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Landslide Debris Movement and its Effects on Slope and River Channel in Mountainous Watershed*

By

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山地上流域における地すべり変動と斜面・河道形状への影響*

マルロン アイファンフー アイパッサ**

Abstract

The processes of landslide debris movement on hillslopes, slope deformation and river channel change due to landslide debris movement, and the analysis of the conditions favoring landslide were studied in the Toikanbetsu and Saru River Basins by means of the interpretation of time-sequential sets of aerial photographs and field surveys including tree-ring dating and geomorphological investigations.

Voluminous sediment was produced by deep-seated landslide and transported to the river channel during major climatic events. On the other hand, surface slide and creep were, however, mostly delivered from the hillslope in a persistent process. The type of landslide debris movement and the slope form after landsliding in the study basins varied in accordance with lithology.

The effect of landslide debris movement can be observed not only on the slope deformation in the moving sloping sites but also on geomorphic changes in the river channel. The type of sediment storage varied from zone to other zone within the river basins. Different bed-sediment transport processes and the resulting channel and valley forms characterize each zone. The response of river channel to landslide debris greatly differed from one site to another in accordance with the rate of landslide debris production from hillslopes and the capability of river flow to transport the landslide debris.

Key words: Landslide scar, Geomorphic process, Debris movement, Aerial photograph, Sediment production.

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Introduction

Every year Japan experiences natural disasters caused by mass movement as debris flow or landslide that threaten lives and properties particularly in the densely populated areas. This may seem to be related to the geographical condition of Japan, located at the circum-pan-Pacific belt, which chiefly consist of mountainous area (73 per cent) having steep topography; their major topography covers a large area. These mountainous areas owe their topography to mass movement. In addition, sediment disasters seem to be related to climatic conditions since Japan is situated in a region of heavy rainfall where the continental air current merges with the oceanic air current in its vicinity. Moreover, Japan is frequently hit by typhoons.

Landslide is a part of the geomorphic process which has a variety of negative effects on natural resources and property. These impacts include on-site damages to standing timber and roads, and off-site impacts such as increasing sediment production on river, degradation of water quality, and damages to aquatic habitat (Miles et. al, 1984).

Landslide is caused by the instability of slopes and may involve displacement of large volumes of earth materials.

An examination of the past history of landslides, the recent geomorphic processes observed on landslide scars particularly in an area with a potential risk of slope instability, and also the effects of landslide on river channels are important in providing significant information for the design of remedial measures to reduce risk to acceptable levels.

It is quite difficult and even impossible to entirely understand geomorphic and fluvial processes entirely in a river basin. Therefore, it is important as a first step to transform conceptual thoughts or models of geomorphic processes into a simpler method that can be used to extrapolate field data from smaller and shorter to a relatively larger and longer spatial and temporal aspects.

The objectives of this study are to clarify landslide debris movement on hillslopes, slope deformation and river channel changes due to landslide debris movement. Emphasis was placed on the use of tree rings analysis and the interpretation of time-sequential sets of aerial photographs to the study of the relationship between hillslope processes and change of river valley morphology.

I. Study method

1. Study methods

The study method generally consists of the interpretation of aerial photographs and field survey on the hillslopes and river system (Fig. 1).

Aerial photograph interpretation

Aerophotos are available for most parts of the world, and they provide an overview of both regional conditions and specific site features. Although satellite imagery is readily available, the scale is only suited to broad scale investigations (Norman 1969, Burton 1970,

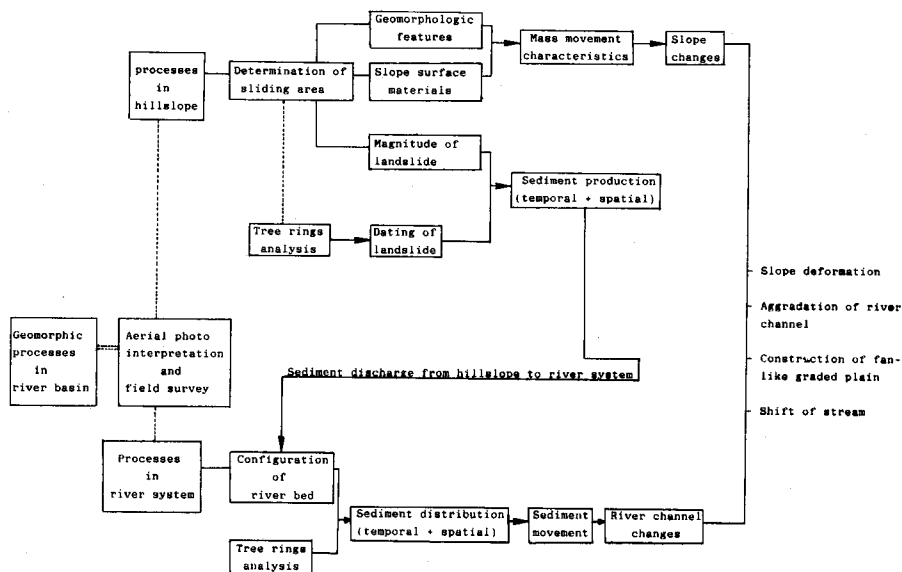


Fig. 1. Methodology of study for effects of landslide on slope and river channel.

Watson 1971).

Several sets of available aerial photographs of the middle reach of the Saru River (taken in 1956, 1963, 1968, 1974, 1978, 1983, and 1988), lower reach of the Jyurokusen Creek (taken in 1969, 1974, 1984), and the Mukaihassen River Basin (taken in 1947, 1960, 1964, 1965, 1969, 1974, 1977, and 1984) were used to describe the history of the successive landslides and river valley changes. The examination under a stereoscope of aerial photographs for landslide areas enables the interpretation of specific related features of landslide which include scarps, hummocky ground surface, areas of concentrated seepage, expansion of headscarp, extension of talus on foot slope, and the distribution of landslide scar within a river basin.

It was practicable to trace the manifestation of recent instability and the dating of landsliding by using these series of aerial photographs since they were available for the area over an extended period of time. Landslides were more difficult to be recognized in heavily forested areas because these areas are less accurately mapped than barren ones. In addition to the interpretation of air photos, topographic maps of the studied areas were used for plotting the distribution and dimension of landslides.

Field survey

The recent geomorphological features associated with landslides were undertaken by means of field surveys, examining the geomorphologic features of the landslide scar such as slope ruptures, headscarps, cliffs, the longitudinal slope form, the planar shape of the slope, and deposition areas. In addition to the geomorphologic features, slope surface materials were examined to clarify the characteristics of mass movement and slope changes.

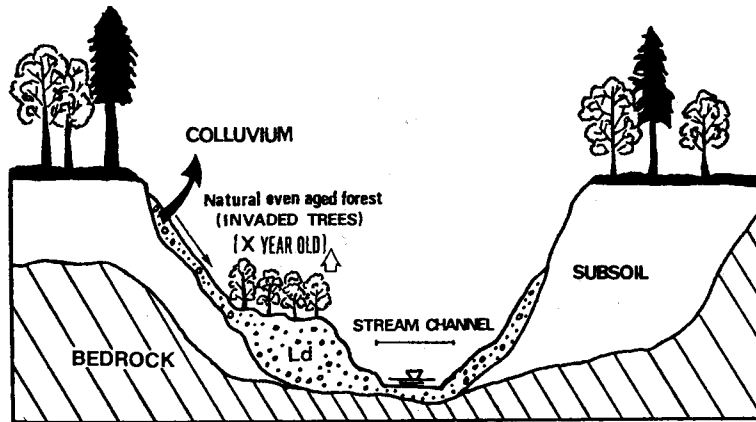
The vegetational conditions related to landslides such as natural revegetation and the curvature of tree trunks were studied to analyze geomorphological processes such as the areas affected by landslides, the activity of movement, and the chronological distribution of channel deposits.

The configuration of the river bed which was effected by the sediment supply from hillslopes was carefully studied. The growth rings of the invaded trees on the river bed were used to determine the ages of deposits. Accordingly, the temporal and spatial distribution of sediment movement and river channel changes.

Figures 2 and 3 show the method to date the initiation of landsliding and to estimate the ages of deposit stored on the river channel. This method actually has long been applied by Araya (1986). The effectiveness of this method has been proved in various parts of Hokkaido, particularly in the study of the changes of topography caused by landslide (Higashi, 1979).

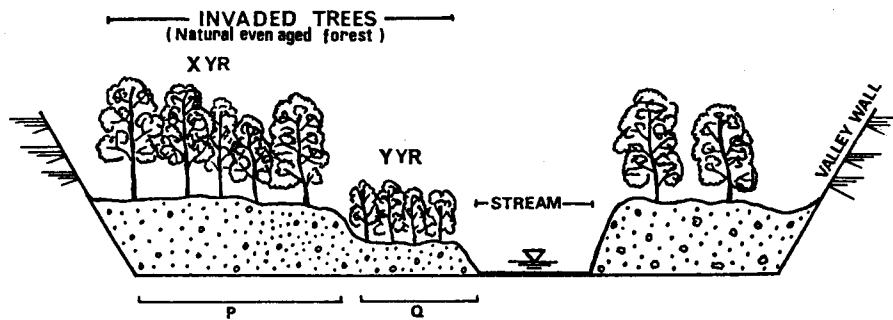
The tree species growing in these deposition sites are pioneer trees like Alder (*Alnus* spp), Birch (*Betula* spp), and Willow tree (*Salix* spp). These trees may instantly invade exposed sites such as landslide scars or new deposition sites on river bed. They may start growing at the same time and eventually form an evenaged forest. The past history of any geomorphologically changing sites like these two sites could then be dendrochronologically analyzed.

Landslide could be dated through tree-ring analysis of leaning trees with adventitious sprouts, stem deformations, and corrosion scars. Tree ages on new deposits provide a minimum time since relative stability was reached. Tree trunks grow radially during



Ld: Deposition of landslide debris (aged x year)

Fig. 2. Schematic cross section of landslide scar.



P: Deposit aged x year

Q: Deposit aged y year

Fig. 3. Schematic cross section of deposit on active channel.

spring and early summer. Wood formed in spring is different from wood formed the previous summer. This difference produce an annual ring, so each year's growth could be identified and dated. Some species have ring morphologies that allow for ease of measurement. These trees are "ring porous" that is, the wood that forms in the spring has large pores that form a conspicuous ring when viewed in cross section. Others are "diffuse porous", with uniform pores throughout the annual ring (Hupp and Sigafos, 1982)

2. Study sites

Three study areas lying in north and central Hokkaido were selected (Fig. 4). The first study basin is located in the Mukaihassen River Basin (Fig. 5) which is a tributary of the Toikanbetsu River flowing south to the lower reach of the Teshio River which ends in the Japan Sea. This river is located about 8 km downstream from the junction with the Jyurokusen River. The second study basin is the Jyurokusen River basin which is also a tributary of the Toikanbetsu River. The third study basin is the Saru River Basin. The

study basin was located in the middle reach of the Saru River, about 1.6km downstream from the junction with the Niseu River. The first study basin was selected since it is a small river basin which consists of almost homogenous bedrock. As such it was expected to provide a nearly ideal study site that is not complicated by various geomorphic processes and numerous landform types. Aside from that this small river basin has a high density of landslide scars that is either old or presently active landslide ; it has also a workable size. The second study basin was chosen since the landslide debris movement on channel in terms of temporal and spatial aspects could be clearly traced. The third study basin was selected in order to describe the pattern of the landslide recurrence and also the accumulation of voluminous landslide debris on the toe of slope which caused the constriction of river channel. Moreover, these study sites which were chosen to understand the type and process of landslides, are geologically different from each other. The Mukaihassen River Basin is mainly underlined by serpentine, which was probably formed at the end of the Mesozoic era. The upland slopes (altitude of more than 300meters) range from 5 to 12 centigrade degrees, while valley side-slopes (altitude of 100 to 300 meters) are 20-50 centigrade degrees. Table 1 shows the general description of the study sites.

Pure forests of *Picea glehnii* are distributed together with some special floral communities from the north-facing slope of the middle to upper reach of the basin. Grass

Table 1. General description of the study sites.

	TOIKANBETSU RIVER		SARU RIVER
	Mukaihassen R.	Jyurokusen R.	
GEOLOGIC STRUCTURE			
-Bedrock	Serpentine	Mudstone, Sandy mudstone	Sandstone, Mudstone, Sedimentary rock
-System/Period	Cretaceous	Neogene	Cretaceous, Miocene
-Era	Mesozoic	Cenozoic	Mesozoic, Cenozoic, Quaternary
PHYSIOGRAPHIC CONDITIONS			
-Area of basin	19 km ²	2.5 km ²	1345 km ²
-Length of river	10 km	2.3 km	97 km
-Land use	Forest (primary, secondary, grassland)	Forest (primary, secondary)	Various land use (Forest, cultivated area, housing, grazing land)
CLIMATIC CONDITIONS			
-Annual precipitation		1200 mm	1153 mm
-Mean annual temperature		5.2°C	6.5°C
Maximum		32.0°C	30.5°C
Minimum		-33.5°C	-23.3°C
-Maximum snow depth		297 cm	92 cm

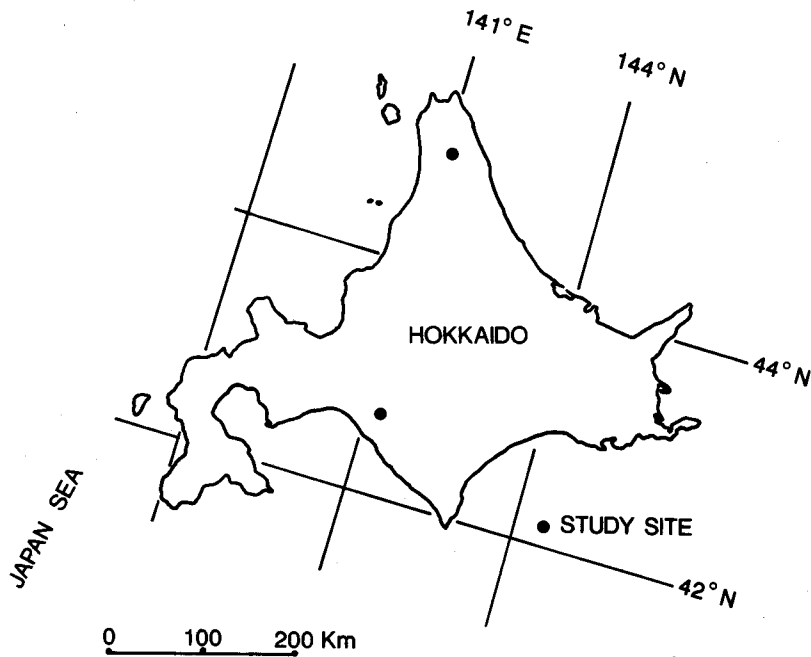


Fig. 4. Location map of study areas.

