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CHARACTERISTICS OF HEAVY RAINFALL AND DEBRIS HAZARD

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ABSTRACT

The relationship between area and intensity of heavy rainfall in the Kinki district of Japan was investigated. Some causes and locality of heavy rainfall were discussed in consideration of this relationship. Two cases of dense occurrence of landslides caused by heavy rainfall were studied on the basis of geological and geomorphological conditions, and the local singularity of debris hazard was analyzed as the combined effects of rainfall and various physiographic factors.

1. INTRODUCTION

In 1972, Information Processing Center for Disaster Prevention Sciences was established as an attached facility to the Disaster Prevention Research Institute, Kyoto University, and as one of the projects of the Center, a study on the relation between the characteristics of heavy rainfall and water catastrophes was adopted in consideration of special damage pattern from the nature in Japan.

Water catastrophes can be classified roughly into two categories: flood hazard and debris hazard. There are few scientific data available that have been collected systematically regarding debris hazards caused by heavy rainfalls, and only two cases of disastrously heavy rainfall have been analyzed. These cases were selected for use here because damages were serious and distributed over a wide area and because the records and data on the damages have been comparatively well preserved and could be easily collected.

To elucidate the characteristics of heavy rainfall, the relationships between area and intensity of heavy rainfall in Japan's Kinki district for various durations were analyzed. Included were the cases of extraordinarily heavy rainfall in 1953 in the southern Kinki district and the Minamiyamashiro region where serious landslides and debris flows were brought about by the heavy rainfalls. Some causes and locality of heavy rainfall were discussed in consideration of the relationship between its area and intensity. The combined effects of meteorological and physiographical factors on the occurrence of landslides were studied for the southern Kinki district and Minamiyamashiro region, taking into consideration the distribution of rainfall and differences in geological and geomorphological conditions.

2. CHARACTERISTICS OF HEAVY RAINFALL

To estimate regional flood peaks, recently Kadoya and Nagai investigated DAD characteristics of heavy rainfall in different drainage areas in Japan [1, 2]. But in this paper,

KEY WORDS: Heavy rainfall, Maximum precipitation, Area of rainfall, Landslide, Landslide density, Multivariate analysis, Debris hazard

to elucidate the characteristics of heavy rainfall itself, the relationship between area and intensity of rainfall for various durations is studied, taking an almost whole area of the Kinki district much broader than a river basin as the objective domain (Fig. 1).

The cases of heavy rainfall with 24-hour precipitation of 200mm or more for 11 years

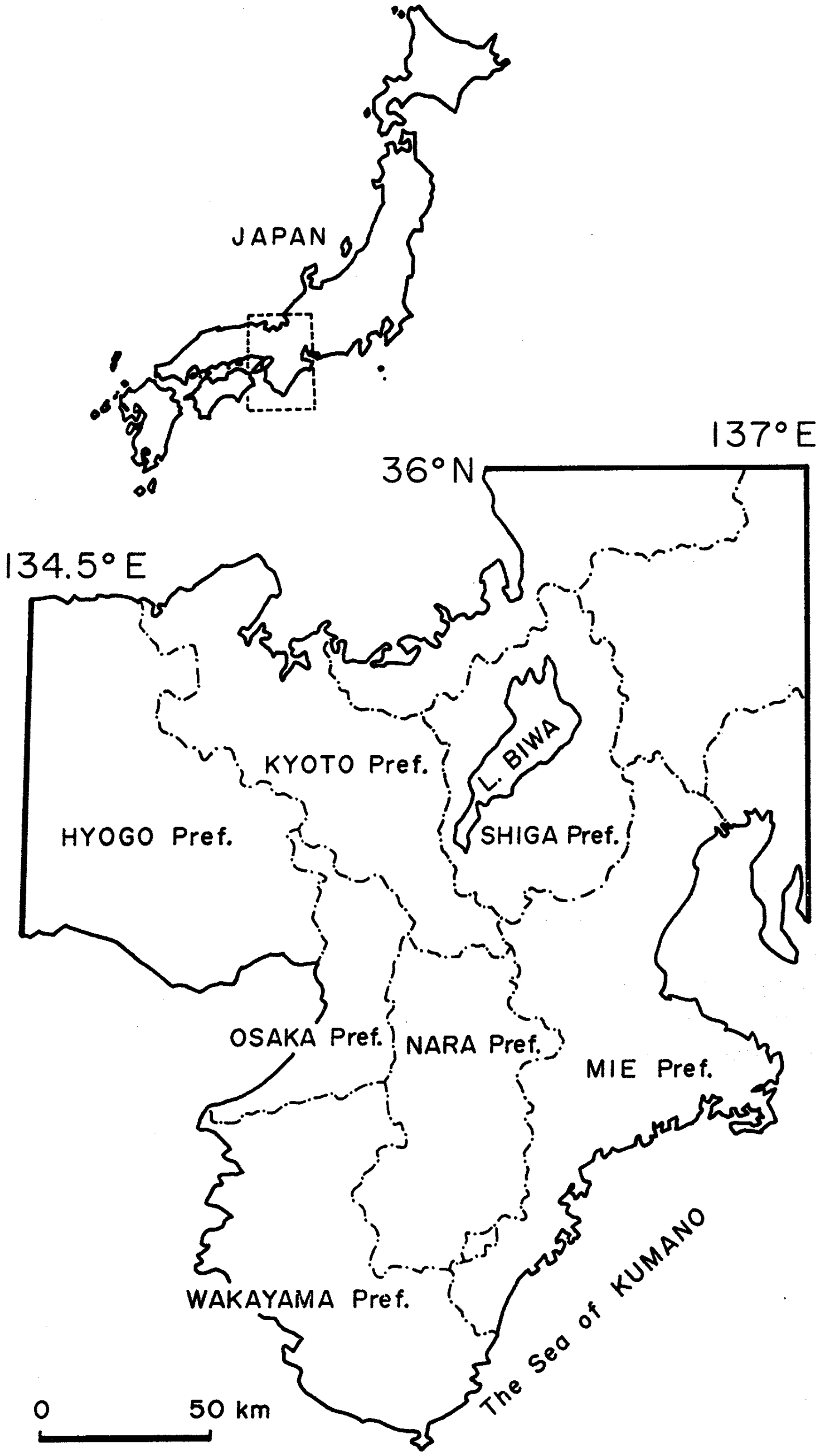

Fig. 1 Objective area (the Kinki district of Japan).

