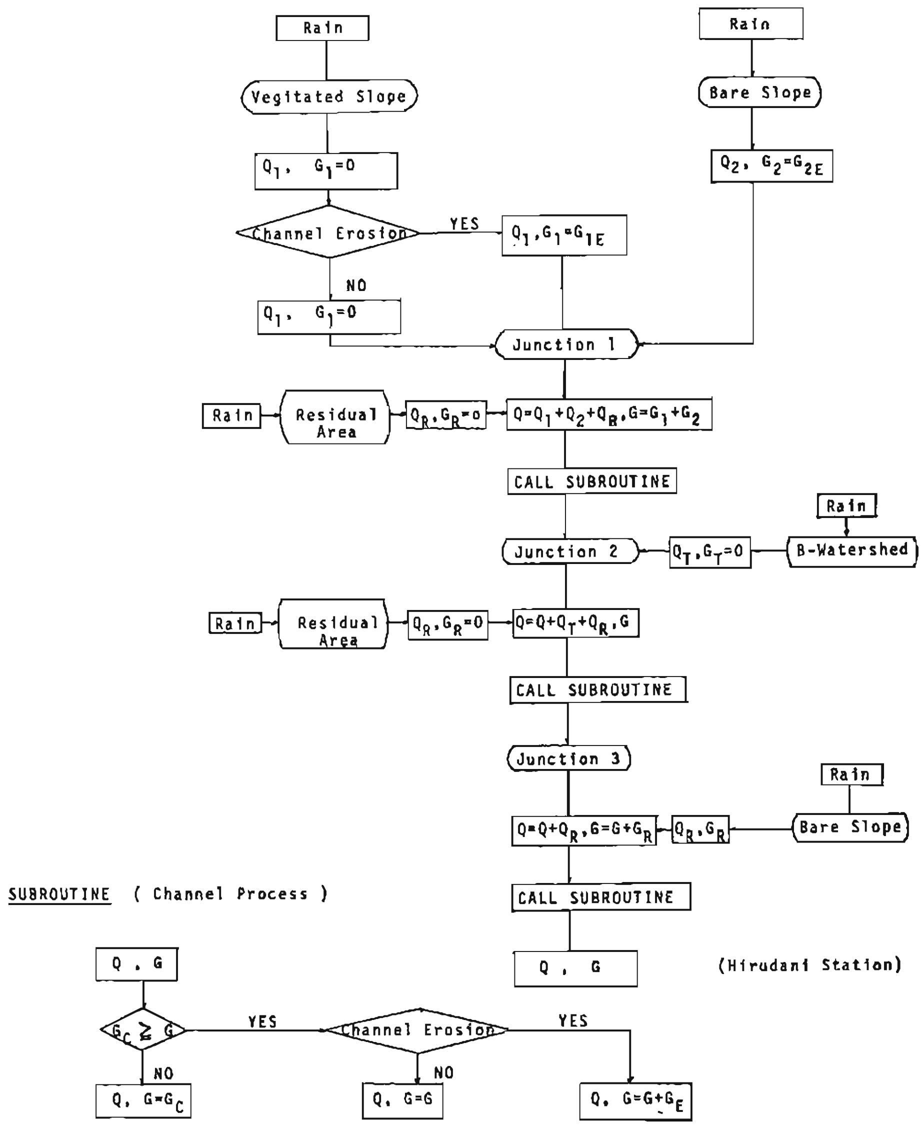

Fig. 23. The flow chart of sediment runoff process in Hirudani watershed.
Q: Flow rate, G; Sediment discharge, G_B; Sediment discharge due to erosion, G_c; Sediment transporting capacity.
Suffiex 1, 2, R and T respectively mean 1, 2, residual and tributary basins.

mean that in this watershed new landslide or an enlargement of existing landslide areas or the channel erosion in B-Watershed will never happen. Much heavier rainfall, which has never been experienced might cause landslides or channel erosions and produce vast amounts of sediment. In such cases, the sediment production processes due to landslides or channel erosions in B-Watershed should be added to the flow chart.

It will be understood from Fig. 23 that the channel process shown as "SUBROUTINE" is critically important to the phenomena. It is where the run off sediment is stored or increased in volume by scouring and as the consequence of these channel processes the sediment discharge hydrograph is transformed. The first consideration in developing the channel process model is to identify the mode of transportation either as suspension or as contact load. Unfortunately, there is no observation data of the actual flow on the stream channel during flood, and so one must guess the mode of transportation from the available data.