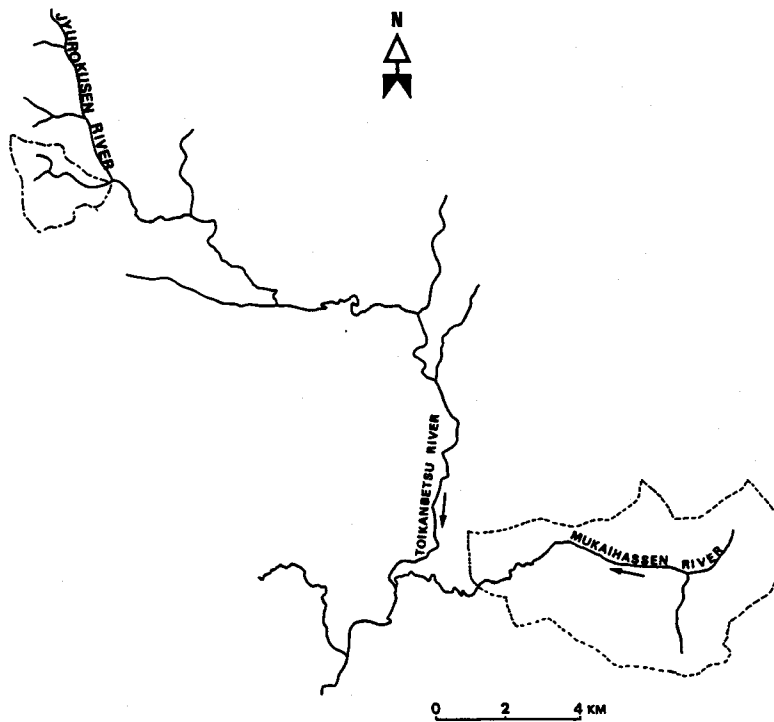


Fig. 5. Location map of the Mukaihassen and Jyurokusen River Basins.

land covers almost 50 per cent of the river basin. They occupy most of the valley bottom and south-facing slope along the river.

Based on the historical record of natural disaster and ecological evidence, forest fire had occasionally occurred since the end of Meiji Period (1910). In burnt areas, secondary forests are partially growing, but treeless land also widely remains.

The mean annual temperature for these second and third study sites is about 5.2 degrees centigrade, and the maximum and minimum temperatures 32 and -33.5 degrees centigrade a warm index of 53. Wind is generally strong throughout the year and yearly precipitation is about 1,200mm; snow falls on these areas from November to April of the following year.

Based on its geologic structure, the Jyurokusen Creek Basin is chiefly composed of sandy mudstone and mudstone which belong to the Neogene System of the Tertiary era. Debris slides and rock falls are widespread along the steep slope sites which are dissected by this creek. Debris slides tend to produce a relatively higher volume of material. They often recur in the same sites and can form a talus cone on the foot slopes. Unlike debris slides, rock falls involve small volumes of coarse material.

Mixed forest of coniferous and broad-leaved trees are widely distributed in this creek basin. *Abies sachalinensis*, *Picea jezoensis*, *Quercus mongolica* var. *grosseserrata*, *Kalopanax pictus*, *Ulmus davidiana* var. *japonica*, *Betula ermanii*, *B. maximowicziana* etc. are widely distributed: The forest floor is densely covered with *Sasa kurilensis* or/and *S. senanensis*.

The Saru River flows from the Hidaka mountain range and ends in the Pacific Ocean. Most of the Saru River Basin is underlined mainly by sedimentary rocks including metamorphic rocks of the Cretaceous period, with sedimentary rocks of the Tertiary period distributed in the riversides of the lower reaches.

A dam ("Nibutani Dam") is being constructed on the lower reach of the Saru River to control floods and sediment stemming from two main sources, the upper reach of the Saru River itself and the Nukabira River.

Stream-side sliding due to heavy rainfall temporarily occurred in many areas of this basin. Rotational slides were frequently seen along the river side.

II. Landslide distribution and slope form after landsliding

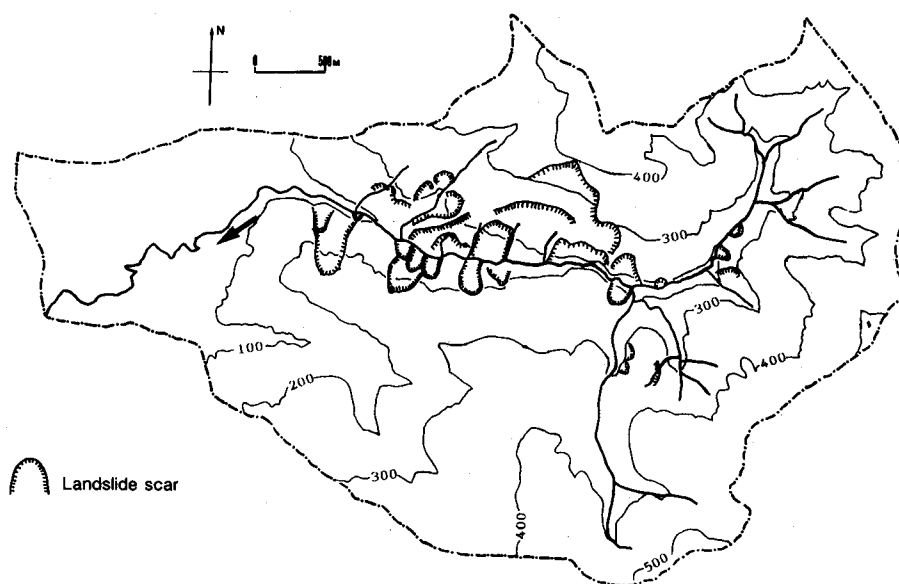
1. Distribution and area of landslides

Figure 6 shows the distribution of landslide in river basin. It was clearly recognized that landslide mostly occurred in the middle reach of the river basin. They are higher either in number or area. Landslide scar was found to be as many as 19 in number in the middle reach occupying an area as large as 88 hectares (Table 2). Most of the landslide scars are located near or in contact with the main river or first order stream. As for the upper reach of the basin, landslide was found to be 10 in number and about 4 hectares in area. No landslide scar was found in the lower reach of the river basin.

Figure 7 shows the distribution of vegetation types in the Mukaihassen River Basin. Basically, three types of vegetation can be observed in this river basin. Primary forest which mainly consist of natural forest of *Picea* spp. can be found in the upper reach and partially in the middle reach. In the lower reach and part of the middle reach, treeless areas predominantly composed of *Micanthus* spp. abound.

Table 2. Distribution of landslide area in river basin.

Average dimension of landslide :		Width 204 m	Length 133 m	Area 3 ha	
Area of landslide based on vegetation type :		Area	Ratio		
-Grass area	61 ha	66%			
-Secondary forest	10 ha	11%			
-Primary forest	21 ha	23%			
Total		92 ha	100%		
Area of landslide based on proximity to river channel :		Area	Ratio	Number	Ratio
-In contact with river channel	62 ha	67%	19	66%	
-Not in contact with river channel	30 ha	33%	10	34%	
Total		92 ha	100%	29	100%
Area of landslide based on segment of river basin :		Area	Ratio	Number	Ratio
-Upper reach	4 ha	4 %	10	34%	
-Middle reach	88 ha	96%	19	66%	
-Lower reach	—	—	—	—	
Total		92 ha	100%	29	100%

**Fig. 6.** Distribution of landslide in the Mukaihassen River Basin.

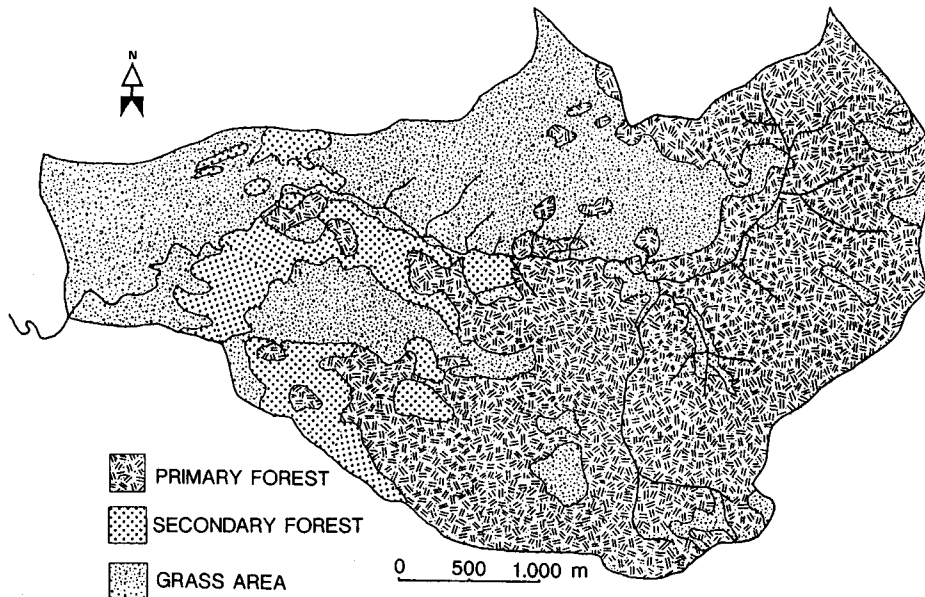


Fig. 7. Distribution of vegetation types in the Mukaihassen River Basin.

To understand the conditions favoring landslides or factors which increase the susceptibility of an area to landsliding and factors which trigger the movement of the landslide debris, is of extreme importance since only a precise and correct diagnosis could serve as a basis for effective remedial measures.

The establishment of features associated with slope instability requires an accurate plan providing the location and elevation of the ground surface throughout the study basin. The detail of survey information required depends on the extent and objectives of the particular study.

Based on the vegetation appearances it was suggested that fire had played a prominent role in the Mukaihassen River Basin. It was recognized too that fires frequently occurred in this basin since the end of Meiji Period (1910).

In broad out line, the secondary forest distributes in the lower reach. The perennial grass conversion distribute mainly in either the lower reach and left portion (south aspect) of the middle reach. While the primary forest covers predominantly in the upper reach and partly in the middle reach. The distribution of these vegetation types were most likely closely related to past fire occurrences. Based on the historical record of disaster fires had occurred mainly in the lower reach and partly in the middle reach in 1910, 1929, and 1940. The secondary forest and perennial grass vegetation were most likely related to the fires. Most of the landslides area are located in these fire-consumed areas, particularly in the middle reach. The absence of tree and the creation of water-repellent layer were the limiting factor for the lower resistance of slope against heavy rains.

In addition to wind and humidity which are important determinants of fire occurrence, topography plays a role in determining the ultimate consequences of a fire. Fires starting

low on the slopes usually have a better chance of spreading and inflicting drainage basin damage than those starting on ridges. Fire might not only consumes vegetation, but also might has an impact on soil. The most common impact on soil is the creation of water-repellent (hydrophobic) layer. The water repellent layer might minimize percolation of water to potential failures surfaces during the times of storm.

Unlike in the case of landslide which has been mentioned previously, surface slide which can be observed in this river basin is a kind of slope failure with a relatively thin sliding depth or a small landslide as a result of frictional failure along a slip surface parallel to the topographic surface involving only material above the unweathered bedrock. The detached soil mantle moves downslope, leaving the subsoil or unweathered bedrock exposed and forms a disarranged deposit at the base. In many cases there is no deposit when the material spreads very thinly over the side slopes or is washed away by streamflow. This kind of landsliding usually occur when rainfall is heavy enough to saturate the soil at the slip surface and where slopes are very steep.

The total area affected by slope surface slope failure in this river basin is about 20 hectares. The total number of slope surface slides is 146 spread out from the lower to upper reach (Table 3).

Table 3. Total barren area due to surface slides.

	Number	Ratio (%)	Area (ha)	Ratio (%)	Average dimensions		
					Length (m)	Width (m)	Area (m ²)
<u>Proximity to stream</u>							
1. Contact to channel	89	61	12.4	63	28	52	1394
2. Midslope	33	23	3.3	17	32	40	993
3. Upslope	24	16	3.9	20	20	122	1613
Total	146	100	19.6	100			

Hydrologic and topographic conditions were observed to clarify how far these site conditions were related to the occurrence of slope surface slides. In the middle reach, most of the slope surface failure were found to have occurred either in the sites of the active landslide or in the slope sites contiguous to channel. The sites of the active landslides which were unvegetative were more prone to the occurrence of slope surface failure since it would be more easy to get sufficient moisture into them to cause failure. While in the upper reach, it was found that they mostly occurred either in the steeper slope sites or in the sites next to stream channel.

Stream order system was found to contribute practically nothing to the occurrence of surface slide. The slope surface failure was prevalent either in the zero or first order basin. As it was expected, proximity to stream channels proved to be an important variable. They were associated with both more frequent and larger slope surface failure. Sixty-one per cent of the slope surface failure occurred contiguous to stream channels, twenty three per cent were found in midslope, and only sixteen per cent were in the upper slope. It was suggested that the stream channel accelerates the growth of slope surface

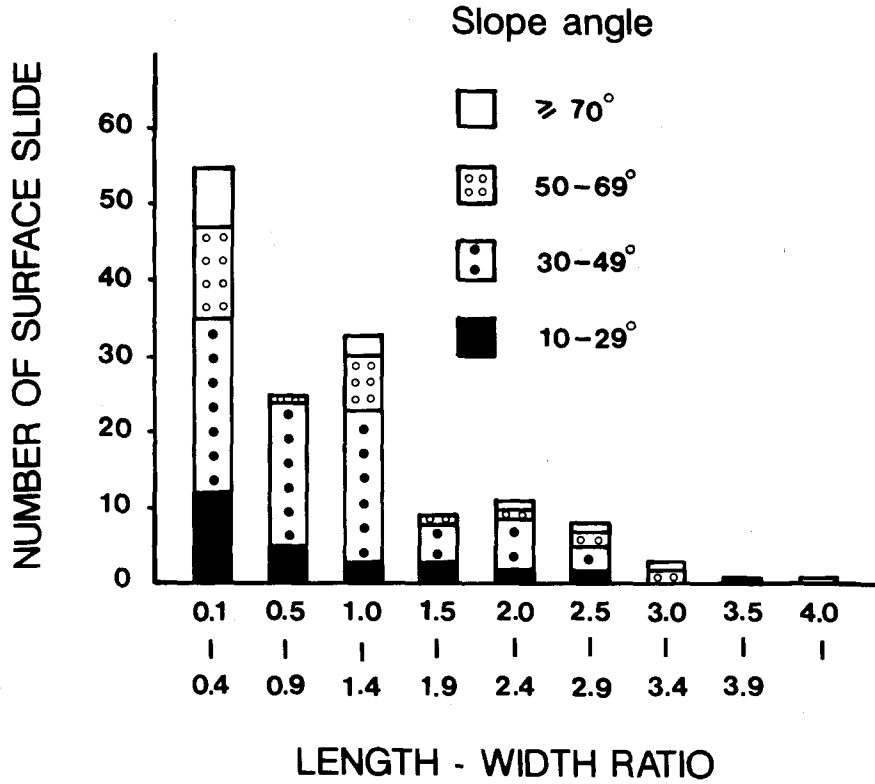


Fig. 8. Relation between number and length-width ratio of surface slide.

failure by undercutting the foot of the slope. The slope sites adjacent or contact to the stream channel might be also subject to higher pore pressures and seepage forces.

