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GROUND WATER REGIME OF THE KAMENOSE LANDSLIDE AREA, OSAKA PREFECTURE

By

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Abstract

This paper describes the principal part of the ground water investigation carried out from 1964 to 1969 in the Kamenose landslide area, Osaka Prefecture, Japan. The investigation of infiltration and runoff with an infiltrometer and runoff plot, and through the analysis of the direct runoff of the stream in this area revealed that the ground water recharge accounts for about sixty percent of the rainfall. The results of the observation of the water level and the sounding of the ground water flow in the boreholes were compared with the geological structure based on the test boring, and it is shown that the ground water can be treated as phreatic water. The flow regime of the ground water was estimated according to the result of the ground water tracing, the contour map of the water table, the regional distribution of the water quality of the land waters. The ground water in this area was classified into shallow water, circulating water, stagnant water, and upwelling water from great depths, according to hydrochemical analysis and the consideration of the hydrologic cycle. It was found that the ground water and its flow are quantitatively evaluated through a detailed analysis of the water balance of the drainage basin. The utility of the soil moisture logging for the hydrological and geological investigation in the landslide areas was ascertained.

1. Introduction

It is generally recognized that landslide[1] is closely related to the occurrence of ground water. Increase of ground water is supposed to be the direct cause of most landslides in Japan. Artificial removal of ground water from the landslide areas has been one of the most effective methods of controlling the landslide motion. Therefore investigation of ground water is needed in every landslide area. On the other hand, the field observation of ground water in the landslide areas offers valuable information concerning the ground water of the mountainous areas, because detailed investigation of the ground water

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[1] The word 'landslide' in this paper means a slow and continuous slide of soil mass.

is difficult in ordinary mountainous areas.

In the case of the Kamenose landslide area in Kashihara City, Osaka Prefecture, Japan, extraordinarily detailed research has been carried out concerning the mechanism and the geological-geophysical background of the landslides, because heavy damage to the rivers, the roads, and the rail road is feared. Many different methods of ground water investigation have been applied and tested including some never before applied to ground water investigation of landslide areas. Therefore the results obtained in this area will be useful for ground water investigation in other landslide areas and the usual mountainous areas.