(1955–1965) in the Kinki district were chosen from the cases listed by the Japan Meteorological Agency [3]. Incidents of extraordinarily heavy rainfall in the southern Kinki district and the southernmost part of Kyoto Prefecture (Minamiyamashiro region) which caused large disasters in 1953 were added [4, 5]. Isohyetal maps for 1, 3, 6, 12 and 24 hours, in which the maximum precipitations were observed respectively, were drawn in principle for these cases. In some early cases, where hourly precipitation was unknown for lack of recording rain gauges, daily isohyetal maps (9^h–9^h) were used for 24–hour periods and maps for 1, 3, 6 and 12 hours were not made. There were 59 24–hour maps and 42 1, 3, 6 and 12–hour maps. The intensity of rainfall was defined as the maximum precipitation in the domain surrounded by a certain isohyet for each duration and area was defined as the area of that domain. The isohyet of 100mm for a 24–hour duration was chosen as the comprehensive standard. Equivalent values of isohyets for the other durations were examined by comparing the domain surrounded by their isohyets with the one surrounded by the isohyet of 100mm for a 24–hour duration. It was found that the nearly equivalent isohyets were 10mm for a 1–hour duration, 30mm for 3 hours, 50mm for 6 hours and 75mm for 12 hours. Maximum rainfall rate, I_t, during t hours at a certain observation point is empirically expressed [6] as

$$I_t=\frac{a}{b+t}\ \text{(mm/h)}. \tag{1}$$

Constants a and b are 164.3 and 15.4, respectively, when rainfall rates are 100mm for 24 hours ($I_{24}=4.17$mm/h) and 10mm for 1 hour. The curve of $I_t t$ and the values of the isohyet corresponding to the durations are shown in Fig. 2. Because each value is nearly on the curve, the values of isohyets are believed to be reasonable and are adopted.

The measurement of the area of a domain surrounded by an isohyet has been made for the Kinki district as shown in Fig. 1. The district is surrounded by natural coastlines and artificial longitudes and latitude, and for present purposes the islands are excluded. The area of the whole domain is about 40,000km^2. In the case in which measured domain is divided into two or more parts, the areas were measured in the following ways: If the divided domain is surrounded by a single isohyet of half the value of the original isohyet, the divided domain is regarded as one, and the summed area of the parts is regarded as the area of that domain; If each part of the divided domain is surrounded by the separate isohyets, only the area of domain with the maximum precipitation is regarded as the area of the domain to be used for this analysis. As mentioned above, the selected time of

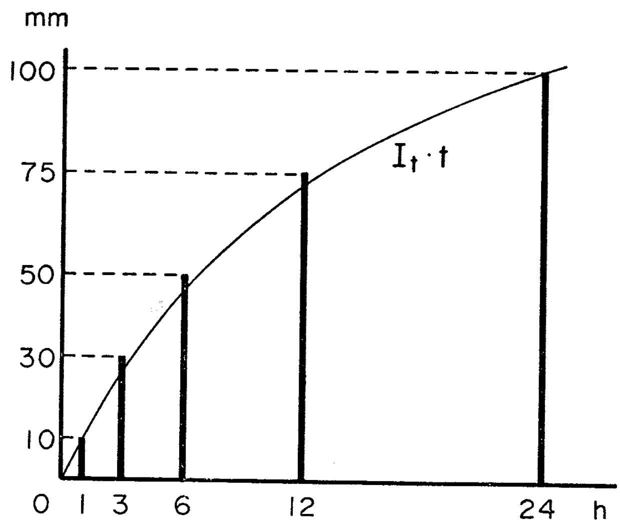

Fig. 2 Adopted values of isohyets for different durations and the curve of $I_t t$.

heavy rainfall was the one in which the maximum precipitation was observed for each duration. However, when the areal rainfall depth for another time is larger than that for the time with the maximum preciptation, the time with larger areal rainfall is chosen in spite of the fact that the maximum decreases slightly.

The relationship between the area and intensity of heavy rainfall is shown in Figs. 3–7 for durations of 24, 12, 6, 3 and 1 hour, respectively, in which the abscissa and ordinate indicate area and intensity of rainfall, respectively. In every case, points showing the

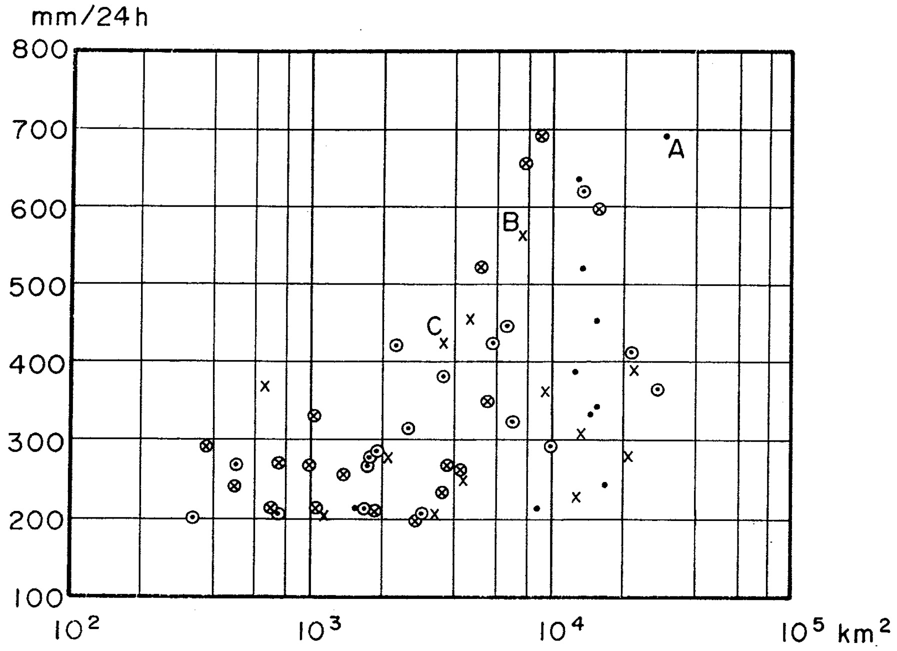

Fig. 3 Relationship between area and intensity of rainfall for a 24-hour duration. • : due to typhoon, × : due to the disturbances other than typhoon, ○: in the rainy southeastern part of Kinki district. A: due to Typhoon Vera, B: in the southern Kinki district, C: in Minamiyamashiro region.