In attempt to characterize the shape and nature of the slope surface failure in the watershed unit, length-width ratios were measured, and these were then categorized in term of slope angle (Figure 8). This figure shows the characteristic of slope surface failure for 4 classes slope angles to have a length-width ratio in the range 0.1-3.9 that is from circular to ellipse (elongated or broaden) shapes. The ratios of 0.1-0.9 (broaden ellipse) are the most common in this river basin. The sites of the active landslide were apparently the sites prone to the occurrence of slope surface failure, particularly in their head scarps. The extent width of the head scarp of the active landslide might indicates the commonest shape of slope surface failure. These phenomena were mainly observable in the middle reach especially on the upslope position of the zero order system which were the most common site of the active landslide. No clearly typical relationship of length-width ratio is evident for any class of slope. As in the common cases, most of the slope surface failure occurred in the slope 30-49 centigrade degrees. The number of slope surface failure gradually decrease as the slope gradient increase and eventually they drop sharply when slope gradient exceed 70 degrees centigrade.

2. Slope material and slope form

Slope material

The natures of slope material and slope forms in these study basins have been initially examined by Aipassa and Shimizu (1988 a, b). The overlying landslide debris on landslide scars in the Mukaihassen River Basin was known to be mainly composed of fine materials and somewhat impermeable. Based on the geological structure, this river basin is chiefly composed of serpentine soil. Investigation of soil plasticity was undertaken in the similar geological structure (serpentine) of the neighboring areas. Table 4 shows the Atterberg Limits of the overlying landslide debris in a serpentine area. The plastic limit and both plasticity index and its range show high values. Based on the Casagrande Plasticity Chart, the soil is classified as an inorganic clay of high plasticity (Casagrande, 1948). This might indicate the increase of the bounding properties of fine clay and colloidal fraction of material. Accordingly it may have high consolidation characteristics under stress (Karol, 1960).

Table 4. The Atterberg Limits of the landslide debris on serpentine and mudstone areas in Nakagawa District (after Araya and Murai, 1966).

	Site	Sample	Mean (%)	Estimated range
Liquid Limit	Serpentine	18	80.7	66.6–94.8
	Mudstone	17	49.2	42.0–56.4
Plastic Limit	Serpentine	18	36.7	32.0–41.4
	Mudstone	17	23.5	21.4–25.6
Plasticity Index	Serpentine	18	44.0	33.3–54.7
	Mudstone	17	25.7	18.3–33.1
Flow Index	Serpentine	18	49.8	35.5–64.1
	Mudstone	17	9.0	7.8–10.2

Unlike in the case of overlying landslide debris observed in the Mukaihassen River Basin, overlying landslide debris in Jyurokusen River Basin are mostly composed of coarse materials and are unconsolidated. By using the Atterberg Limits of the soils investigated in the similar geological structure of the adjacent area, the plastic limit index and its range in the Jyurokusen River Basin were found to have low values. They could be classified as an inorganic clay of medium plasticity, having increasingly poorer compaction characteristics and low densities. Accordingly, it might have high consolidation characteristics under stress (Karol, 1960).

Figure 9 shows the particle size of overlying debris on the landslide scar which was investigated in the Jyurokusen River Basin. Grain size of materials was analyzed and classified into several sizes according to the JIS (Japan Industrial Standard). Unlike in the Mukaihassen and Saru River Basin, landslide debris mostly moved downslope in a form of separate grain in the Jyurokusen River Basin. Therefore, analysis of grain size was considered to be an important element in understanding the movement of landslide debris.

The size of overlying debris varied from 2 to 20 millimeters. In the upper part of slope, materials were mainly composed of finer materials. This part was mostly dominated by materials with sizes varying from 2-10 millimeters (occupy 48.8%), followed by the materials with sizes less than 2 millimeters. The coarser materials (10-20

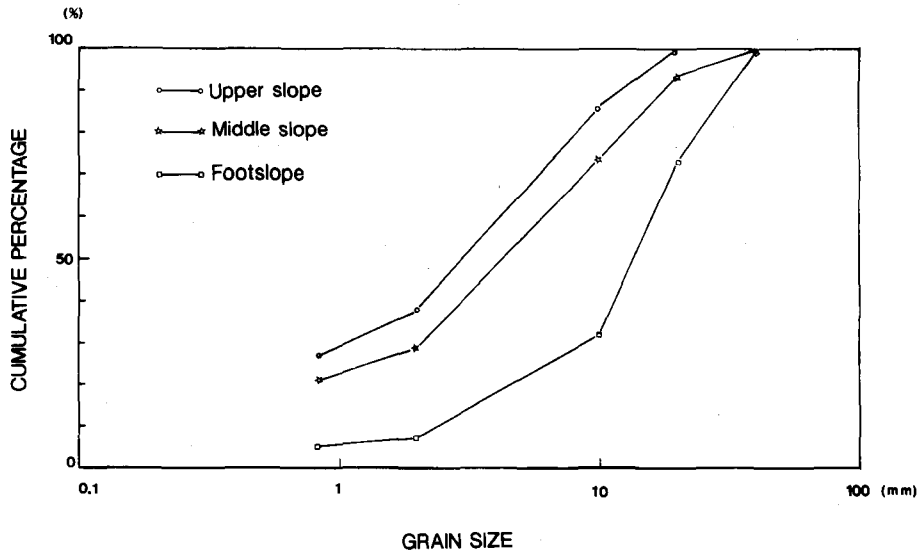


Fig. 9. Curve of particle size distribution.

millimeters) existed in confined amounts (13.7%). Materials with sizes bigger than 20 millimeters were not found entirely in this part.

In the middle part of slope, composition of grain size tend to change. As observed in the upper part of slope, the percentage of finer materials begins to decrease even if they still dominate. Concurrently, the materials with sizes bigger than 20 millimeters and with sizes between 10-20 millimeters start to occupy this part of the slope. However, the percentage is still small, about 6.2% and 19.7%, respectively. Based on these percentages, it can be said that this part is the transition site of grain size change.

In the lower part of the slope, coarser materials especially those materials with sizes between 10-20 millimeters occupy as the dominant materials bigger than 20 millimeters (26.9%). The percentage for finer materials decreased.

Based on the tendencies seen above and in term of transport potential it can be stated that the coarser the material the more distant the materials are pushed downward from the summit of the slope. On the contrary, the finer materials tend to move downward with relatively slight transport potential. The action of these materials is suggested to be affected by the gravitational force as it is found in the most natural phenomena. The slope materials detached from the upper part were firstly accumulated on the downslope site (as a dominant particle) because of the momentum they gain during the sliding movement. The finer material and finally formed a talus form. The characteristics of soil action mentioned above may reflect the type of slope material movement itself on slope. The materials seem to be moved downward in a form of separate grain as favored by gravitational force.

Slope form

As a prelude to a detailed discussion of the principle of slope deformation due to landslide, it is essential to examine the actual forms. Some information, particularly regarding mean and maximum slope angles, can be obtained from the study of accurate

topographical maps, but the most useful method is to survey profiles and gradients in the field, and then to analyze carefully the data obtained.

The determination of slope form due to landslide was undertaken based on the survey of the longitudinal profiles of landslide scar. The survey was carried out in the Mukaihassen and Jyurokusen River Basins which are composed of serpentine and mudstone bedrocks, respectively. The longitudinal profiles of landslide scar investigated in serpentine and mudstone areas are presented in Figures 10 and 11. In the serpentine area, complex form of slope (convex, concave, and rectilinear) was found; simple slope form (rectilinear or straight in profile) was observable in the mudstone area.

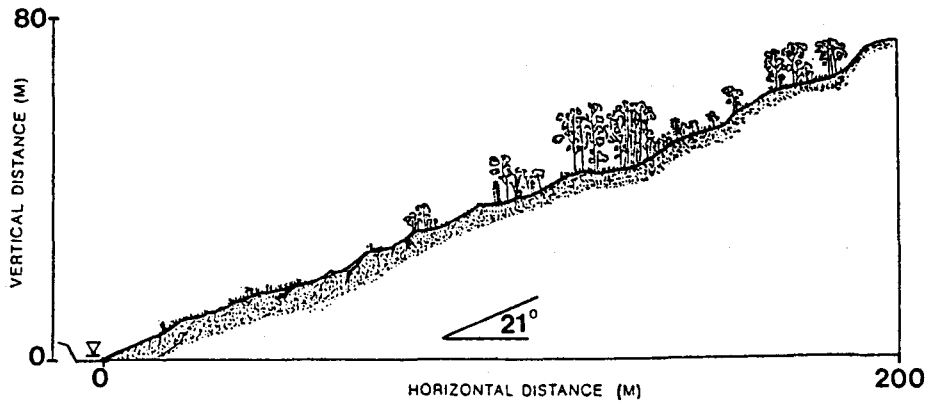


Fig. 10. Longitudinal profile of the landslide scar, investigated in the serpentine area.

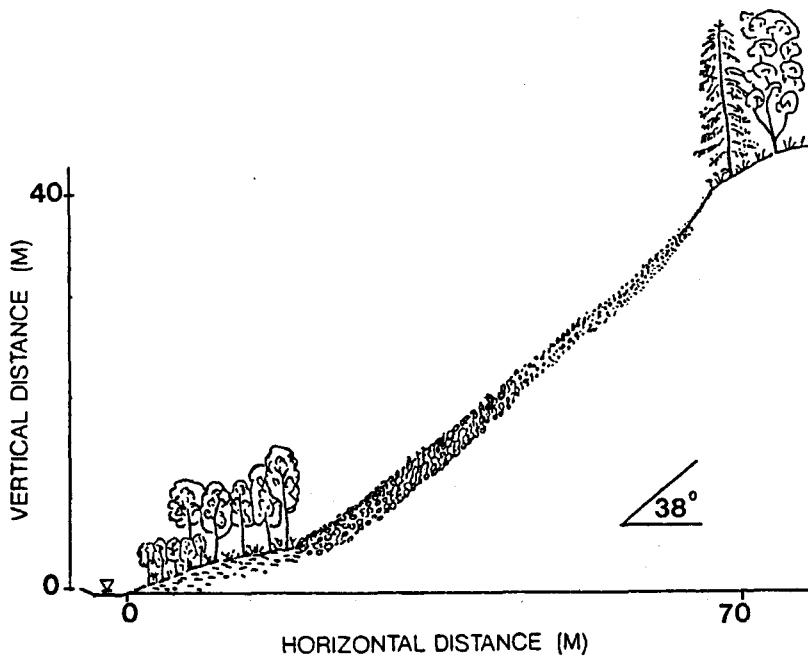


Fig. 11. Longitudinal profile of the landslide scar, investigated in the mudstone area.

The immense variety of slope form observable in the field is regarded as due to the transport process which operates in varying combinations according to the lithology and topographic conditions. The results of slope form studies could not be fully and precisely solved by considering these factors only since there are so many factors affecting the slope form and its processes. Moreover, these factors usually acts simultaneously. Several main types of slope forms were observable under the different slope dimensions, shape of slope, transportation processes in the landslide areas of the studied river basins.

Two forms of slope was observable in the study basins (Fig. 12). The slope form in the Mukaihassen River Basins, was found to be complex (concave, convex and rectilinear slopes). This was inferred to have been formed as a result of rainwash and deposition processes which took place alternately over the extensive length of the relatively gentle slope. Unlike the slope form in the Mukaihassen River Basin, extensive rectilinear slope was found to be the prominent slope form in the Jyurokusen River Basin.

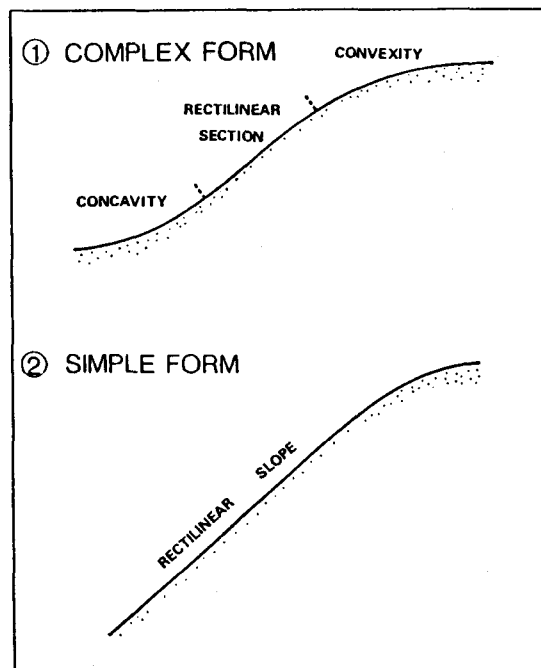


Fig. 12. Slope forms after landsliding observed in the study basins.

“Concave slope” was formed where rainwash effectively took place particularly on the steep part of slope. The slope material in this part of slope was mostly transported downward from the crest and finally resulted in the waning development (concavity section). It is theoretically possible to envisage rainwash as an important formative process on the steeper part of slope, particularly near and at the summit of slope. This process was also found at the lower part of slope, where surface flow had increased to the extent that small scale channels could occur. Thus, it is believed that unconcentrated wash of upper convexity becomes concentrated into numerous surface flows toward

subsequent slope profile. Accordingly, the surface flow was assumed to have been more abundant toward this slope base owing to the decreased soil permeability. These surface flows may effect considerable erosion and impose on this lower slope its characteristic concavity of profile.

The concave profile of the lower part greatly resembles the long profile of a river and readily leads to the assumption that running water is probably the main process in operation on the lower part of the slope. Small (1979) suggested that in the lower part, a slope will commonly exhibit a concavity section. In some cases this concavity will result from depositional processes. The increased proportion of clay material might affect the permeability of the slope, causing concentrated rill action to extend higher up the slope with a corresponding increase in the concave portion and a decrease in the convex portion.

"Convex slope" was commonly formed by the accumulation of transported materials. These materials are deposited on the gentle part of the slope and they finally lead to a gradual waxing development (convexity section). This section was ordinarily found on the absence of effective wash, and so soil creep activity is usually and on the contrary highly developed in some convex sections of slope.