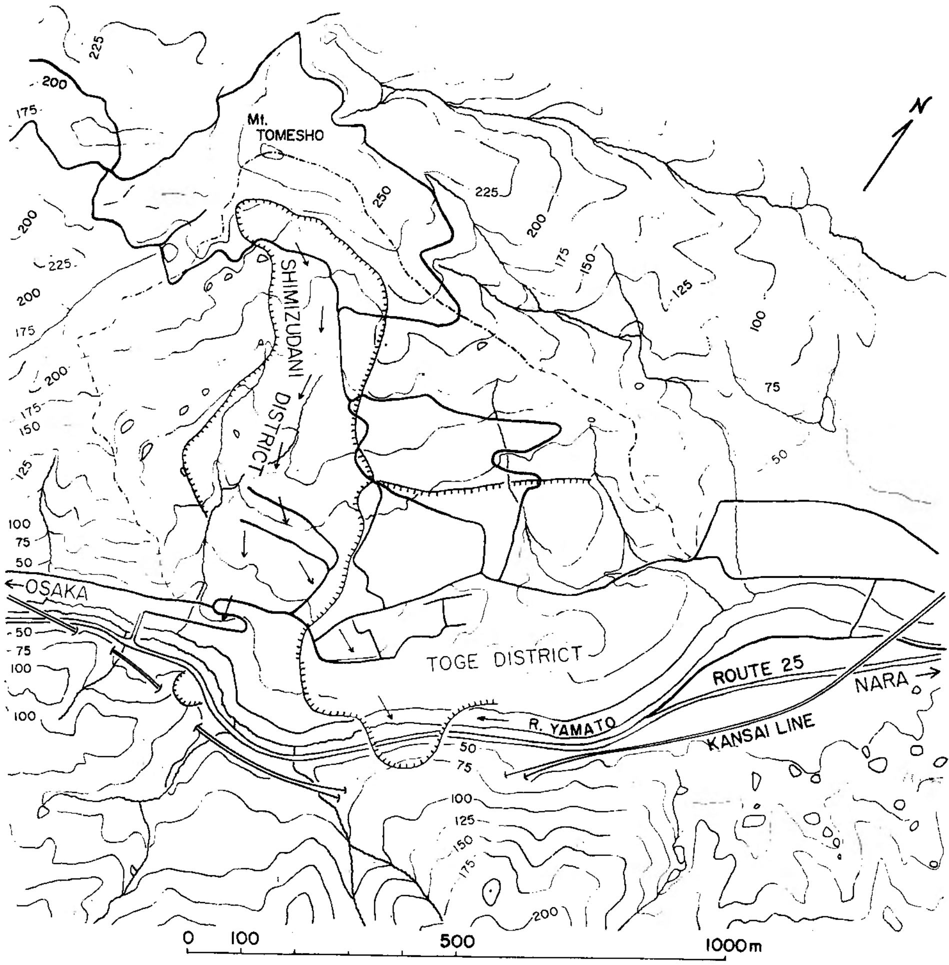

Fig. 1. A skeleton map of the Kamenose landslide area. The watershed is shown with a chain line.

2. Outline of the Kamenose landslide

The Kamenose landslide area is located at the intersecting point of the Ikoma-Kongo mountain range and the Yamato River which drains the water of the Nara basin to Osaka Bay. A skeleton map of the landslide area is shown in Fig. 1. Landslides occurring repeatedly in this area, have been investigated and recorded in detail in the literatures since the year 1931 (Matsu-