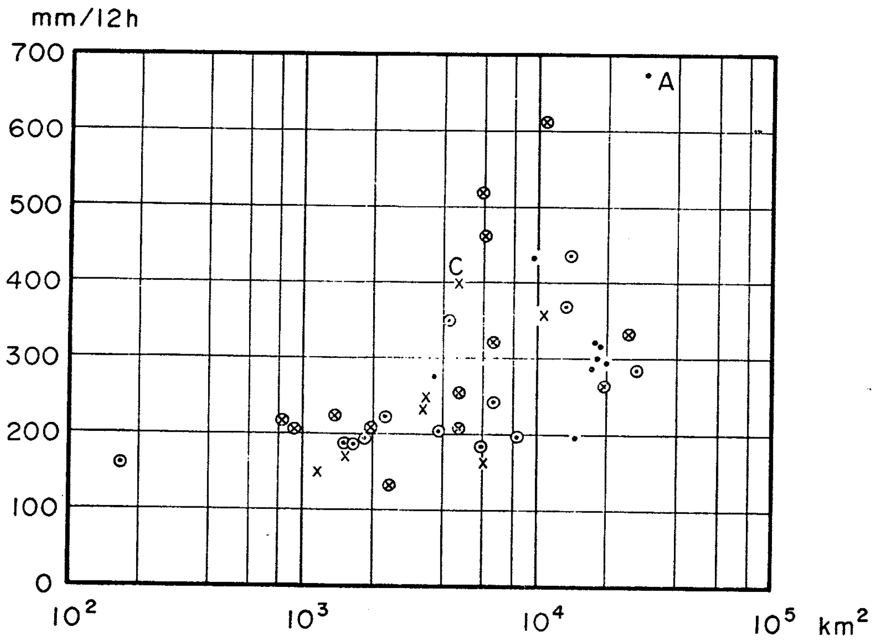

Fig. 4 As in Fig. 3 for 12-hour duration.

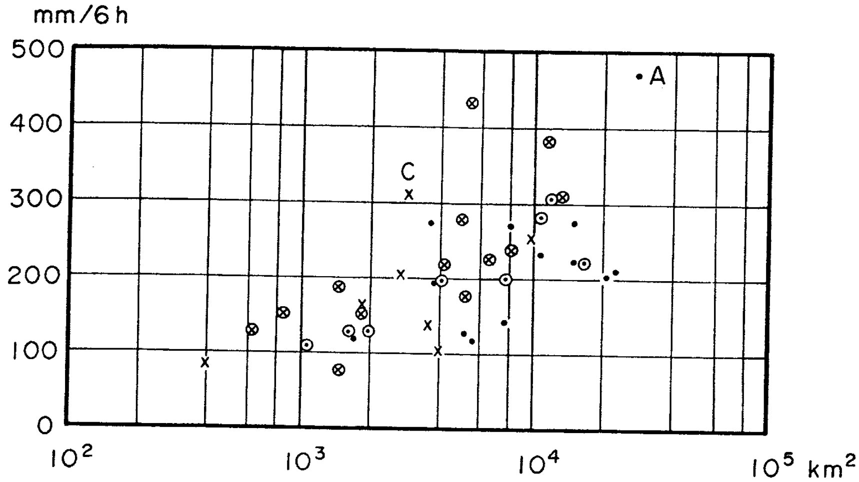

Fig. 5 As in Fig. 3 for 6-hour duration.

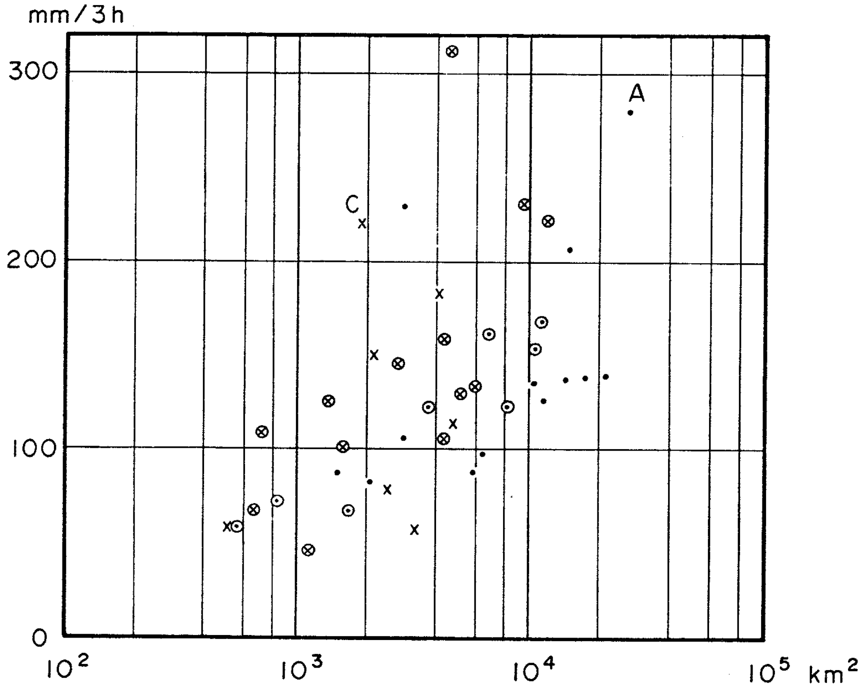

Fig. 6 As in Fig. 3 for 3-hour duration.

relationship are scattered because intensity does not always increase with area. But the domains of points appear to have upper boundaries similar to each other. This means that the maximum precipitation seems to have a limit and its extreme value appears to increase with the area of rainfall. Although this is important for disaster prevention studies, no conclusion can be drawn because of the small number of cases, and because cases with large maximum precipitation for a short duration might be excluded where 24-hour precipitation was less than 200mm.

Although heavy rainfall is caused by certain meteorological disturbances, two general cases were considered: those due to typhoons or tropical depressions that struck or moved in close to Japan and those due to other disturbances. The latter is thought to be caused by fronts and by cyclones of different scales. In the Figs. 3–7, the point of the former case is expressed by dot and the point of the latter by ×. The southeastern part of the Kinki district is the rainiest in Japan. The points in the figures were roughly divided into two groups due to the locations of observation points with the maximum precipitation.