"Rectilinear slope" appeared to be more characteristic of areas with steeper slopes and was restricted to the central part of the slope profile, where it separates a convex section above from a concave section below. This section may reflect a condition of approximate balance between the downslope increment of load and the downslope increase of efficiency of slope transportation. This kind of slope form were widely found in the Jyurokusen River Basin. Slopes not containing upper slope convexity and lower slope concavity, however, were also found. In the Mukaihassen River Basin, slopes bordering a heavily aggraded river valley show no lower concavity as it was buried beneath the alluvium. The absence of talus accumulation suggests narrow valleys in which the rivers were engaged in active downcutting.

The feature of the slope after sliding is mainly characterized by the presence of an extensive rectilinear section (straight in profile). On the other hand, the convex slope, which is mainly formed by the deposition of the slope materials from the upper part of slope, occupied the downslope site forming a talus. However, this section is confined only in the downslope site. This rectilinear section is most likely related to the slope material characteristics. The coarser and consolidated particles are assumed to be the factor greatly promoting the rectilinear slope form. The concavity and convexity sections are conversely displayed at minimum since the downslope transportation of slope materials becomes more increased, and so the slope load is moved straight downward without making any concave and/or convex slope profiles through the gravitational force.

The proportion of slope profiles in two areas is presented in Figure 13. The concavity observed in serpentine area was found to be the dominant form (44.8%) of the total length of slope, while the convex slope was found to be a minor slope form (15.5%). The rectilinear slope form was also found to be as extensive (39.7%) as the concave slope form. The slope form observable in mudstone area in somewhat different from what was found in serpentine area, where marked rectilinear section dominated about 77.5 percent of the total length of the slope, while convex and concave slope forms are conversely displayed at minimum.

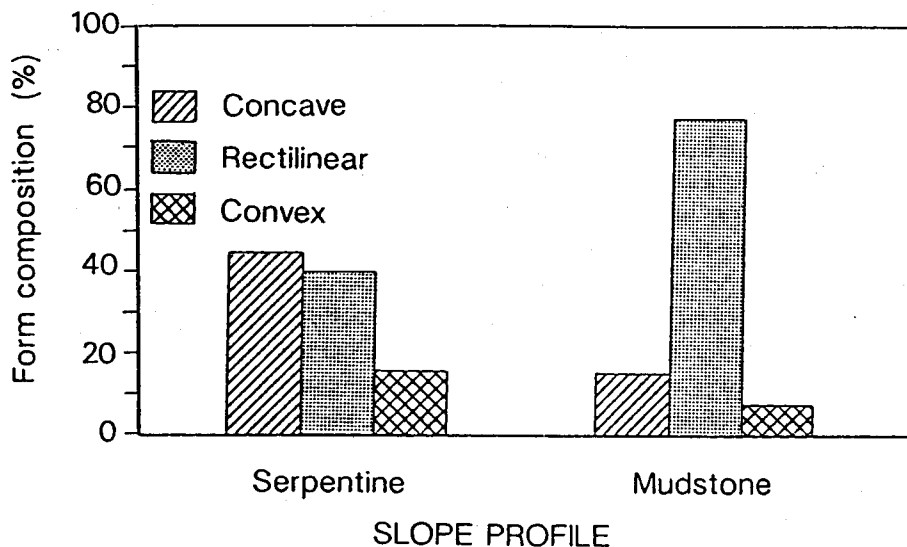


Fig. 13. Proportion of slope surface form of landslide scars in the Mukaihassen and Jyurokusen River Basins.

III. Debris movement on slope

1. Landslides activity

Based on the interpretation of time-sequential of air photos for 32 years (1956-1988) and tree rings analysis for Saru River Basin, the type of mass movement, the expansion of head scarps, the extension of foot slope, and the effect of landslide debris on the main channel were chronologically studied (Aipassa, Shimizu and Araya, 1990 a, b). The results of the study are summarized as follows (Fig. 14):

Surface erosion and deep-seated landslides occurred prior to 1956, accumulating the debris on the foot slope. The area affected by slope failure was estimated to be about 2.0 hectares.

In 1963, deep-seated landslides were found to be the major type of slope failure. Most of the debris avalanches occurred on mid slopes and directly coalesced into the main channel. The landslide debris deposited on the foot slope was mostly washed away by fluvial transport. The river valley was widened to a high degree by downcutting as bank erosion continued headward. Strong lateral erosion of the river induced the failure of foot slope. It was suggested that the successive storms in the summer of 1961 and 1962 were the major sediment transporting events (Table 5).

Landslides were estimated to have occurred again in 1966 during a single storm and retreated about 12 meters. Landslide debris moved downslope and accumulated on the foot slope forming a talus cone as large as 1500 square meters and several meters thick. The headscarp subsequently enlarged and deepened after successive deep-seated landslides in 1970 and 1973. The total area of the landslide scar became gradually larger (2.6 hectares), affected especially by the deep-seated landslide and surface slides.

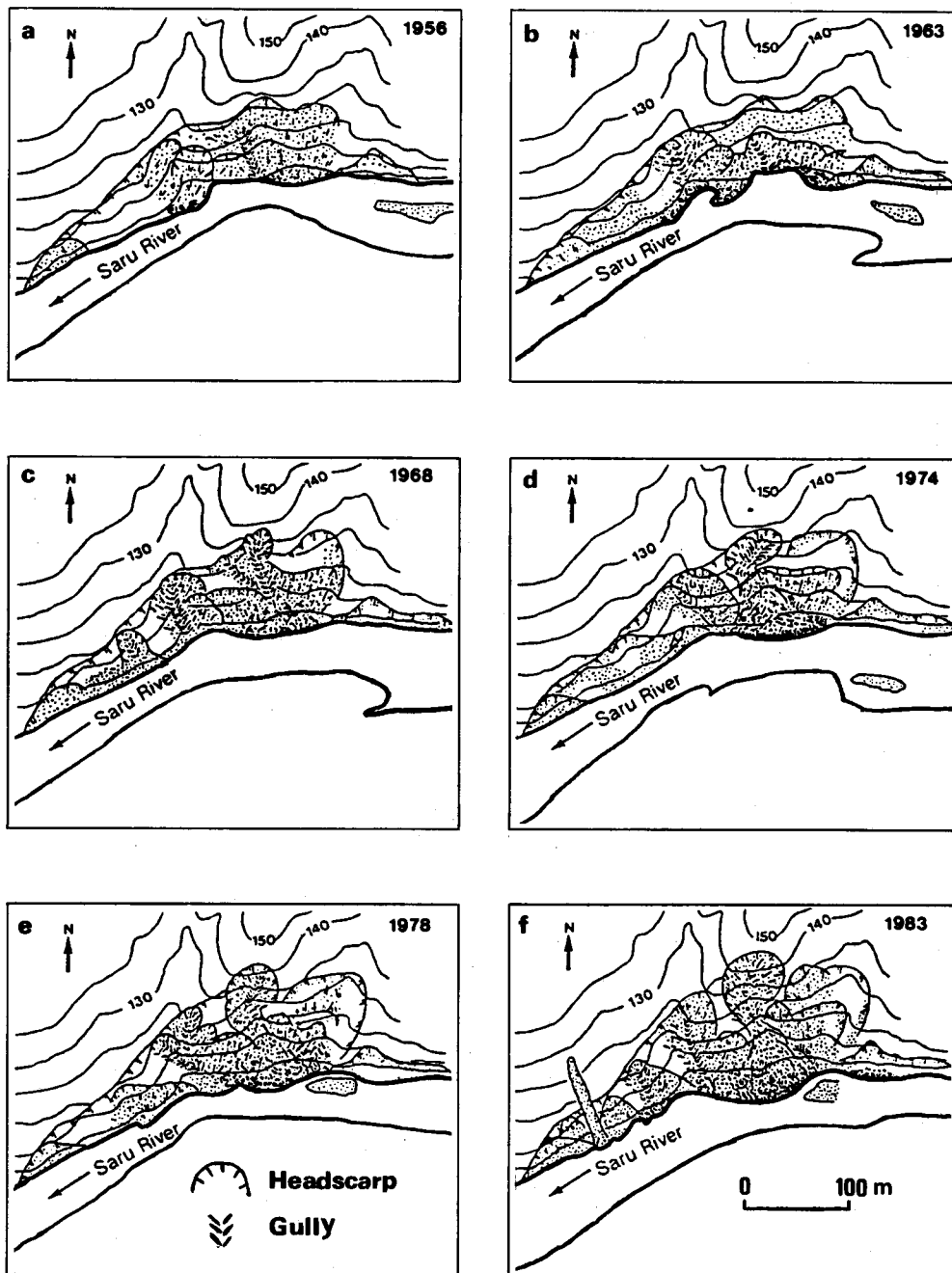


Fig. 14. Landslide scars based on the interpretation of the time-sequential sets of air photos (redrawn from Aipassa et al, 1990).

Table 5. Historical record of heavy rain in Hidaka District (after Aipassa et al, 1990).

No.	Date of heavy rainfall	Successive rain (mm/day)
1.	September 26-27, 1954	No data
2.	July 3-5, 1955	No data
3.	July 24-26, 1961	274
4.	August 2-6, 1962	248
5.	August 19, 1966	164
6.	October 16, 1970	156
7.	August 17, 1973	173
8.	August 27, 1974	111
9.	August 24, 1975	115
10.	August 5, 1981	132

Source: Hokkaido Development Agency (Division of construction, Muroran).

Due to the successive heavy rains in the summer of 1974 and 1975, deep-seated landslides and shallow slides have repeatedly occurred and resulted in the enlargement of the former headscarp retreating about 15 meters from the previous scarp. Most of the colluvial soil accumulated in the foot slope formed a gentle and large talus. From 1978 to 1983, the major enlargement (about 15m) of the main scar by a deep-seated landslide and a shallow slide as well as a little surface erosion was recognized.

Many small block slides on the mid-slope were considered to have occurred during the 1981 typhoon, discharged voluminous sediment either from the new failures or from the colluvial deposits perched on the scars. These sediment deposits partly constrained the river channel, forming an area as large as 5400 square meters of talus. Measurement by using the aerialphotos taken in 1963-1983 showed that the colluvial deposits on the foot slope had moved at an average of 1.3m per year in the 15-years period from 1966 to 1981. The area of the scar in 1983 was calculated to be 3.2 hectares, gradually growing larger and larger since the first major enlargement in 1970-1973.

2. Zoning of mass movements on scars

In the sense of debris movement and of slope morphology, at least three definite areas of landslide scars could obviously be distinguished as the failure area, earth flow area and deposition area (Fig. 15). The failure area is mainly located on the upper slope froming a concavity plane. In the area of the largest deep-seated landslide, the failure area might have reached an area of about 0.3 hectare with a 40 meter failure-plane length. Cliff became gradually steeper as the scar overtopped, dipping at an inclination of around 43 degrees. The steep-sided inner scar reached a maximum depth of 5 meters, and it consisted of 4 meters of thick sandy soil and a meter thick upper and lower layer of stratified gravels, respectively. Deep gullies, swales and scarps were formed in this area. In the earth flow area, many young pioneer tress were displaced by the active flow which was generally accelerated by the increased water content of the mass during heavy rains or by the thawing of snow cover. This area can be classified as a creeping area since the debris movement in this area is relatively higher than the other areas.

The maximum length of the earth flow area was about 80 meters. The landslide

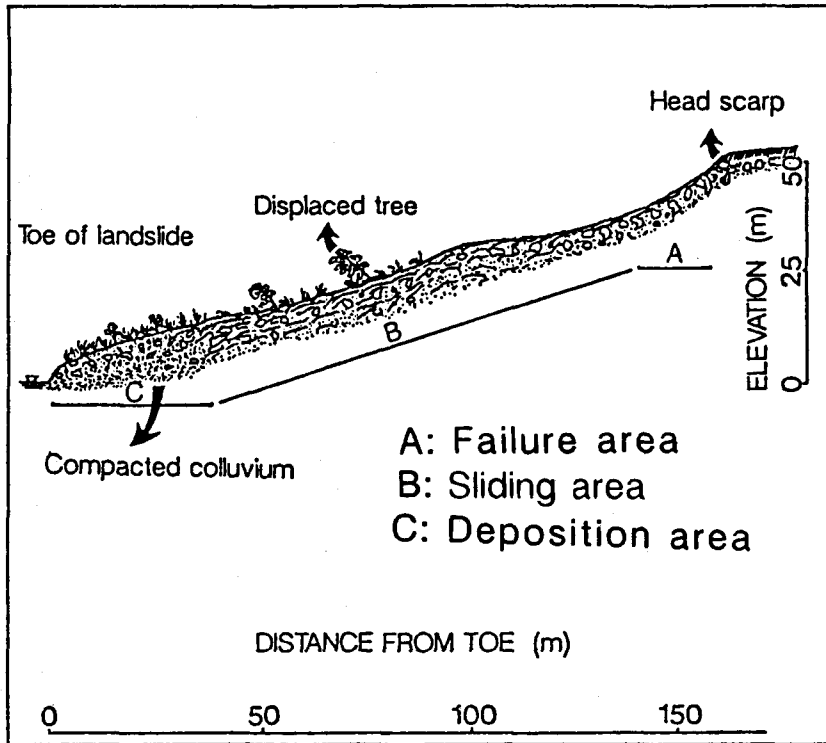


Fig. 15. Longitudinal profile of landslide scar, showing mass movement zoning (after Aipassa et al, 1990).

debris was transmitted through the earth flow area and finally accumulated in the deposition area as a gentler slope located at the foot slope, forming a terraced-shaped talus, with some of the debris blocking the adjacent main channel. The materials in this area consisted of compacted colluvial. The maximum length of this area was about 40 meters with a 16-degree average inclination. Most of this area have been covered with bushes and young trees invaded since the latest storm in 1981.

3. Landslide scar enlargement and debris movement

Landslide scar enlargement

Voluminous debris was produced by deep-seated landslides which occurred in 1961 and 1962. The length of the main scar was about 72 meters, being shorter than the previous one (Fig. 16). This might be caused by the intense lateral erosion of the river which washed out a large amount of either the previous debris perched on the foot slope or the debris produced during these times.

The scar became longer (92 meters) after the landslides during the single storm of 1966, causing the expansion of the upper scar and the extension of the foot slope. It was found that although the amount of failure debris was smaller than of the previous debris (1961, 1962), the area of talus on the foot slope was 6 times larger than former one.