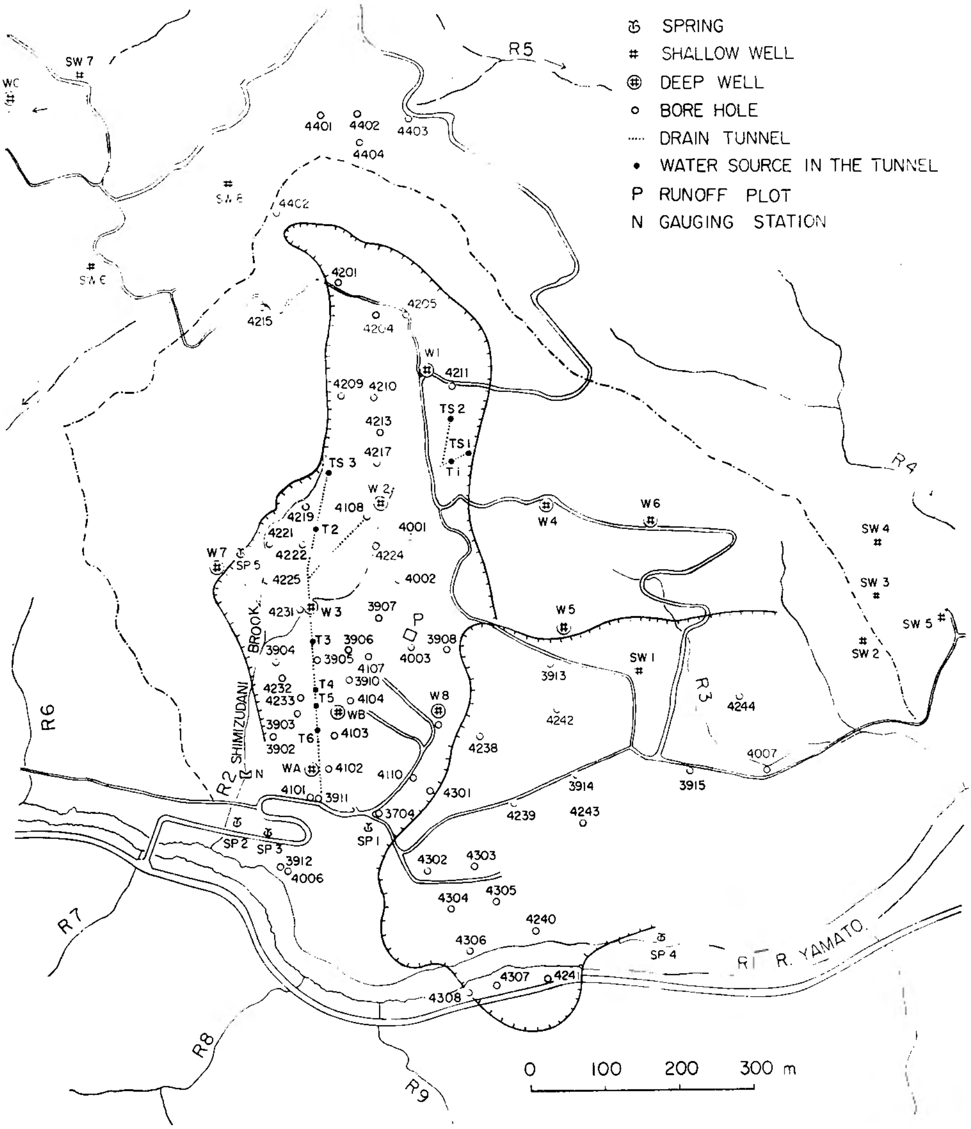

Fig. 2. The hydrological stations in the Kamenose landslide area.

yama [1932] and Kinki Regional Construction Bureau [1963, 1965, 1969]). Landslides occurred in the Toge district from 1931 to 1932, in the downstream part of the Shimizudani district from 1951, and in both the Shimizudani and Toge districts from 1967. The direction of the landslide flow and the cracks dividing the moving land and the standing land are shown in Fig. 1 for the landslide from 1967.

Almost all the landslide area is occupied by the orchards of grape and oranges. There had been rice fields in the region to the west of the Shimizudani Brook before the landslide in 1967. The houses are concentrated along the road crossing the Toge district from east to west, to the west of the downstream reach of the Shimizudani Brook, and to the southwest of Mt. Tomesho. According to the geological investigations carried out by many researchers (Fujita [1967]), the sliding soil mass consists mainly of volcanic deposits (weathered andesite and pyroclastic rocks) underlain by tuff and breccia, and further by granite.

The location of the hydrological stations in the landslide area is shown in Fig. 2. The boreholes which were not used as observation wells are not shown. Many irrigation ponds seen in this area (Fig. 1) are ignored in this paper because it was found that they store only the surface and subsurface waters, and are unrelated to the ground water regime.

The landslide from 1931 to 1932 was overcome by the excavation of the channel of the Yamato River and the replacement of the railroad. The landslide frm 1951 was dealt with by the removal of the sliding earth. The area of the earth removal is shown in Fig. 1 with a fine dotted line. For the landslide from 1967 the removal of the ground water was planned with the construction of deep wells (collector wells) and drain tunnels now in progress and partly completed (Fig. 2).

Though the direct cause of the landslide has not yet been ascertained, it is certain that the rainfall and recharge of the ground water are closely related to the landslide motion (Kawamoto [1966]).

3. The results of the ground water investigation

(a) Water balance

The investigation of water balance was carried out from 1965 to 1967 in order to determine the quantity of the ground water recharge in the drainage basin of the Shimizudani Brook (Okuda and Okunishi [1969]).

Infiltration capacity measured with a flooding type infiltrometer in 1966 at four locations near the runoff plot is shown in Fig. 3. It is seen that the

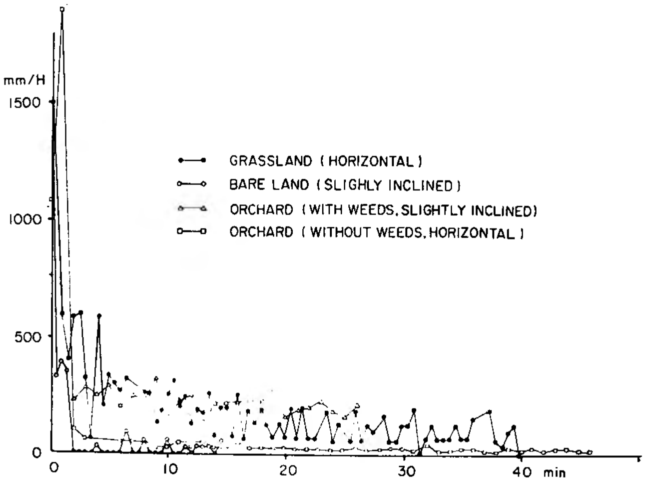

Fig. 3. Infiltration capacity of the ground surface near the runoff plot.