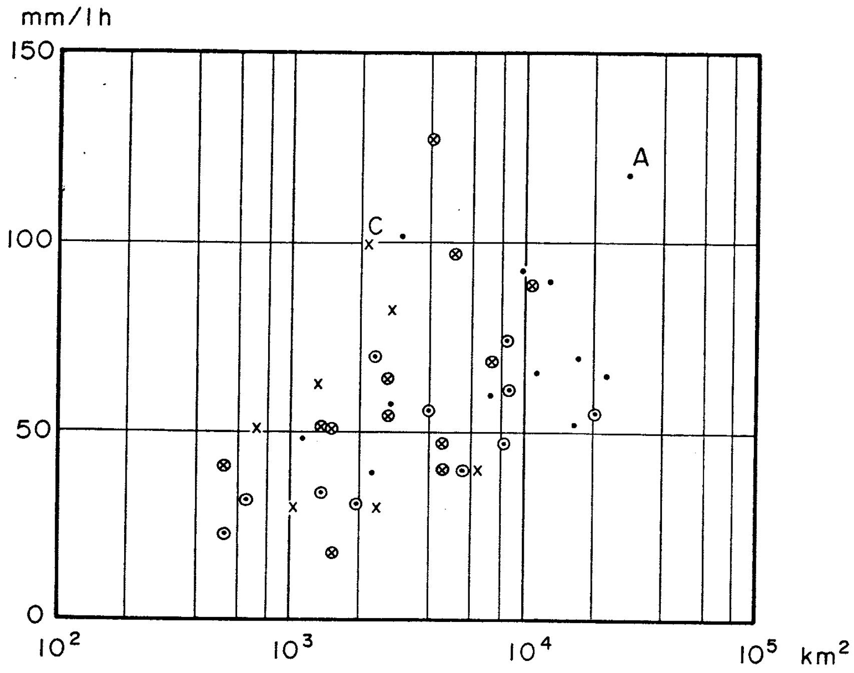

Fig. 7 As in Fig. 3 for 1-hour duration.

One is the southeast slope facing on the Sea of Kumano (Fig. 1) and the other is the remainder of the district. The points for the southeast are surrounded by circle to distinguish between them in these figures. The number of cases of heavy rainfall due to typhoons is nearly the same as that due to other causes. For 24-hour durations in which the number of cases was the greatest, cases of heavy rainfall due to typhoons numbered 28 and others numbered 31 (Fig. 3). Heavy rainfall with maximum precipitation in the rainy southeastern region was more frequent than that in the other regions. The number for the southeast was 36 and that for the remainder was 23, for 24-hour durations (Fig. 3).

The number of heavy rainfalls due to typhoons tended to increase with area. For 24-hour durations (Fig. 3), the number due to typhoons was 12 and 16 for areas smaller and larger than 1,500km^2, respectively, while the number due to the other causes was 20 and 11, respectively. This difference seems to be brought about by the differences in the scale and moving speed of meteorological disturbances. Those characteristics of heavy rainfall are common to all durations.

Cases of heavy rainfall with extremely high intensity are, on the whole, due to disturbances other than typhoons for each duration. However, it is interesting that this characteristic tends to become more apparent as the duration becomes shorter. In other words, heavy rainfall due to typhoons may be of even greater intensity than in the non-typhoon cases, for duration longer than 24 hours. This means that relatively more intense rain may fall for a relatively shorter duration due to disturbances other than typhoons. Therefore, it is suggested that convection is more active in the non-typhoon cases.

The cases in which 75 percent or more of the maxima of 24-hour precipitation fell during 6 and 12 hours were distinguished from the cases shown in Fig. 3 and the relation between the area and intensity of rainfall for the various durations was shown in Fig. 8. In no case did 75 percent or more of the maximum of 24-hour precipitation fall for 3 and 1 hour and cases for which hourly precipitation was unknown were excluded. The upper boundary for each duration was also seen in the figure. In this way the characteristics of heavy rainfall seem to be represented clearly.

In Figs. 3-8, three cases of heavy rainfall that brought about serious disasters were distinguished: Typhoon Vera in 1959, which caused extraordinarily extreme "water catastro-

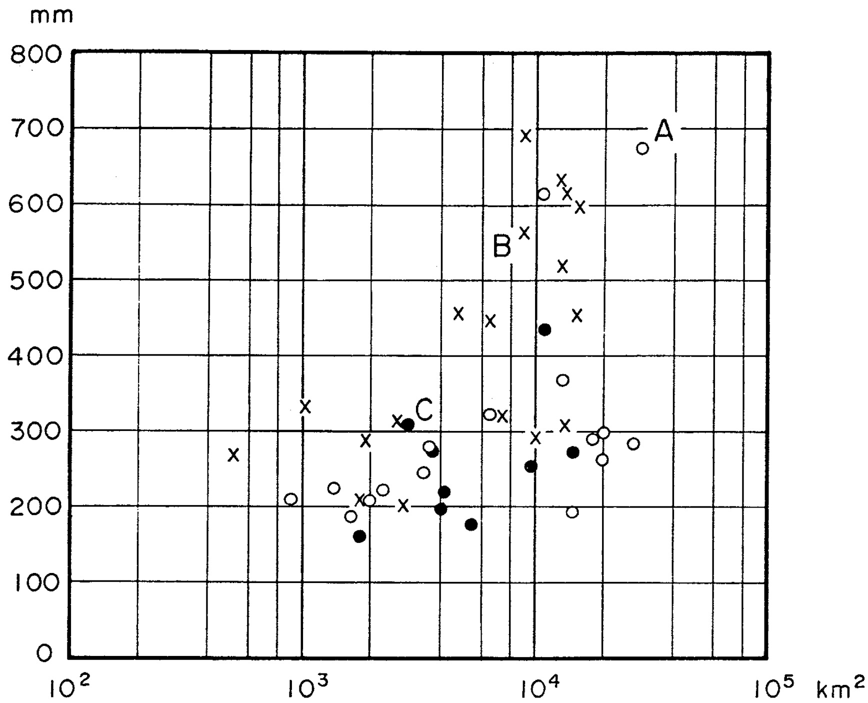

Fig. 8 Relationship between area and intensity of rainfall.
× : for 24-hour duration, ○ : in which 75 percent or more of the maximum of 24-hour precipitation fell during 12 hours, ● : in which 75 percent or more of the maximum of 24-hour precipitation fell during 6 hours.

phe" to most of Japan and especially to the entire Kinki district; and two other cases which brought disasters to the southern Kinki district and to the Minamiyamashiro region. These are expressed by letter A, B and C, respectively. The latter two cases were due to frontal activities, but meteorological conditions could not be known in detail for lack of data. It is found that these three were the few cases in which the maximum precipitation was inland and that their maxima were all near the extreme values, while most of observation points with the nearly extreme values were in the rainy southeastern part of Kinki district. These heavy rainfalls were in the class of highest intensity, particularly the rainfall due to Typhoon Vera was also in the class with the largest area.

3. DEBRIS HAZARD CAUSED BY LANDSLIDES DUE TO HEAVY RAINFALLS

The final purpose of this study was to develop a method for predicting how many landslides will occur for a given condition of heavy rainfall. This problem is difficult, because landslides depend not only on the rain but also on conditions concerning the land such as geology, geomorphology, vegetation and soil properties. Therefore, the study was conducted in co-operation with researchers in related fields, by taking two special cases both of which are considered to be typical of severe hazards experienced in Japan.

The relationship between the occurrence of landslides and rainfall intensity and more general conclusions for landslide prediction can be derived through the analysis presented here if the data from other places can be compiled.