The expansion of the headscarp and extension of the foot slope during the next period

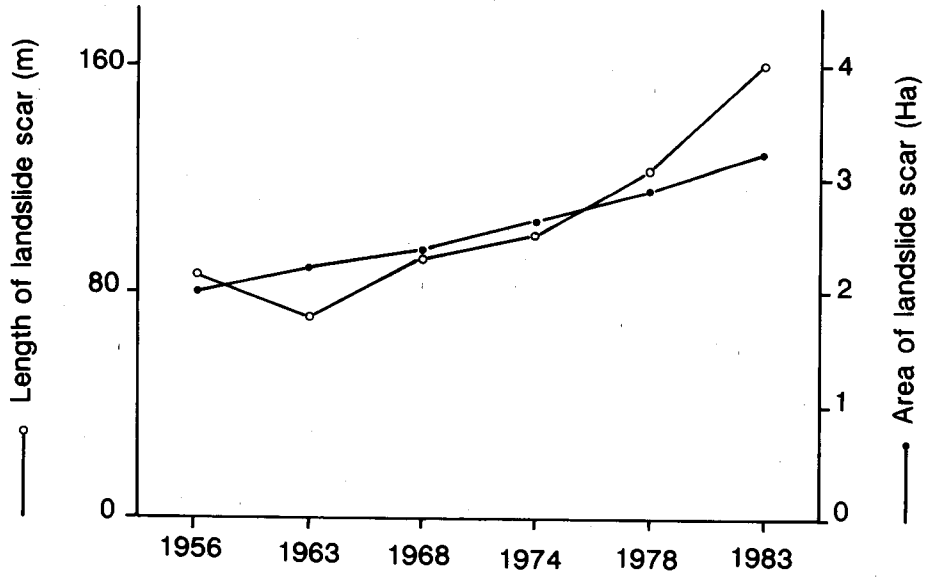


Fig. 16. Curve of extension and enlargement of landslide scar.

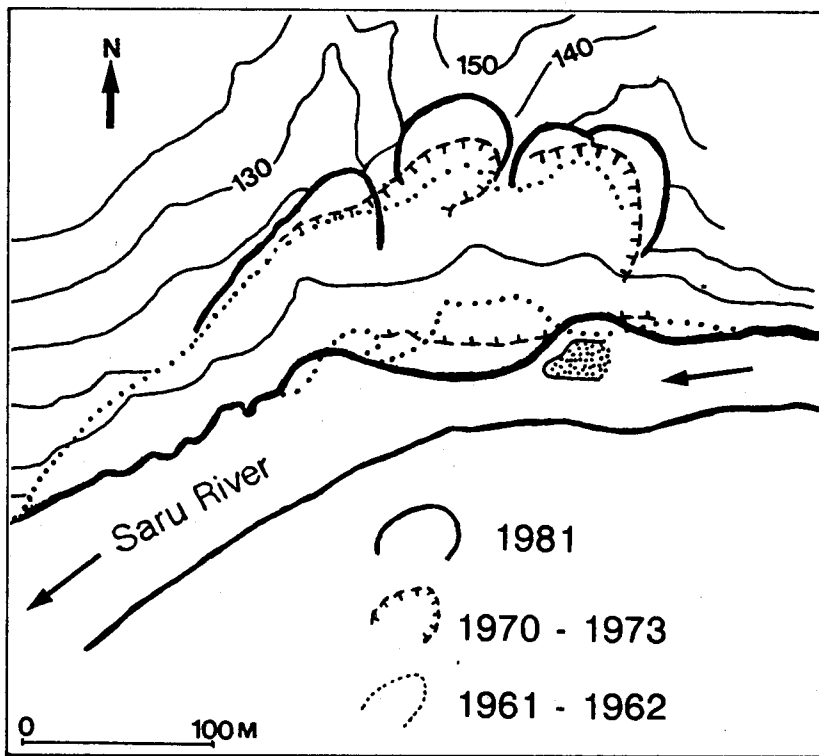


Fig. 17. Expansion of headscarp and extension of footslope by successive landslides (redrawn from Aipassa et al, 1990).

of successive heavy rains (1970, 1973, 1974, 1975) is shown in Figure 17. Duplication on the same plane with upper slope expansion and overlap to the adjacent plane were found during the storms of 1966, 1970 and 1973. Upper slope expansion was found to be the most frequent type during the successive landslides and was the single type of landslide recurrence in 1961 and 1962. These successive landslides caused the length of the main scar to gradually become longer and longer. The landslide debris, moreover, accumulated on the foot slope, moving rapidly into the main channel during the landslides occurrence without the intense lateral erosion.

Debris movement

In order to understand landslide debris supply to river, soil creep activity was measured particularly in the landslide scar area. Soil creep measurement was performed by installing several red-painted wooden stakes which were embedded vertically into the ground surface. Figures 18 and 19 show the position of the stakes embedded on the landslide scar in the Saru and Mukaihassen River Basins within the 2 and 4-years periods from 1989 to 1990 and 1987 to 1990, respectively.

Figures 20 and 21 present the values of soil creep. It was found that the soil creep in the sites in contact with the river channel (F1) was relatively higher than that of the sites not in contact with the river channel both in the two investigated sites. It was suggested that these sites might be subject to higher pore pressure either from river flow power or

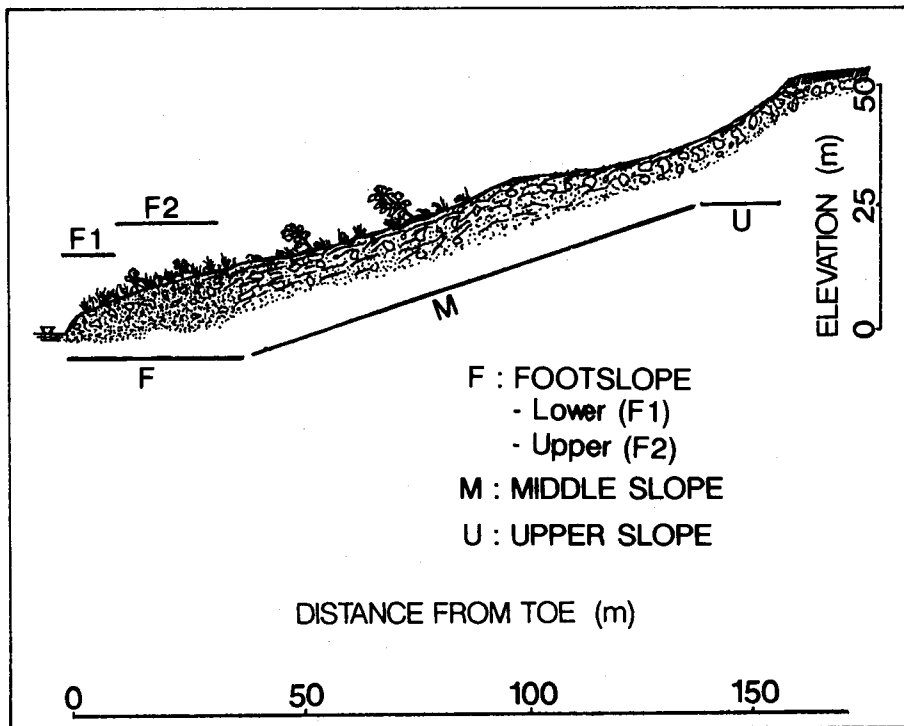


Fig. 18. Position of stakes embedded on landslide scar to measure soil creep in the Saru River Basin.

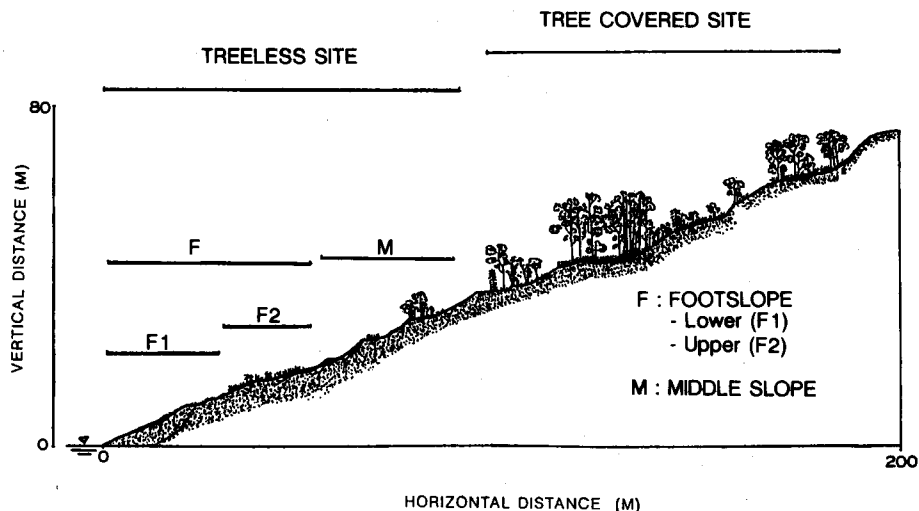


Fig. 19. Position of stakes embedded on landslide scar to measure soil creep in the Mukaihassen River Basin.

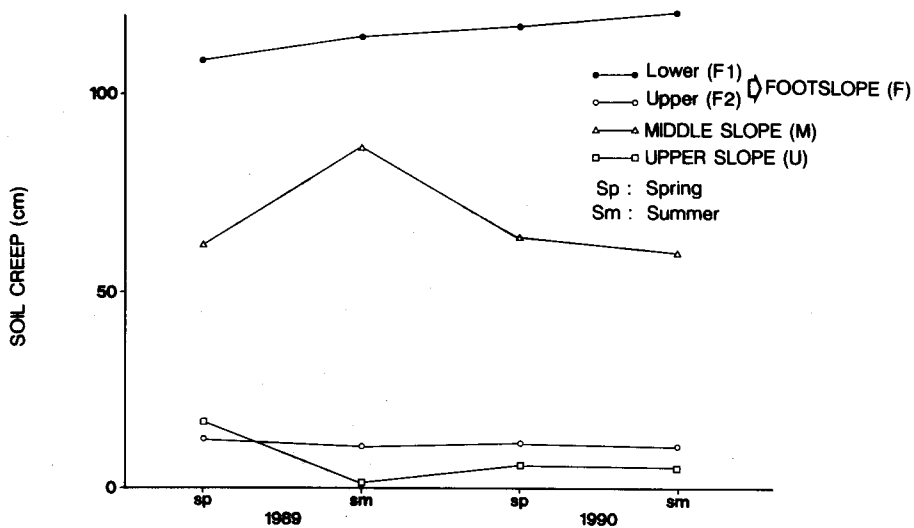


Fig. 20. Soil creep measured on landslide scar in the Saru River Basin.

upslope seepage forces. In the middle slope sites (M), soil creep was found to be higher than that of the sites just near the river bank (F2). These sites are usually filled with a huge colluvium deposit from the collapsed area and are the deposit transmitting sites to the downslope site which may also be periodically active erosive debris sites. In the debris depositing sites (F2), soil generally undergo a compaction which proceeds at much lower value of creep. Unlike in the river bank and middle slope sites, sites just near the river

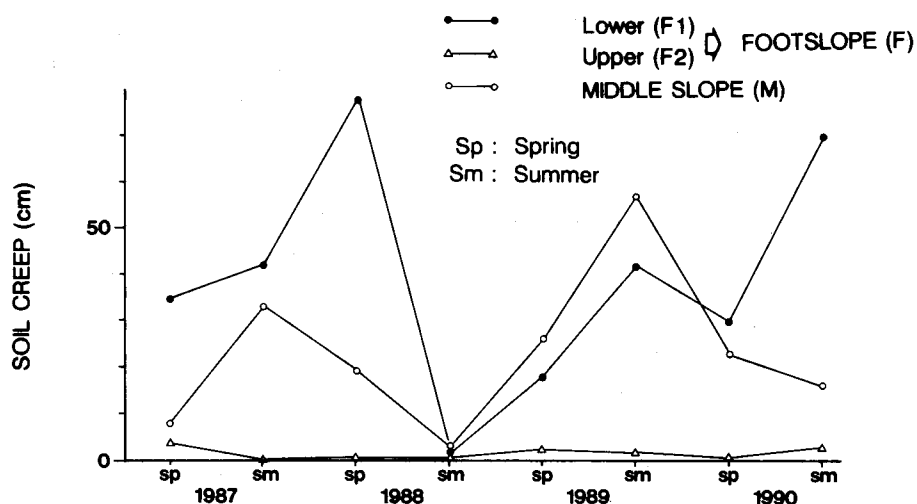


Fig. 21. Soil creep measured on landslide scar in the Mukaihassen River Basin.

bank and upper slope do not show active soil creep.

It was found that the values of soil creep on each site of slope measured in the Saru River Basin was relatively constant, while in the Mukaihassen River Basin soil creep values fluctuated all along the measured periods. High values were seen during summer (rainy seasons) in the Mukaihassen River Basin. Water action is intermittent and is really effective only during and after prolonged or heavy rainfall or when thawing of snow cover takes place. Complete water saturation by heavy rains might greatly increase the value of soil creep and might lead to a sudden and even catastrophic displacement of overlying debris on slope.

IV. Sediment production in river channels

1. Sources of sediment in river basins

It is quite difficult to identify the secondary sources of sediment in a river basin. Generally, however, four major sources of sediment can be distinctly seen in this drainage basin. The sources are landslides, gullies and channels. The sediment in this drainage basin may predominantly come from a single type of source or a combination of several types. The contribution from each source is remarkably difficult to estimate since during large storms, when most of the sediment is produced, events that take place late in the storm tend to obscure evidences of earlier erosion.

Deep-seated landslides observable along hillslope profiles particularly in the middle reach of the basin conveyed voluminous displaced sediment to the river channel. They are considered to be the dominant sediment sources. This type of sediment source involves soil, weathered or fresh bedrock and extend to tens of meters below the soil surface.

Surface slides typically occur on the foot slopes of hills or on the headscarp of a large landslide and produce relatively small soil and weathered bedrock into adjacent channels of zero or first order system.

Gullies were developed in swales. Swales were usually initiated on the landslide scar. Water concentrated by the scar may initiate a gully downslope which operates headward and joins the scar to the channel system. These gullies generally widen and deepen significantly after connection to the scar. Sediment was contributed to the gully by small sliding and sheet erosion of their scarps. Gully also received sediment eroded from the scar upslope. Much of the sediment entering the gully was deposited either on a small fan downslope, or in the bed of the channel system (mostly first order system).

Broadly, hillslope erosional processes cover the sediment movement from point to point on hillslopes and from the hillslope to channel system. Not all of the sediment move directly to the channel system. Since the proportion reaching the channel system, frequency of transport, and transport processes were not sufficiently understood, the roles of sediment production from hillslopes to channel system remain relatively unknown.

2. Sediment production

The area of scars and debris deposits can be accurately calculated by means of the interpretation of time-sequential aerialphotographs. The difficulty of determining the precise thickness of the earth mass and the debris deposition, however, has been a continual problem. The earth mass produced by deep-seated landslides and surface slides was assumed to be similarly distributed with an average thickness of 3 meters and 0.5 meter, respectively, by the field surveys. The thickness of landslide debris accumulated in the foot slope can also be determined. The values ranged from 2.5 to 8.0 meters (Table 6).