surface runoff may occur only in bare soil land and when the rainfall intensity exceeds 50 mm/h. Infiltration characteristics of slope surfaces were investigated from 1965 to 1966 with a runoff plot established in an abandoned orchard with dense weeds. The location of the plot is shown in Fig. 2 with the mark 'P'. The runoff water from the plot (area : 75 m^2, inclination : 12.5° to the east) was collected into a water tank and measured with a float-potentiometer type water level recorder. The rainfall intensity was measured with a storing type rainfall intensity recorder for each period of one minute. The relation between rainfall and runoff thus obtained in 1967 is shown in Fig. 4. This relation is similar to that obtained by Okunishi [1966] at a runoff plot in permeable forest land, where the surface runoff occurred when the rainfall exceeded a critical value much lower than the infiltration capacity. Though the rainfall-runoff

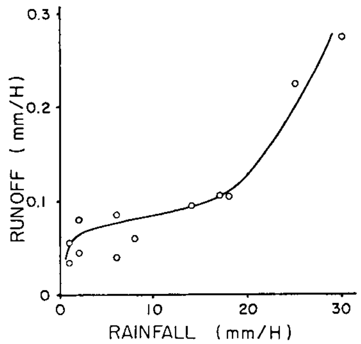

Fig. 4. The relation between rainfall and runoff at the runoff plot.

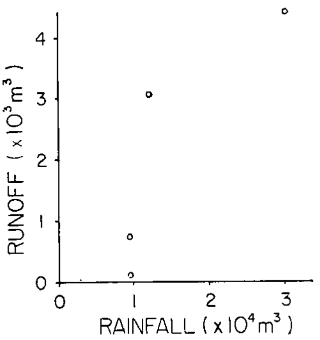

Fig. 5. The relation between rainfall and direct runoff of the Shimizudani Brook.

relation in Fig. 4 is not linear it can be said in general that about 10 % of the rainfall becomes surface runoff on a weed-covered slope surface.

Discharge of the Shimizudani Brook was measured with a V-shaped notch and a recording water level gauge in 1966, and compared with hourly rainfall. The location of the notch is shown in Fig. 2 with the mark 'N'. Discharge of the Shimizudani Brook contains the base flow as well as the direct runoff. The direct runoff was separated from the hydrograph and accumulated for each period of rainfall, and then compared with the volume of rainfall over the drainage basin of the brook (Fig. 5). Though the data are scattered it is seen that the direct runoff is about 10 % of the rainfall. This result coincides with the result of the runoff plot. The recession curve of the Shimizudani Brook showed that the direct runoff of the brook is a kind of subsurface runoff (Okuda and Okunishi [1969]).

The evapotranspiration loss was not determined through the field observation, but assumed to be about 30 % of the rainfall. Thus the quantity of the ground water recharge was estimated to be about 60 % of the rainfall. A rough balance sheet of the ground water in the drainage basin of the Shimizudani Brook was estimated as follows on the basis of the observations in 1966.

(A) Rainfall	$1{,}341\ \mathrm{mm} \times 376{,}000\ \mathrm{m}^2 \doteqdot 504{,}000\ \mathrm{m}^3$
(B) Ground water recharge	$0.6 \times 504{,}000\ \mathrm{m}^3 \doteqdot 303{,}000\ \mathrm{m}^3$
(C) Ground water runoff to the Shimizudani Brook	$365d \times 100\ \mathrm{m}^3/\mathrm{d} \doteqdot 37{,}000\ \mathrm{m}^3$
(D) Total discharge of springs (except SP1)	$365d \times 100\ \mathrm{m}^3/\mathrm{d} \doteqdot 37{,}000\ \mathrm{m}^3$
(E) Extraction of water from SP1 for the water supply	$365d \times 20\ \mathrm{m}^3/\mathrm{d} \doteqdot 7{,}000\ \mathrm{m}^3$
(F) Discharge of the excess water from SP1	$365d \times 100\ \mathrm{m}^3/\mathrm{d} \doteqdot 37{,}000\ \mathrm{m}^3$
(G) Residual ground water which directly flows into the Yamato River	$\mathrm{B}-\mathrm{C}-\mathrm{D}-\mathrm{E}-\mathrm{F} \doteqdot 185{,}000\ \mathrm{m}^3$

As the annual rainfall in 1966 was nearly equal to the normal value, it can be assumed that the values shown above approximate the normal values. It is suggested that the artificial drainage of ground water from the landslide area may be affect the landslide condition in the direction of preventing landslide.