3. 1 Data Analysis for Southern Kinki

3. 1. 1 *Distribution of rainfall and landslides*

A heavy rainstorm on July 17–18, 1953 caused many landslides and debris flows mainly

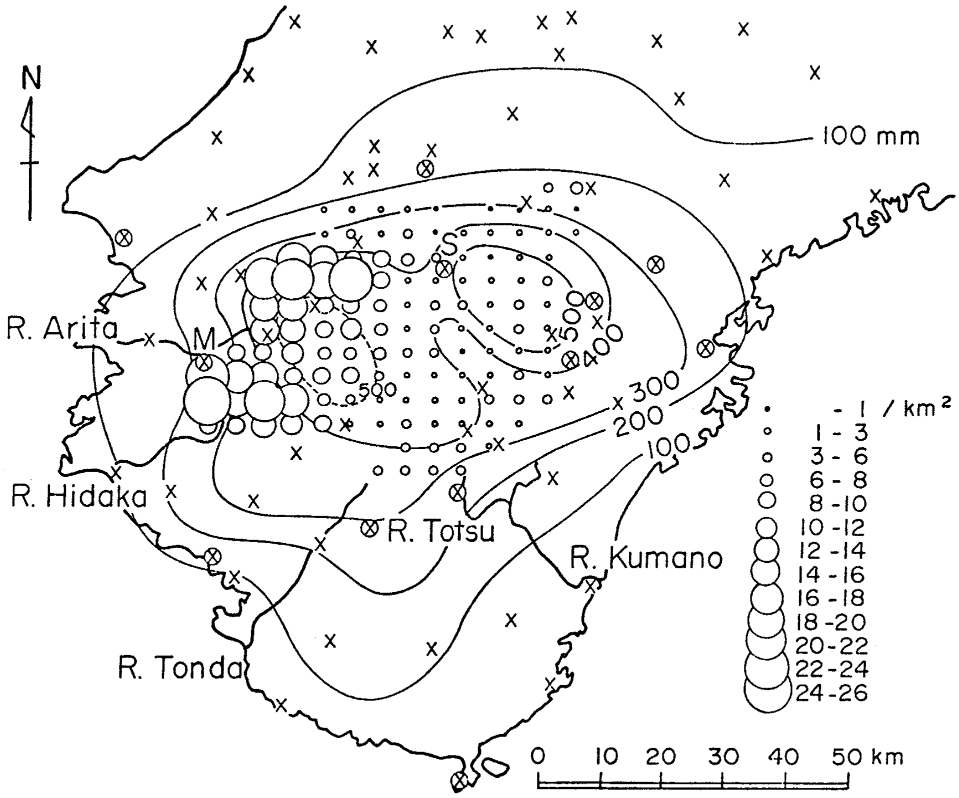

Fig. 9 Distribution of daily precipitation of the heavy rainfall in the southern Kinki district (17 July 1953) and distribution of density of landslides. Dotted isohyet is drawn by estimation.
× : observation point of daily precipitation, ⊗ : observation point with recording rain gauge, M: Matsubara, S: Sarutani.

Table 1 Distribution of area of landslids in the upstream region of the Arita River.

Area of landslides (m^2)	Number of occurrences
0 ～ 500	570
500 ～ 2000	31
2000 ～ 3000	10
3000 ～ over	2

in Wakayama Pref. Investigations were conducted by several groups [7, 8] soon after the disaster. Although the area of the storm was rather large, detailed investigation has not been conducted except in the upstream region of the Arita River, where the disaster was most severe. Therefor, features of the landslides in the whole storm region have not been clarified. Recently, the authors obtained aerial photo of the whole region taken soon after the disaster. By using these maps, the landslide distribution has been examined.

The region was divided into a grid of 4km intervals. For each cell, the authors counted the number of landslides wider than 10m.

The number of landslides per unit area (km^2) for each cell and the distribution of daily precipitation on July 17 are shown (Fig. 9).

The distribution of the area of the landslides in the upstream region of the Arita River is recorded in Table 1.

The number of landslides was rather large in the region of the Hidaka River, but generally most of the landslides were small in area. The intensity of the rainfall during a short time would be as important as the characteristics of the total rainfall for such small landslides. For the lack of such data, the authors have used daily precipitation (Fig. 9). The district with many landslides is consistent with the district with a daily precipitation of more than 200～300mm. However, the correlation between the number of landslides and the daily precipitation is not as good. For example, the district with precipitation of more than 500mm has not so high density of landslides. Moreover, the daily rainfall in the district with high density of landslides—such as the upper Arita River and the Hidaka River—is about same as or rather smaller than that in the district with the lower density of landslides. This difference may be attributed to the difference of the geological conditions in those places, and also to the difference in rainfall intensity.

Two stations in the district with high density of landslides have recording rain gauges: the Matsubara Station (M) in the midsection of the Arita River (Wakayama Pref.), and the Sarutani Station (S) in the upper Totsu River (Nara Pref.) (Fig. 9). Because maximum rainfall intensities recorded at Sarutani and Masubara were 67mm/hr and 97mm/hr, respectively, it is inferred that the rainfall intensity in Wakayama Pref. was higher than that in Nara Pref. This would be the reason why a many, small-scale landslides occurred in Wakayama Pref.

Another interesting characteristic of rainfall relates to landslide occurrence: Because of geographical and climatological conditions, the watershed of Totsu River has experienced heavy rains more frequently than Wakayama Pref. The land slope would be stabilized by the frequent heavy rains, and even 500mm of daily precipitation would not induce so many landslides in the watershed of Totsu River.

3.1.2 *Distribution of landslides and the geology*

The geology in the Kinki district varies from north to south and is homogeneous from