During the heavy rainstorms of 1961, about 17,000 cubic meters debris was produced from mid-slope. Most of the debris was carried by the river flow. About 10,000 cubic meters of debris was discharged in 1966. Most of the debris moved downslope and deposited in the foot slope. It was recognized that about 10,000 cubic meters of debris was subsequently produced during the storms of 1974 and 1975. After the 1981 landslide, no large amounts of debris flowed to the talus area, even when deep-seated landslides produced voluminous debris. Total debris production by successive landslides since 1961 has been about 60,000 cubic meters. While about half of this debris accumulated on the foot slope, the other half was either perched on the scar or had entered the main channel from the scar.

Based on the field measurement and interpretation of aerophotos of debris movements

Table 6. Sediment production by successive landslides (Saru River Basin) (after Aipassa et al, 1990).

Time of landslide	Surface slides		Deep-seated landslides		Accumulation of debris in the foot slope	
	area (m ²)	vol. (m ³)	area (m ²)	vol. (m ³)	area (m ²)	vol (m ³)
Prior to 1956	12,000	6,000	4,800	14,400	670	3,500
1961, 1962	400	200	5,800	17,400	300	1,600
1966	400	200	3,600	10,800	1,500	7,800
1970, 1973	500	250	3,400	10,200	2,000	10,400
1974, 1975	900	450	3,600	10,800	4,200	22,000
1981	1,600	800	4,400	13,100	5,400	28,000
No landslide					5,500	28,600

at hillslopes, the estimation of annual sediment supply from hillslope particularly from the footslope to river channel can be made. The length of the footslope of the landslide scar investigated in the Saru and Mukaihassen River Basins which are in contact with the river channel are 400m and 4700m, respectively. The average debris movement in these two sites was found to be a meter per year. Supposing the average depth of landslide debris which moved to river channel is 1.5m, the annual sediment supply in these sites might reached 600 cubic meters and 7,000 cubic meters, respectively. It was clearly seen that sediment supply volume from footslope is relatively higher than that from other sites on the landslide scar.

3. Landslide frequency and sediment deposition

Landslide frequency

An investigation of a relatively small river basin was made in order to understand the relation between landslide occurrence and river channel change. The investigation was undertaken in the Jyurokusen River Basin. Based on the analysis of the annual rings obtained from the pioneer trees growing in landslide scars, the times when landslides occurred were determined. Three groups of natural even-aged forests in landslide scars were found. The result of the dating of landslide occurrences is presented in Figure 22 (redrawn from Shimizu and Aipassa, 1988). The existence of natural even-aged forests indicated that landslides had repeatedly occurred in different times.

The older landslide was estimated to have occurred in 1962. The scar area about 4,500 square meters and the average horizontal distance of the slope was 70 meters, dipping 38 degrees. The volume of debris can be roughly calculated to be as large as 9,000 cubic meters. It was suggested that this landslide was triggered by the major climatic event of

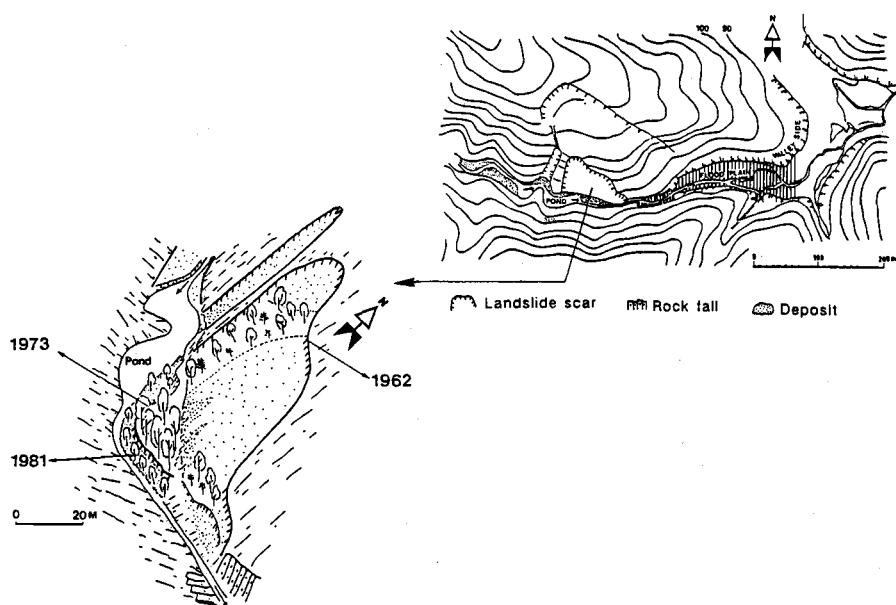


Fig. 22. Dating of landslide occurrence by means of tree rings analysis (redrawn from Aipassa et al, 1990).

heavy rains with typhoon recorded in the neighboring areas in summer of 1962. Most of the sediment discharged by the landslide on the scar, particularly on the foot slope and on the river bed. The accumulation of landslide debris was recognized to have created a pond by invading and blocking the stream channel in the foot slope.

Subsequent landslides were considered to have repeatedly occurred on the same slope plane as the one in 1973. The area affected by the landslides were relatively small. The debris moved with an average sliding depth of 1.5 meters. This landslide activity probably occurred on August 18-19, 1973. Most of the landslide debris was transported to the adjacent downstream channel. At the heavy rains (more than 100mm) on August 3-6, 1981 in the neighboring area (Otoineppu Village), no major landslide occurred in the previous scar. Some of the older deposits, however, had been transported to the downstream channel.

Sediment deposition

The growth rings of trees on the flood plain were used to determine the age of deposits and the deposit distribution in terms of its spatial and temporal aspects. Cross sectional profiles of the stream bed were measured in an attempt to estimate the sediment volume (Fig. 23).

The lower area was mostly occupied by the older deposit which was widely distributed, its length and thickness being about 190 meters and 0.4 meter. In this area the stream-bed material was composed of coarser and finer surface materials. Most of the coarser surface materials existed in the upper site and had presumably been sorted out from the finer material and left as a residual accumulation. The finer surface materials were mostly carried farther, either as a thinner layer or a vertical accretion deposit on the lower site.

The higher area was covered by a thicker newer deposit. This area was established primarily as a deposit bedding above the water level. The surface material of this area was finer and gradually grew coarser vertically approaching the water level.

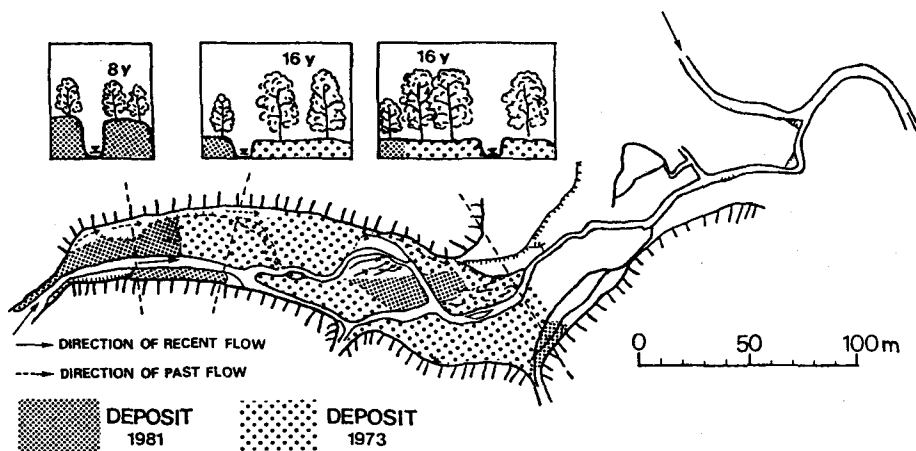


Fig. 23. Distribution of deposit on overloaded channel, based on tree age (after Aipassa et al, 1990).

The sediment deposition produced by landslides which was distributed in landslide scars and river channel is summarized in Table 7. Sediment produced by the older landslide (1962-1963) was known to be about 9,000 cubic meters. Most of the landslide debris perched on the foot slope contact to the river channel. However, no clear sediment deposition was built in the downstream channel. Sediment as large as 3,000 cubic meters was discharged by the subsequent landslide in 1973. Sediment deposition was recognized to have been built in the landslide scar, and river channel as well in this time. In 1981, newer sediment deposition was observed in the downstream channel but no definite indication of sediment deposition on landslide scar.

Table 7. Sediment discharge by landslides and sediment deposition in the lower reach of Jyurokusen Creek (after Aipassa et al, 1990).

Time of torrent	Sediment produced by landslide		Location of sediment deposition	
	area (m ²)	vol. (m ³)	Landslide scar (m ²)	Stream channel (m ³)
1962	4500	9000	?	No definite
1973	2000	3000	760	1800
1981	—	—	No definite indication	1500

Note: is referred to the flood plain site which is situated about 150 meters from landslide scar.

V. Effects of landslides on river channels

1. Landslide debris discharge to river channels

Landslide debris discharge to the foot slope and river channel during successive major climatic events in the middle reach of Saru River was intensively studied by means of the interpretation of time-sequential sets of aerial photos.

Figure 24 shows the relation between sediment volume discharge from hillslope through landsliding and landslide debris deposited on the foot slope. Landslides were recognized to have occurred in 1962-1963. Most of the failure occurred on mid slopes just near the river channel. The landslide debris enters the river channel directly. The transport capability seems to have exceeded the sediment discharge rate from hillslope so that almost all landslide debris were washed away by the river flow. Moreover, the river valley was widened to a high degree by downcutting as bank erosion continued headward. No sediment perched on the foot slope during these periods even though it was recognized that sediment production was relatively higher.

Landslide debris produced by the subsequent landslide (1966) was recognized to have been smaller in volume as compared to the previous one. An extensive deep-seated landslide toward the upslope site was found. Since this time sediment production by landslides seemed to have decreased. On the contrary, landslide debris deposited on the foot slope increased. It was suggested that these tendencies were most likely related to the capability of the river flow to transport the landslide debris discharged from hillslope and the change in the geomorphic features of the footslope. When the transport capacity of the river is relatively lower than the sediment production from hillslope, a large area of

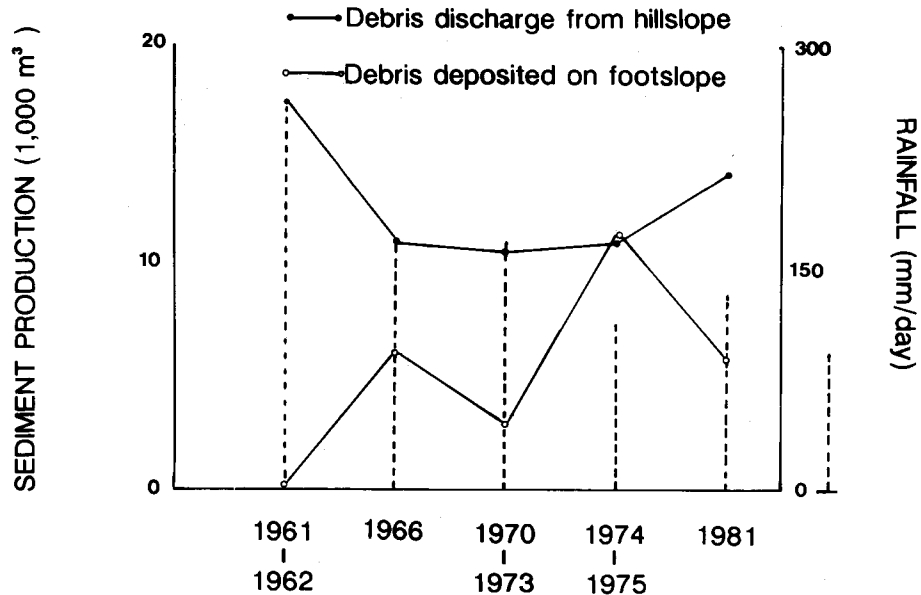


Fig. 24. Relation between sediment production and rainfall.

landslide debris accumulation would be formed on the foot slope particularly when the landslide occurred relatively far from river channel as in the case of the landslides that occurred in 1974–1975. The accumulation of debris will increase as the geomorphologic feature of the footslope becomes relatively gentler.

A similar case of landslide debris discharge from hillslope to river channel was also studied in the small river basin. The landslide debris movement was traced from the initial source to the river channel system.

The sediment in these two deposit areas was assumed to be closely related to the heavy rainfall events which occurred in 1973 and 1981. During the 1973 storm, the sediment discharged by landslide was mostly transported from the moving hillslope to the adjacent downstream area. The transport velocity became gradually slower when they entered the wider valley floor area. The storage capacity in this area was relatively high so that the debris flow was widely distributed with a thinner stream-bed elevation. The sediment production was smaller in 1981 than that in 1973. It was suggested that some older deposit on the foot slope of landslide scar was carried downstream at this time. The transport capacity was considered to be relatively slower so that the debris flow could not be washed as far as at 1973. Since the transport capacity was relatively slower, the sediment was not readily delivered to a longer distance.

In terms of spatial and temporal aspects, the sediment filled regressively to the upper area after spreading widely over the lower area. In other words, the locus of deposition progressed from the lower area to the upper area.

2. Responses of river channels to landslide debris

The dimensions of river morphology and sediment storage are listed in Table 8. In term of stream gradient, river valley width and sediment storage, three distinct segments

of the river basin can be clearly grouped. Stream gradient in the upper reach of basin was found to be steeper (1/19-1/8). River width was found to be relatively narrow (25 meters), even though stream width was found to be wider than that in the middle and lower reaches. As the usual case, the farther the distance from the head water, the gentler is the stream gradient. On the other hand, the river width became wider toward the middle (55 meters) and the width of the river in the subsequent areas was found to be 75 meters.

Little sediment production was found in the upper reach, while voluminous sediment was observable in the middle reach. In the lower reach, sediment production was known to be 3,100 cubic meters per kilometer. This quantity was only obtained in the relatively recent active channel. This volume doesn't include the sediment in the relatively older alluvial plain which has a width of a hundred meters.

The development of a system of drainage basin is composed of the development of the feature of many individual valleys. Careful study of the long profile of a river may reveal

Table 8. Summary of river morphology and sediment storage.