Fig. 9 and Fig. 12 show that the run off of granite-porphyry sediment is very similar in size distribution to that sampled at the site of production as long as the flow rate is higher than some threshold value. This implies that the tractive forces of the flow in the stream for such cases exceed the threshold value to transport the maximum size particles in produced sediment. But, if one assumes the tractive force is far beyond the threshold value and almost all sediments are transported in suspension, he should come to the conclusion that there should exist a negligible time lag, at longest ten minutes, between water flow hydrograph and the sediment discharge hydrograph. However, observed lags, as shown in Fig. 16, sometimes exceed ten hours. These results suggest the majority of sediments are transported, at least up to the flow rate of 100–150 l/s, as contact load. The cases which have practically no lag time would imply that there has been much stored sediment on the bed and side banks of the stream channel to be picked up and transported as contact load. So lag time and quantity of runoff would be affected by the antecedent storage of sediment on the stream channel. This storage should be given as a process parameter in the channel process subroutine.

In order to estimate the order of variation of antecedent storage of sediment, field surveys of storage volume for every 20 m in the reach shown in Fig. 24 have been done. The results are shown in Fig. 25. The volume of sediment in each section

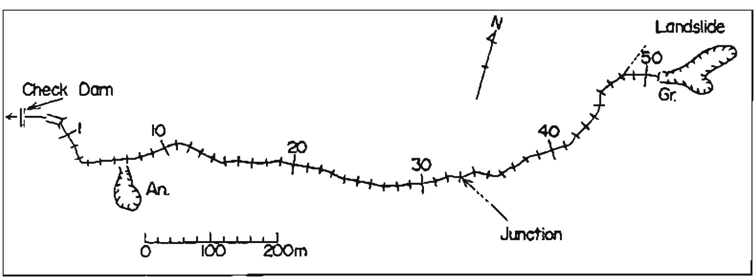

Fig. 24. Plan of the Hirudani channel course and its surveying marks.

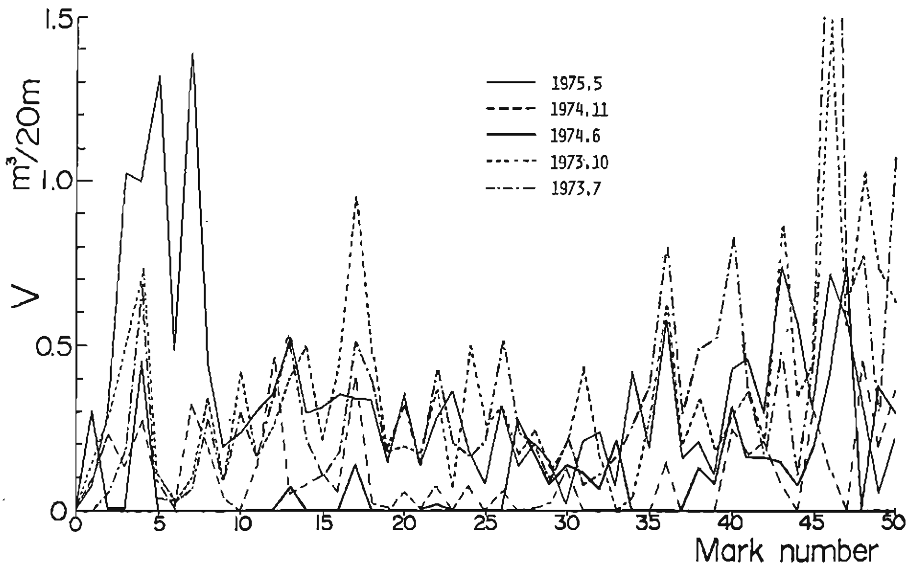

Fig. 25. Sediment storage variation for every 20 m on the course of the Hirudani stream channel.

was measured by multiplication of the storing area by the accumulation thickness, where the thickness was measured by penetrating a steel bar of 2 cm in diameter. Since the bar could not penetrate through the cobble (larger than 10 cm in diameter) coated bed, simply the thickness of accumulation of sand and gravel was rather accurately measured. One can see, in Fig. 25, the sediment depositted on the channel bed and banks at the end of October, 1973, had been thoroughly swept off by the spring floods. Accordingly, little storage of sediment was available in June 1974, and so the antecedent storage for the first flood of the year due to rainfall (1974.7.5 Flood), was practically zero. For this case, the capacity of transportation was larger than supply, but was not large enough to destroy the armoured channel bed. Sediment supply from Hirudani Branch Station should have begun as soon as the flood occured, because the channel reach upstream of the station always stores the sediment. Supplied at the junction, the sediment should have traveled the coated bed through many falls and pools taking about ten hours. The distance from the junction to the mouth (Hirudani Station) being 600 m, the velocity of the sediment particles was about 1.8 cm/s. This is the same order of velocity as the case of 1975.8 Flood (Fig. 21).