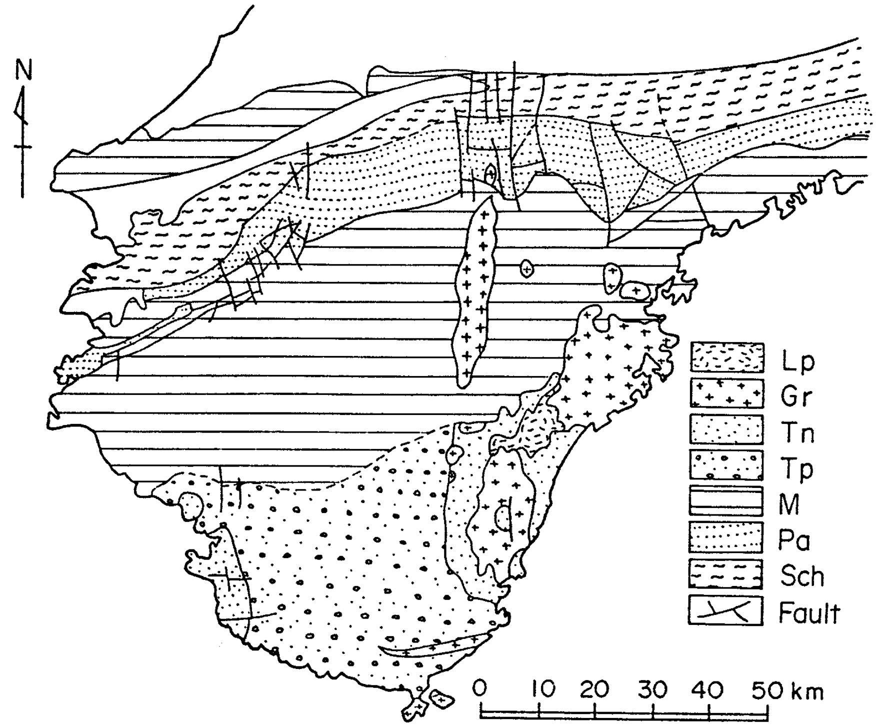

Fig. 10 Geological map of the southern Kinki district.
Lp : Liparite, Gr : Granite,
Tn : Neogene system, Tp : Palaeogene system,
M : Mesozoic, Pa : Paleozoic,
Sch : Schist.

east to west (Fig. 10). The geological structure is characterized by strata of Paleozoicera and Mesozoicera touching and forming a big fault stretching from east to west on both sides of which many minor fault groups parallel to the fault are induced.

From the map of landslides distribution (Fig. 9), it is recognized that the district with a high density of landslides stretches in the east-west direction.

The most severe landslides occurred in the Paleozoic region for the Arita River basin, and in the Mesozoic region for the Hidaka River basin. Neither district is in the main part of the big fault zone but along the minor fault groups. The main part of the big fault zone is not now active because most of the unstable materials have been lost by previous landslides; landslides in the minor fault groups are active, because discontinuous infiltration capacity due to minor fault would induce the pore pressure increase which causes landslides.

3.2 Data Analysis for the Minamiyamashiro Disaster

A heavy rainstorm hit the Minamiyamashiro region in the early morning of August 15, 1953, causing landslides, debris flows, and inundations. Physical and sociological aspects of this famous disaster have been reported in [5, 9, 10, 11].

While aerial photo analysis of landslide has advanced our knowledge about their geomorphological conditions, it can not give a correct estimation of the depth and the volume of the landslide mass (especially for landslides of the topsoil). Consequently, the report by the Debris Control Section of Kyoto Prefecture [11] maintains its fundamental value because it contains the detpth and the volume data for all the landslides (5,553) in the catchment area of the Watsuka River and on the right bank of the Kizu River. Moreover, different categories of landslide and a variety of lithological and geomorphological conditions are described.

This data, however, has not yet been fully analyzed because of its great quantity and because of the complexity of the physical relationships involved in it. However, recent development of the multivariate analysis by the computer has made it possible to derive essential relationships from the complicated data.

The MT-file of the data of the landslides at the Minamiyamashiro Disaster [12] consists of two parts: "data set of individuality" is a set of the descriptions of the individual landslides including size and physiographic conditions, and "data set of frequency" describes the physiographic conditions of the catchment area of each third-order stream and the number of the landslides in it. This data file is accompanied by a simplified program package for the multivariate analysis for the computers with small- to medium-memory size. This package can be utilized to make an intensive analysis of this disaster or to compare its characteristics with those of other landslide hazards.

The result of a preliminary analysis of the data file suggests the possibility and significance of many-sided analysis of landslides.

3.2.1 *Distribution of rainfall and the landslides*

The distribution of daily precipitation is shown in Fig. 11. The rain-gauge network at this time was so poor that a detailed estimation of the distribution of the precipitation is difficult. A histogram of precipitation on each third order basin can be drawn at best as in Fig. 12. In a geographic distribution of the density of the landslides (Fig. 13), the axis of concentrated landslide runs in an ENE-WSW direction, about 2km south of the axis of the isohyets. Though it would be possible to assume that it is simply due to error in the estimation of rainfall distribution, it is suggested that the density of the landslides depends on some physiographic conditons as much as on precipitation. The great density of landslides is distributed over the basins with precipitation varying from 300mm to 420 mm. This suggests that the critical precipitation for the occurrence of landslides was much lower in the Minamiyamashiro region than in the southern Kinki district (Fig. 9) because