Segment of basin	Stream gradient	Average river width	Average stream width	Sediment storage
Lower reach (0 -2 km)	1/90-1/35	75m	8m	3100m ³ /km
Middle reach (2 -4.5 km)	1/35-1/19	55m	8m	7600m ³ /km
Upper reach (4.5-6.5 km)	1/19-1/8	25m	9m	700m ³ /km

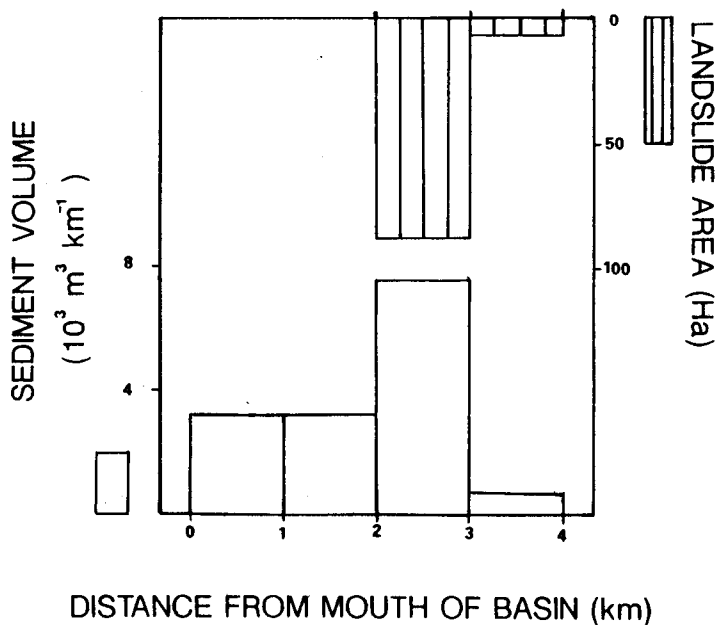


Fig. 25. Relation between sediment volume and landslide area.

a variety of features in each zone. Figure 25 shows the relationship between sediment volume and landslide area along river basin.

In the upper reach (3-4km from the mouth of river basin), debris production is presently inactive and it may take a long period of time to accumulate enough debris to discharge into the higher order of this river basin. Landslides were not considered as an important erosional process in this zone for centuries. Most of sloping sites were well vegetated by older trees.

Small portion of sediment volume in this zone is characterized by the absence of debris producing area, narrow river valley, and steepness of river slope. The sediment supply from small surface slide sites particularly the sites near or in contact with the first order was the only dominant source of sediment from downstream results in the reduction in both competence and capacity, which eventually leads to deposition.

Figure 26 shows the distribution of sediment deposit stored in the river channel, based on age of sediment. It was recognized that at least four groups of sediment of different ages were stored in the river channel. In the middle reach, the older deposits (51 y and 17 y) were predominantly stored. Figure 27 displays the schematic river channel and deposition profile observed in the middle and lower reaches of the Mukaihassen River. Most of the sediment deposit formed higher terraces at the out point of river bed near the valley site, while the 17 years old deposit filled continuously at the face sites of the oldest deposit forming a relatively thinner deposit bedding. The 17 years old deposit was found to be the oldest deposit and the highest in volume in the lower reach. This deposit was located at the out point of river bed like the oldest deposit in upper stream. No 51 years old deposit was found in this zone. The younger deposits (9 y and 4 y) were scattered in these two zones. The oldest deposit stored in this zone was thought to have been supplied

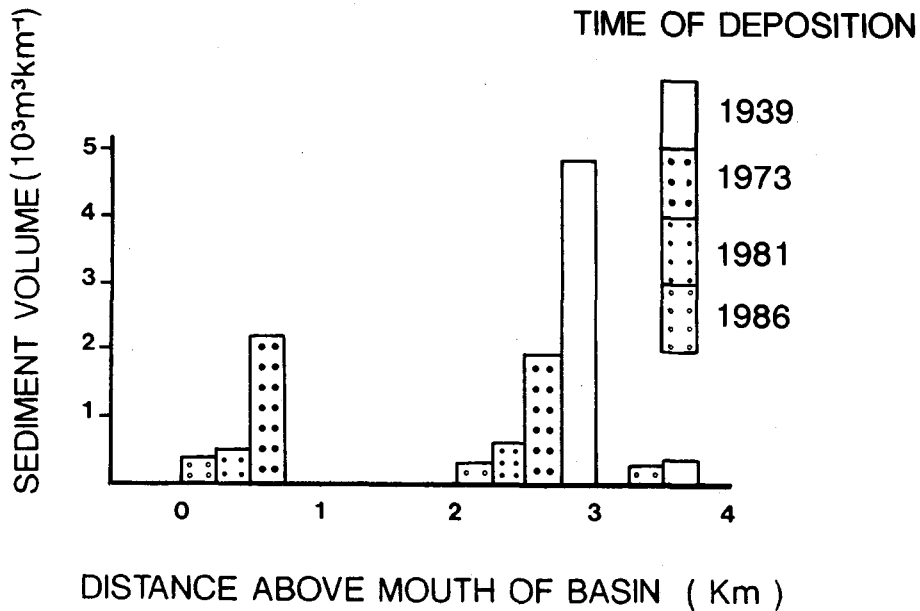


Fig. 26. Distribution of sediment stored in channel, based on age.

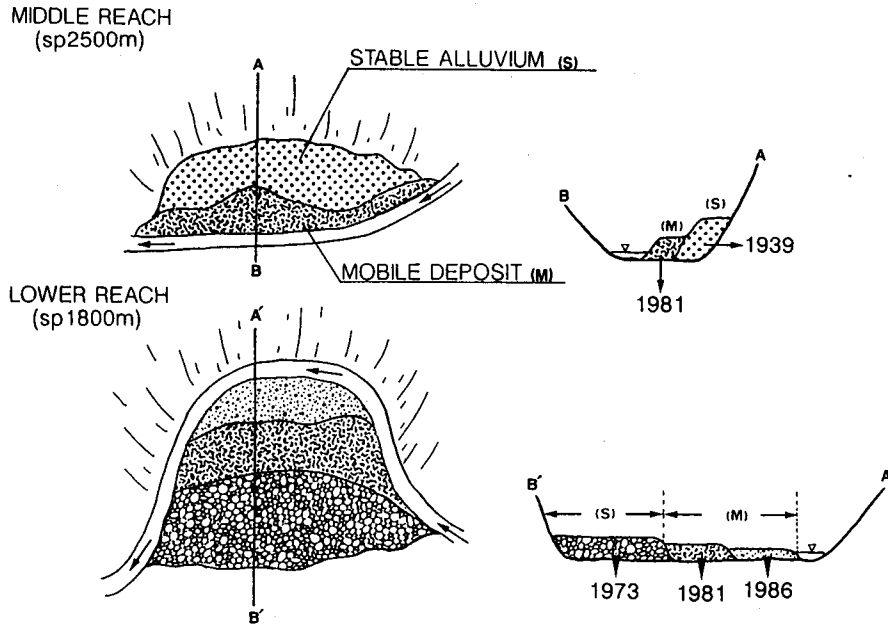


Fig. 27. Schematic river channel and deposition profile in the middle and lower reaches of the Mukaihassen River.

chiefly by hillslope erosion in the middle reach.

The material discharged from hillslope, however, was not readily carried by the stream. Consequently, sediment tends to accumulate abundantly in the river channel. Unlike in the case of the oldest deposit stored in the middle reach, the river bed load could be carried by stream with a longer transport distance to the lower reach. Apart from this, the extensive river width was also seen to have played a role in the transport process. The sources of this sediment might have been from the hillslopes and/or the oldest deposit stored on channel. The newer sediment depositions were most likely supplied from the older deposits as the older deposits were flushed out infrequently by high flows.

Based on age distribution of deposit along the river channel, it was clearly understood that voluminous sediment was initially stored in the narrow river valley. The locus of sediment deposition then progresses toward the downstream.

Based on the field investigation and the interpretation of the time-sequential sets of air photos, the response of the channel to landslide debris was roughly determined in terms of the rate of sediment production by landslides and the capability of the river flow to transport landslide debris. Several types of channel response to landslide debris are broadly enumerated in Figures 28 and 29.

When the capacity of the river flow to remove the landslide debris from hillslope is relatively higher, substantial widening of the valley floor could result (Fig. 28a). This phenomenon can be clearly seen in the Saru River Basin during the major sediment transporting events (1961 and 1962). The failure of foot slopes and the extreme bank erosion was found to have occurred during these torrential rains. We found no significant

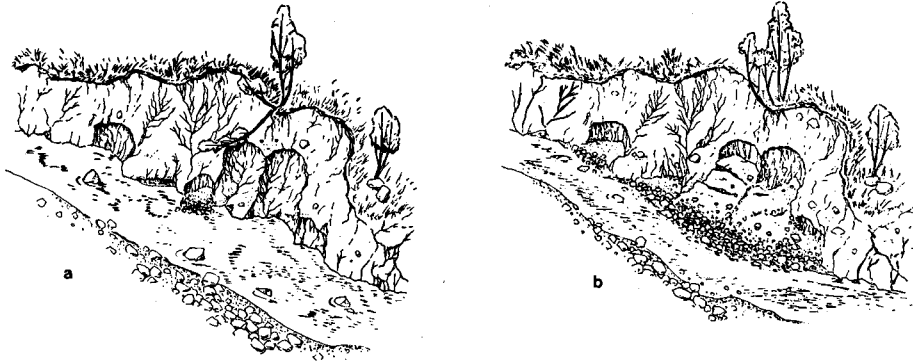


Fig. 28. Illustration of channel response to landslide debris in torrential river (after Aipassa et al, 1990).

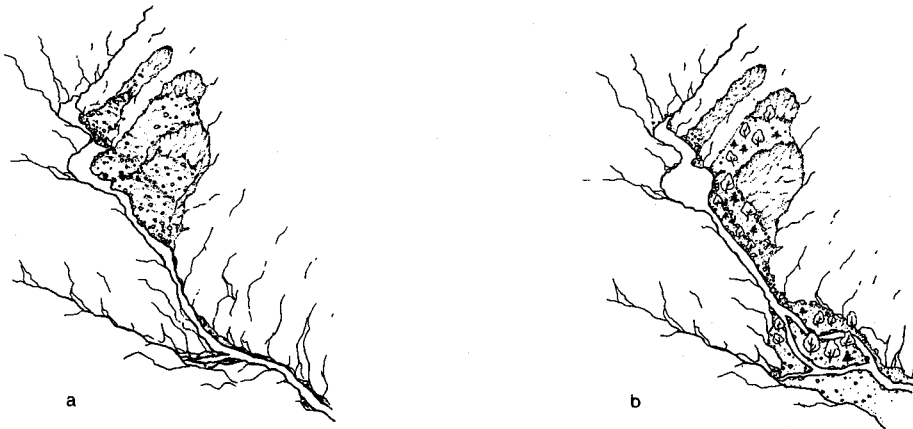


Fig. 29. Illustration of channel response to landslide debris in placid river (redrawn from Aipassa et al, 1990).

effect from the landslide debris on an adjacent lower reach.

On the other hand, when the fluvial transport can not keep pace with the rate of discharge of the landslide debris from the hillslope, the formation of a large talus can be expected on the toe of a slope (Fig. 28b). This may also cause a constriction of the river channel. This phenomenon could be clearly seen in the landslide of 1966 and even more dramatically during the storm of 1981 in the Saru River Basin.

In the case of a placid stream, as with the Jyurokusen River Basin, the responses of the channel were characterized by the formation of a pond in the area of the moving hillslope (Fig. 29a) and an abrupt change in the stream bed in the adjacent lower reach (Fig. 29b). This was because the transport ability of stream flow was insufficient to remove the high rate of sediment produced by landslides.

Most of the landslide debris was transported to the lower reach and could not be delivered to a longer distance as would happen in the case of a torrential river. The

significance of the effect of landslides on a channel could still be distinguished. The debris was not readily delivered downstream and so the stream channel was substantially constricted.

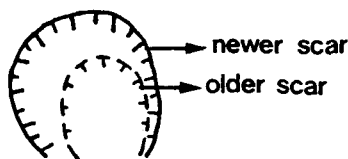
VI. Slope and river channel changes due to landslide debris movement

1. Slope changes

Figure 30 shows the slope changes due to successive landslides from a vertical view. Most of the area having previous landslide scars are prone to subsequent failure. The new failures occur as the reactivation of older phenomena. It was considered probable that many of the scars would have gradually expanded with time. Two types of landslide recurrence can be broadly classified. Firstly, the subsequent failure may occur in the older failure as a "duplication on the same plane". It may expand toward the upper slope (1a), or it may remain a part of the lower slope of the older failure (1b). Secondly, the following failure may partially "overlap to the adjacent plane" (2a), or it may also partially overlap several smaller older scar planes (2b) regardless of the position on the former slope (either upslope or lower slope).

These phenomena may be most likely related to the water concentration of the soil and topographic conditions. Some failures are initiated in partially filled hollows. These unchanneled swales are typically filled with a regolith several meters thick. As a result of their subsurface topography, hollows concentrate abundant water, developing high pore pressures which can finally lead to failure of the soil mass. They might also be related to faults or cracks which were irregularly distributed among or on the older scar plane. These faults and cracks break the strata and accelerate the weathering process.

1. Duplication on the same plane

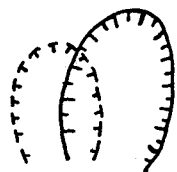


a. UPPER SLOPE EXPANSION

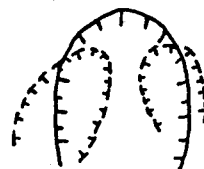


b. LOWER SLOPE INTENSIFICATION

2. Overlap to the adjacent plane



a. SINGLE PLANE



b. MULTIPLE PLANE

Fig. 30. Repetition types of landslide (after Aipassa et al, 1990).

Eventually, they provide a space for storage and movement of ground and underground water, which lead to failures.

Attempts were made to relate slope deformation due to landslide to lithology as a readily observable factor. The action of certain processes and stages of time were also considered. On the basis of subjective observation, the nature of rock was suggested to play a prominent role in the slope form.

Slope changes by landsliding in Mukaihassen (serpentine area) and Jyurokusen (mudstone area) River Basins are presented in Figure 31. In the serpentine area, geomorphic processes associated with fault and crack were found to be the initial processes of landsliding (a). The failure of slope is usually influenced severely by ground water. The soil in this serpentine area were characterized by inorganic clays of high plasticity. This may indicate the increase of the bounding properties of fine clay and colloidal fraction. Accordingly, it may have high consolidation characteristics under stress. These fault and crack may break the strata and accelerate the weathering process. Subsequently, they create a space for storage and movement of rain or underground water. Eventually, mass of rock move downslope in the form of a block of sliding plane (b) which was initially formed by fault and crack. The high cohesiveness of clay and the impermeability of soil seemed to play a main role in this landslide type. Earth flow and creep are dominant processes after the occurrence of landsliding depending on the slope gradient.