Not necessarily all the spring floods sweep the stored sediment off, but sometimes supply the storage. Further observations of spring floods in connection with sediment production during winter time should be necessary.

Fig. 25 also shows the average sediment storage used to amount 0.3 or 0.4 m^3 per each 20 m reach. This suggests that the sediment transportation approaches a sort of equilibrium state under this amount of storage. Allowed this conjecture, the flow rates and sediment discharges should be closely related to each other under this equilibrium state. In other words, the sediment discharge should be calculated using a bed load formula. The stored amount is, however, insufficient to cover all the channel bed and banks. What happens in such cases might be as follows:

The stream channel is composed by linking of many pools and falls as shown in Fig. 26 and Photo. 1. The sediments are mostly deposited, as checked by field survey, at some distance downstream from the bottom of a waterfall, where the sediment to be transported covers the armoured surface and reached an equilibrium state. The slope of energy line at this part of the stream should change in relation to the flow rate from nearly horizontal in case of lower flow up to some percents in case of higher flood; notwithstanding the steep topographical inclination, the effective slope should be much flatter. Assuming a linear effective energy slope variation from 0.002 for 50 *l/s* to 0.01 for 400 *l/s* and further assuming that the breadth of the water surface obeys regime theory, i.e. $B=5Q^{0.5}$, one would be able to calculate sediment discharges using, say, Meyer-Peter and Muller's equation. Cross-sections shown in Fig. 26 imply the regime theory is one reasonable approximation, at least at this flow rate. Fig. 27 shows the results of calculation and observed data. Less amount of storage than that in an equilibrium should result in smaller sediment discharge, so the equilibrium state should be in correspondence to the maximum sediment discharge under particular flow rate. The tendency of the results in Fig. 27 seems to be acceptable.

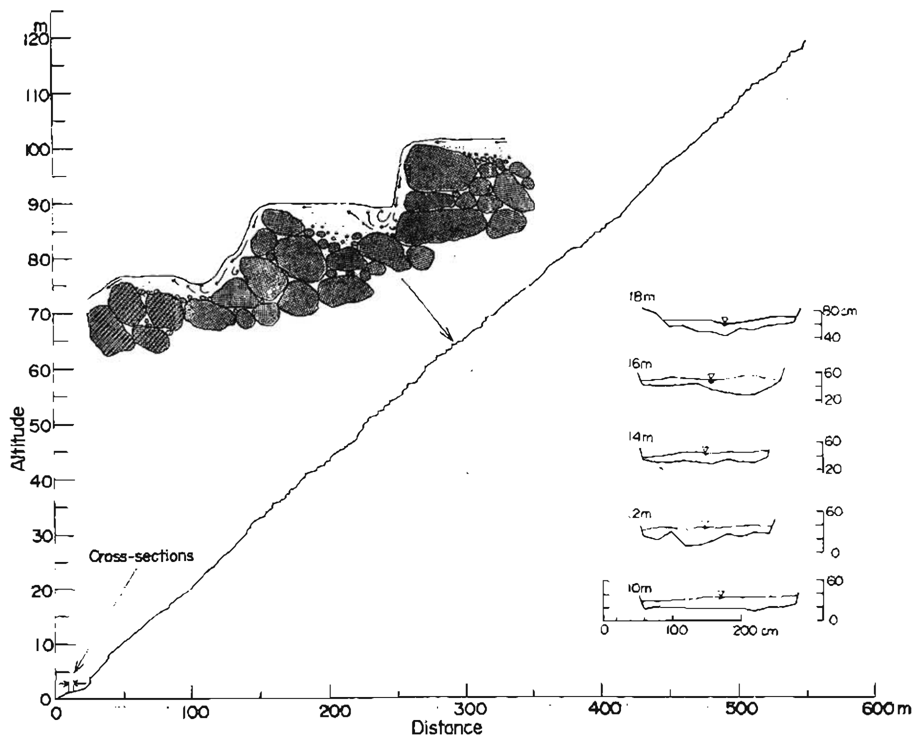

Fig. 26. Longitudinal profile and some representative cross-sections in the Hirudani.