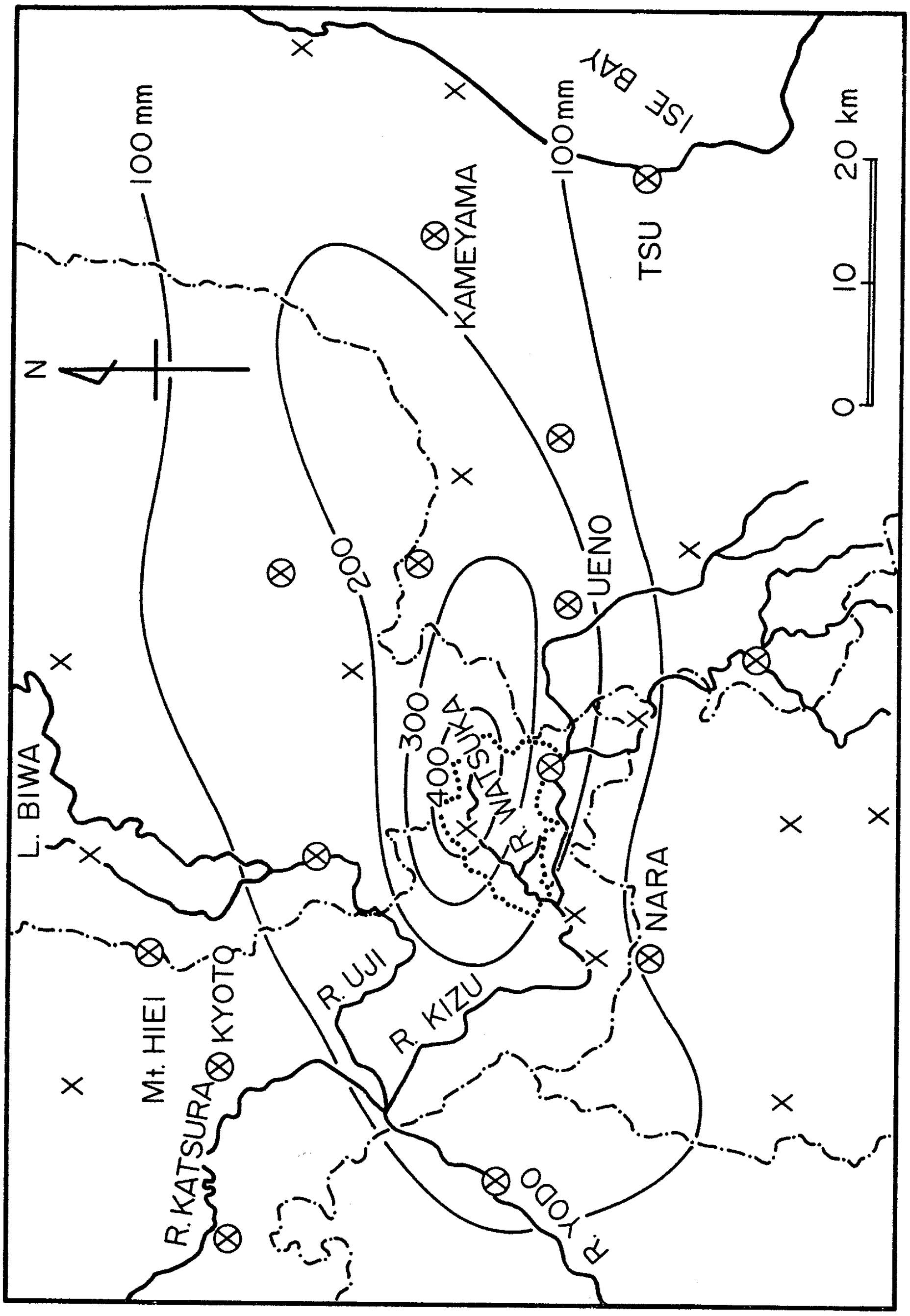

Fig. 11 Distribution of daily precipition of the heavy rainstorm in Minamiyamashiro region (14 Aug., 1953). The basin of R. Watsuka is shown by the dotted line.
× : observation point of daily precipitation, ⊗ : observation point with recording rain gauge.

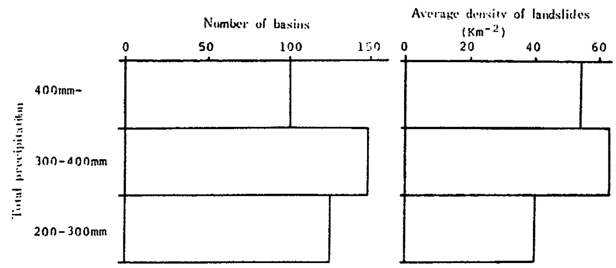

Fig. 12 Number of third-order basins and average density of the landslides within them for different classes of precipitation.

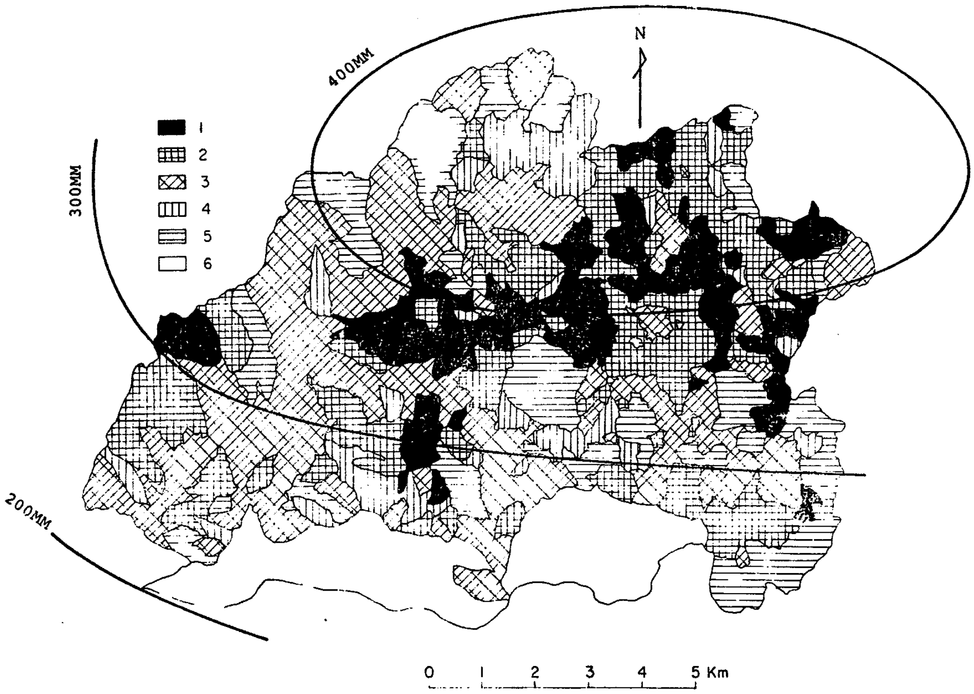

Fig. 13 Distribution of average density of landslides in each third-order basin, in the Minamiyamashiro region. 1: more than 100 km^{-2}, 2: 50-100 km^{-2}, 3: 20-50 km^{-2}, 5: less than 10 km^{-2}, 6: unknown.

Minamiyamashiro did not experience heavy rainstorms as frequently as southern Kinki.

3.2.2 *Geological conditions of the landslides*

The Minamiyamashiro region is geoloically divided into granite, metamorphic rocks, tertiary rocks, diluvial deposits and alluvial deposits. Both of the data sets of individuality and frequency involve the description of the lithology. Of the different lithological conditions, the region of granite has the largest share of the landslides (Fig. 14). For this reason Minamiyashiro Disater has been regarded as a typical catastrophe in the granitic region [10, 13]. However, the paleozoic and metamorphic regions have as dense landslides as the granitic region (Fig. 15).

3.2.3 *Geomorphological conditions of landslides*

The data file involves many items to describe the geomorphological conditions of the landslide slopes and the catchment areas. Table 2 shows the share of the different geomorphological features in the occurrence of landslides. Although histograms of the densities of landslides in the third order basins of different geomorphological conditions are not drastically differnt (Fig. 16), a detailed camparison of them provides interesting results. On the two surfaces of low relief which develop in the granitic region, landslides occurred

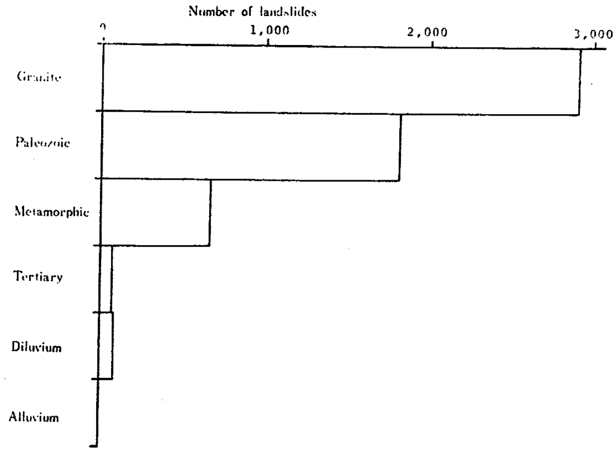

Fig. 14 Number of the landslides under different lithological conditions.