In the mudstone area, no definite geomorphic indication could be seen before landsliding. The slope material in this area is characterized by coarser material and unconsolidated soil. The soil is classified as an inorganic clay of medium plasticity, having increasingly poorer compaction characteristics and low densities. The earth mass

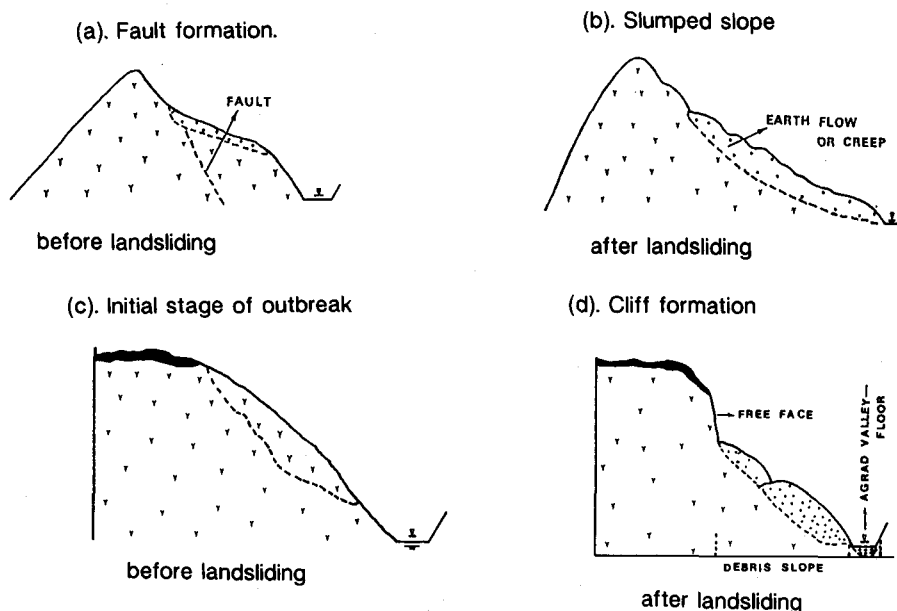


Fig. 31. Slope changes by landsliding in serpentine and mudstone areas.

moved downslope mainly in the form of separate grains by gravity, after getting stress. The magnitude of earth mass produced by landslide is usually small since the slope materials are too poorly consolidated to be classed as rock. The subsequent sliding usually involves relatively small portion of earth mass. Most of the sliding occur in the upper slope of scar which is the site where rainwash seemed to be an important formative process (c). No obvious indication of outbreak is found before sliding. The collapse of slope is usually influenced by rainfall particularly by rainfall intensity. The earth mass did not travel as far as the first landslide debris and left a saddle between the two masses of debris. The last sliding may eventually rest on a very steep cliff (d). There is no or very little accumulation of detritus on the cliff itself, and it is therefore commonly referred to as a free face. Landslide debris may accumulate in the foot slope forming a depositional feature as a debris slope, and some may enter the river channel and finally result in an aggraded valley floor.

2. River channel changes

Geomorphic processes within river basin varied from upper to lower reach according to the amount of material being discharged from the relatively unstable hillslopes, condition of the landslide debris being readily transported into river channel, river channel morphology, and availability of the major climatic event to create energy available to transport material either from hillslope to river channel or from upper reach to succeeding downstream area.

Diagram showing geomorphic processes on segments of the river basin (the Mukaihassen River Basin) for a relatively short term is provided in Figure 32. The relation between sediment source in hillslope and sediment accumulation in river channel within river basin shows three types of process. In the inactive debris producing zone (upper reach), there is no significant relation between the contribution of sediment from hillslope to river channel.

Significant relation between hillslope and river channel was found in the middle reach (active deposit filling zone). This middle reach was characterized by active and high volume of sediment produced from hillslope and high sediment volume stored in the relatively narrow river valley. The landslide debris produced from hillslope in this middle reach was mostly stored just in the adjacent river channel because much of them was not readily carried by the stream. The relatively gentler river slope and lower river-flow capability were suggested to play an important role in the formation of sediment accumulation-related landslide in this middle reach. As voluminous sediment produced from hillslope was transported into the river channel, the bed elevation seemed to have risen and produced paired and unpaired terraces.

Basically, there is no sediment source from the hillslope to be supplied into the river channel in the lower reach. The river channel has no direct response to landslide from the hillslope. Most of the sediment stored in this area were originally derived from the middle reach. The mean bed elevation tends to increase with time during a sedimentation sequence. The sediment stored in the middle reach was infrequently flushed and transported by high flows to this lower reach. The lower reach acts as a sink for sediment, until a sufficiently large hydrologic event causes transport throughout this area.

In the study basins, particularly in the Saru and Jyurokusen River Basins, generally two forms of river changes due to landslide debris movement were clearly observed.

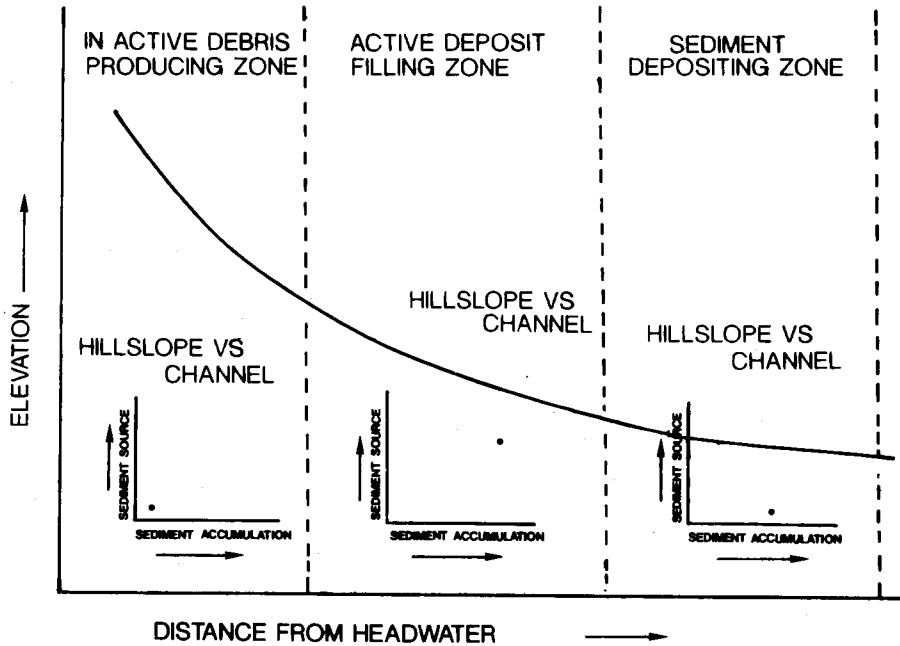


Fig. 32. Diagram showing geomorphic processes on segments of river basin.

These forms of river changes are summarized in Figure 33. The recognition of effects of landslide debris movement on river channel was simply analyzed based on the understanding of the rate of landslide debris delivery from hillslope to the rate of debris transport by fluvial processes. These geomorphic processes usually happen during the occurrence of major climatic events such as rainstorm, abundant snow cover thawing, and they vary greatly from one site to another in the river basin depending on the susceptibility of hillslope against these climatic events. Climatic events are indeed the driving force for geomorphic processes.

The constriction of the river valley, extensive talus formation on foot slopes, and increase of river-bed elevation may be seen in the sites of the moving hillslope and its

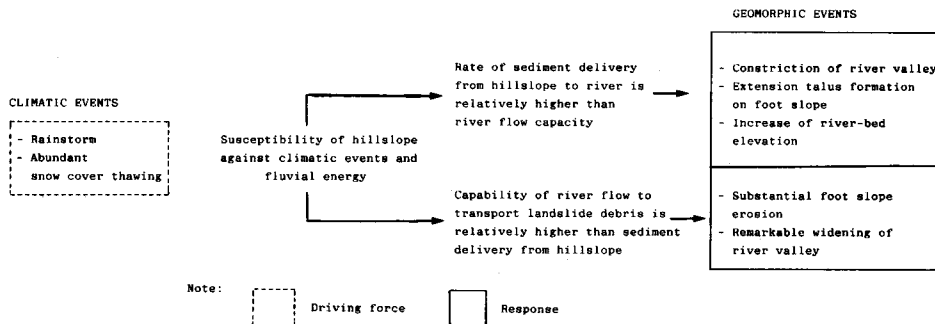


Fig. 33. Conceptual model for river change due to landslide debris movement.

adjacent areas when the rate of sediment delivery from the hillslope is relatively higher than the capability of the river flow to transport landslide debris. Substantial foot slope erosion and remarkable widening of valley floor would be constructed in the sites of the moving hillslope when the capacity of river flow is relatively higher than the delivery of debris from hillslope.

Conclusions

The slope form in the investigated study basins varied in accordance with geological structure. The characteristics of soil seem to play a role in the transport and in facilitating the form of slope as well. The fine grained, impermeable and cohesive soils observable in the serpentine area are assumed to be the factors promoting the complex form of slope. Conversely, in the mudstone area, the coarse, permeable and unconsolidated surface soils are most likely the factors responsible for the extensive rectilinear form of slope. Great difficulties are encountered in determining the processes work on slope, which is imperceptible, and in tracing the changes of form and angle that slopes undergo as time elapses explain for some unsolved questions. It is therefore advised that such investigation needs to be done many times under a wider range of climatic, vegetational and lithological conditions before the true role of a process in slope development can at least be assessed.

The type of movement of landslide debris on hillslopes in the study basins was found to be different for each. In the serpentine area, the landslide debris mostly moved downward by small blocks of slide plane as indicated by cracks and creep before moving. On the other hand, the slope materials in the mudstone area mainly moved abruptly downward in the form of separate grain which gives no indication before moving. These tendencies were most likely related to their soil characteristics.

The conditions favoring landslides may exist for a long time without any movement taking place, but given the proper impetus slides may be touched off either instantaneously or within a short time. Conditions favorable for landslides are too numerous and complex to be treated in detail. The existensce of ground water seemed to play an important role in the occurrence of landsliding. Ground water flow exerts pressure on soil particles, which impairs the stability of slopes. They could also wash out soluble cement and thus weaken the intergranular bonds. Consequently, cohesion decreases and the internal friction drops.

The Stream order system was found to contribute practically nothing to the occurrence of surface slide. The sloping sites adjacent or contacting with the stream channels, however, were the sites most prone to sliding. Stream channels might accelerate the growth of surface slide by undercutting the foot of the slope. These sites may also be subject to higher pore pressures and seepage forces.

The ability of individual trees to recover from damage and still record the event in their annual-ring chronology provides a valuable research tool for geomorphic studies. The relatively short aerial photograph record can sometimes be extended by using dendrochronology to date landslide.

Landslide debris movement affects not only slope deformation in the moving slope sites, but also geomorphic changes in the river channel. The type of sediment storage varied from one to another zone within a river basin. Different bed-sediment transport

processes and resulting channel and valley forms characterize each zone. The response of river channel to landslide debris greatly differed from one site to the other in accordance with the rate of landslide debris production from hillslopes and the capability of river flow to transport the landslide debris.

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要 約

山地上流域における斜面変動は山体斜面形状・植生の変化をもたらすとともに、下流域における河床・流路変動に対しても大きな影響を与えており、流域の土砂災害防止、流域保全・利用管理を計画するうえで重要である。流域変動履歴の時系列化はその手法が未確立なため極めて困難とされ、なかでも斜面変動に関しては未解明分野である。本研究は地すべりによる斜面変動の時系列化、ならびに斜面変動と河床変動の応答実態の解明を目的としたものである。内容は以下のように要約される。

1) 航空写真による斜面変動の推移、現地野外調査による斜面形状の把握と変動情報の収集、さらに樹木年代学的方法による変動年代の確定などによって斜面変動の時系列化を行うこととした。そして研究対象地として、地すべり多発地域である天塩川支流間寒別川上流域(向八線川・十六線川)と、変動頻度・河川影響度の高い沙流川中流域地すべり地(振内地先)を設定した。

2) 向八線川流域における地すべり域は面積率が約15%を占め、その2/3(面積比)が中流域の二次林・無立木地に集中していた。また、斜面表土移動量が3 cm/年(植生地)~30

cm/年（裸地）と実測されたが、とくに河道接触地では60 cm /年と高かった。

3) 表土の粗粒成分比率が斜面下部で高いこと、また斜面形は泥岩地帯で直線形状を、蛇紋岩地帯では凸・凹・直線の複合形状を呈していること、などの特徴が抽出された。

4) 沙流川流域地すべり地の航空写真判読によって、32年間（1956～1988）の斜面形状（滑落崖後退・末端斜面拡大）と河道形状（流路・河床堆積）の変化履歴を明らかにし、地すべりの拡大・縮小（長・面積）がこの間の豪雨に対応したものであることが推測された。

5) 変動斜面をその形状変化と表土構成材料とから滑落域・流動域・堆積域に区分し、変動の激しい流動・堆積域での表土移動量がそれぞれ60 cm/年・5 cm/年と実測された。

6) 表層崩壊、ガリー侵食を含んだ地すべり変動による斜面末端の累積土砂が下流域への主な土砂供給源となっていること、なかでも深層地すべりが細粒～岩礫からなる土砂の大量供給源となっていることが推測された。

7) 斜面と河床の樹齢分布調査結果から、1962年地すべり変動によって河床変動材料の一時的な大量供給が行われ、その後1973・1981年に河川流水によって土砂が輸送されたこと、すなわち斜面変動と河床変動とは時間差があることが指摘された。

8) 地すべりをその安定度から休眠型と活動型に区分し、活動型の60%以上（個数比、面積比）は河岸部斜面（30°～50°）で表層地すべりを多発させていることから、河川への近接状況が注目された。

9) 流域を土砂供給域、土砂貯留域、土砂堆積域に区分し、貯留域に位置する活動型地すべりは河川流水により誘発されるが、土砂の多くは流送されずに貯留されるものであることを明らかにした。すなわち河床堆積地の樹木年代ごとの土砂分布状況から、新堆積物は地すべり変動に由来する河床貯留土砂の再移動によるものであること、また土砂供給量と末端堆積量との比から、地すべり土砂供給量の50%以上が末端堆積域に貯留される一方で、20～30%が豪雨時に河川に流入することを明らかにした。

10) 同一斜面内反復と隣接斜面重合反復によって地すべり地特有の複合斜面形状が形成されるが、この主因である活動型地すべりは休眠型地すべりの部分的な再移動・拡大過程のものであり、流域の土砂供給源として重要であると考えた。

11) 地すべりの河床変動に対する影響は土砂供給量と流水の輸送能力とに規定されるものであり、輸送能力が大きいときは河幅拡大・河岸洗掘・末端崩壊を伴う一方で、土砂供給量が大きいときには大規模崖錐・沼地形成や直下流河床激変などがもたらされるものであると考えた。



Photo 1. Area of intense landslide in the Mukaihassen River Basin. May 1990.



Photo 2. Treeless area due to fires in the Mukaihassen River Basin. May 1990.



Photo 3. Earth flow developing from a landslide scar in the Mukaihassen River Basin. October 1990.



Photo 4. Natural even-aged forest on flood area, the Jyurokusen River Basin. October 1987.