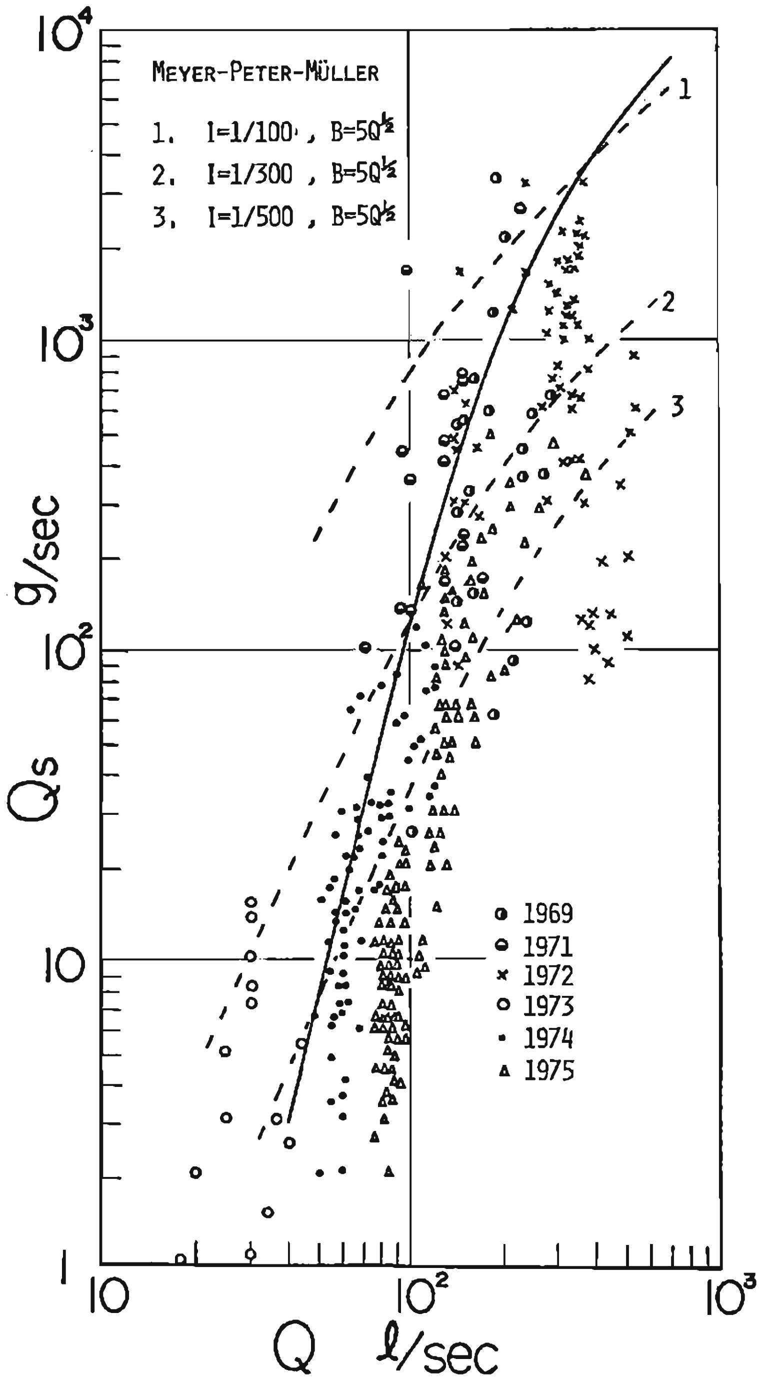

Fig. 27. Relation between flow rates and sediment discharges on the Hirudani.

This model gives no information for the cause of sediment discharge fluctuations even under constant flow rate nor for the prediction of sediment discharge under very high flood, which would destroy the armour coat of the channel or destroy the channel configulations of falls and pools. These are important problems to be discussed as to whether the assumed energy slopes are valid or not. Further investigations should pay attention to solve these problems.

6. Conclusions

Sediment yield and runoff characteristics on a small mountainous watershed called Hirudani have been observed using specially designed apparatuses. Many findings in this study can be summarized as follows:

1) Although the topographical inclination of the stream channel is very steep, the actual effective slope for the sediment transportation should much flatter due to the formation of links of falls and pools along the channel, which are very stable. These falls have the heights from a few decimeters to one meter and the pools have the length of a few meters. An analysis of the relation between sediment discharge and flow rate suggests that the sediment discharge should be controlled at the pools, where the energy slopes which should vary with flow rates could be less than one percent.

2) Prediction of sediment runoff due to a particular flood requires as the process parameters not only the particle size of supplied sediment but also the antecedent sediment storage. It needs a very long time for the supplied sediment to reach the measuring station, if the antecedent storage is small. Sometimes the quantity of run off sediment is limited to a finite value depending on the antecedent storage, even if the flow rate maintains a very high stage.

3) Snow melting flood in this watershed is very important from the point of view of sediment runoff. Sometimes the thawing flood sweeps off the stream channel resulting in the short antecedent sediment storage for the year's first rainfall flood.

4) Subsurface runoff with one or two days lag is the dominating component on the watershed. In some cases, the flow rate increased even long after the ceasing of a rainfall.

5) Electrical conductance in flowing water could be one powerful tool in dividing the runoff components.

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