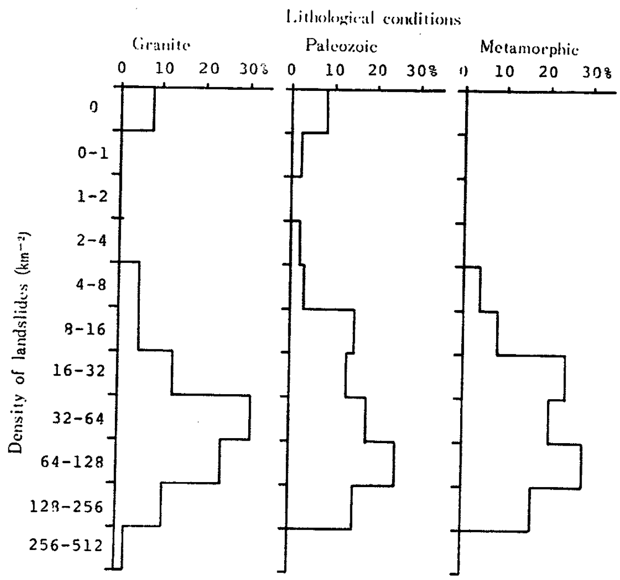

Fig. 15 Histograms of the density of landslides under different lithological conditions.

Table 2 The numbers of the landslides at the different parts of the drainage basins.

Slope bank of brooks	4,155
Midslope part	745
Concave slope	493
Convex slope	21
Ridge part	15

densely, whereas a considerable number of the third order basins were free from landslides. It is suggested that the occurrence of the landslides was primarily subject to the local slope angle rather than the general trend of declivity. On the three kinds of steep slopes, the density of the landslides averages $64/km^2$ with a smaller variation than in the other regions. It is also noted that there are many third order basins which were free from the landslides on the banks of the Watsuka and Kizu Rivers.

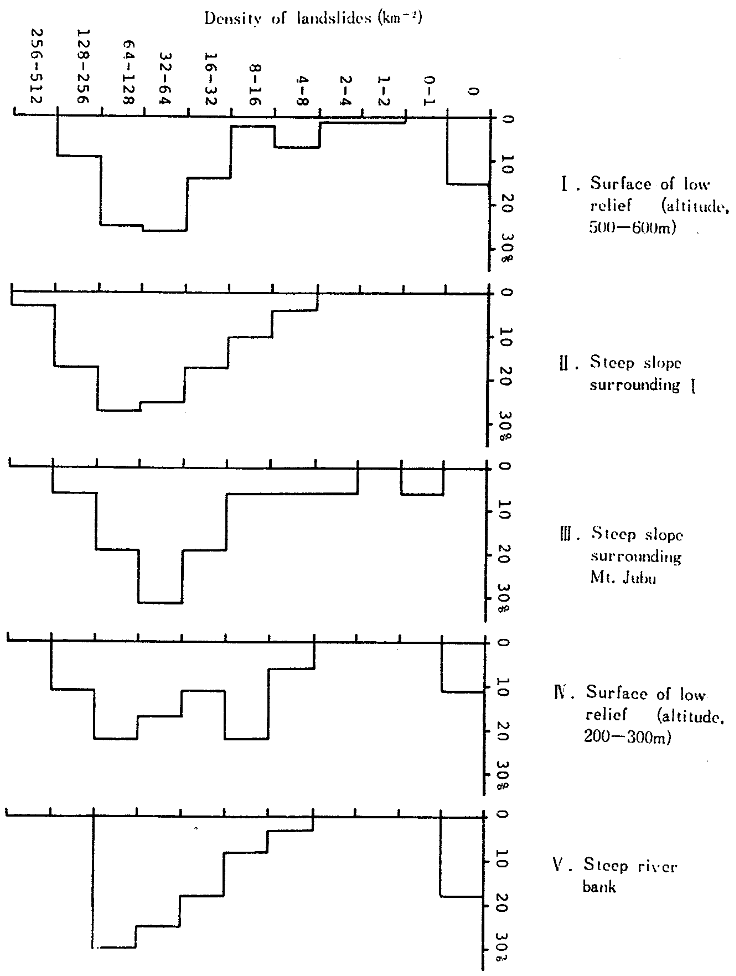

Fig. 16 Histograms of the density of landslides under different geomorphological conditions.

3.2.4. *Possibility of further analyses*

The above analysis is only a preliminary one. The density of the landslides should be analyzed as a combined effect of many factors, requiring the technique of multivariate analysis. More investigation into the characteristics of the individual landslide (height, width, area, and volume) should be made to establish the concept of the magnitude of the landslides and to correlate it to the controlling factors.

The density of the landslides defined as the number of the landslides in unit area (Fig. 15 and 16) is not a correct measure of the intensity of the debris hazard. The cumulative area of the landslide in unit area (or the areal ratio of the landslides) and the cumulative volume of the landslide masses in unit area (or the mean depth of denudation due to landslides) should also be taken into account.

4. SUMMARY AND CONCLUSIONS

The relationship between area and intensity of heavy rainfall in Kinki District of Japan was investigated for durations of 1, 3, 6, 12, and 24 hours. The maximum precipitation appears to have a limit and its extreme value tends to increase according to the area of rainfall for each duration. Although the number of cases of heavy rainfall due to typhoons is nearly the same as that due to other disturbances, the number of cases due to typhoons tends to increase with area. The cases of heavy rainfall of extremely high intensity were, on the whole, due to disturbances other than typhoons especially for short durations.

From these results, it seems necessary to extend both the duration and domain to study the heavy rainfalls that continue for several days and the relationships among area of rainfall and the scale and movement of meteorological disturbance. To investigate in detail the time to damage due to heavy rainfall, the intensity of rainfall for durations shorter than 1 hour and its change over time should be taken into consideration including forerunning rainfall before the outbreak.

The relationship between heavy rainfall and landslides has many complicated aspects: the effect of rainfall is combined with many physiographic factors. To elucidate this aspect, the multivariate analysis would be useful. Another cause of the complication is the past occurrences of sliding at various slopes. In the southern Kinki district, some of the geologically weakest regions had been already stabilized through the removal of the unstable material. On the contrary, in the Minamiyamashiro region, the slopes had been weakened by weathering over the years. To establish the whole picture of the relationship between the rainfall and landslide, an intensive examination of individual aspects is needed as well as a unified interpretation of the phenomenon as a whole.

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