(*b*) *Soil moisture*

The soil moisture problem has often been overlooked in the investigation of landslide. When a considerable part of the sliding mass is unsaturated, soil moisture plays an important role as a factor deciding the ground water recharge, and the weight and strength of the soil mass.

The soil moisture logging was carried out at six boreholes with duralmin casing from 1965 to 1969 using a neutron soil moisture meter. The rain water percolating through the unsaturated zone down to the water table can be traced through the analysis of the time change of the soil moisture profile (Okunishi [1970]). In this case, however, the frequency of the soil moisture logging was not sufficient for this analysis. Fig. 6 shows the vertical distribution of water content and soil density at the borehole 3910 as an example. Soil density (wet density) was measured with a γ-ray density meter on February 8th, 1965. The dry density is calculated from the wet density and the water content with the equation[2],

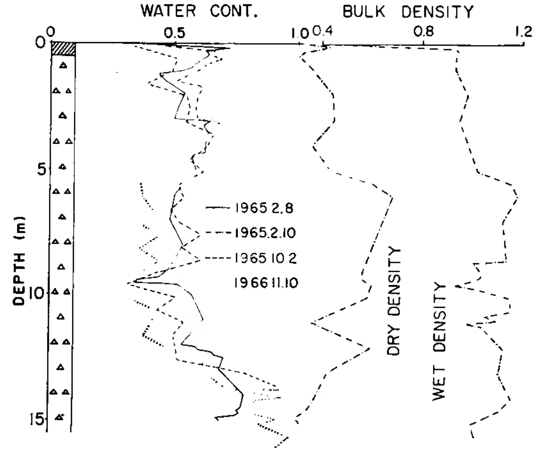

Fig. 6. The soil moisture and density profiles of the sliding earth measured at the borehole 3910. The water table is about 13 m below the ground surface.

$$\gamma_d=\gamma_w-\theta_w, \tag{1}$$

where γ_d is the dry density, γ_w the wet density (both in g/cm^3), and θ_w the soil moisture (in g/cm^3). The earth is composed of the surface soil layer and the weathered tuff breccia. The water table was usually at a depth between 13 m and 15 m. During the period from February 8th to 10th, 1965, the rainfall was 6.0 mm, which cannot account for the increases of the soil moisture over the depth from zero to 3 m shown in Fig. 6. Therefore the difference in the soil moisture between the curves of February 8th and 10th must be considered to be mainly due to observational error. The relatively low value in the soil moisture at a depth from zero to 3 m on October 10th reflects the rainless days before the logging. The storage capacity of the unsaturated soil moisture is

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[2] The value of the soil moisture shown in Fig. 6 is larger than the correct ones because a calibration curve for another condition was used. Therefore the value of the dry density was calculated to be smaller than the correct one.

estimated to be about 50 mm, because a significant rise of the ground water level is seen when the rainfall exceeds 50 mm.

It is seen in Fig. 6 that the peaks and the hollows in the soil moisture profile occurred each time at the same depths (peaks at 0.5 m, 3 m, 11 m, and hollows at 1.5 m, 9.5 m, 12 m). An inverse correlation is seen between the soil moisture and the dry density. The high soil moisture and low dry density means the existence of clayey soil, and the low soil moisture and high dry density means the existence of non-weathered rocks. The soil moisture in the Kamenose landslide area shows much higher and more constant values than were measured in an other mountainous area by Okunishi [1970].

(*c*) *Ground water level*

Observation of ground water level has been carried out by Kinki Regional Construction Bureau [1969] about twice a week at several tens of boreholes in the landslide area since 1964. Observations with electrode type water level recorders were carried out by Okuda and Okunishi [1969] at the boreholes 4004, 4108, 4238, 4239, and 4242 from 1967 to 1969.

The pressure head of the ground water in landslide areas does not always coincides with the water level in the boreholes (Kishimoto [1967] and Nakamura *et al.* [1970]) because of the complicated distribution of the permeability in the ground. In the Kamenose landslide area, however, the sliding soil mass (mainly weathered andesite) is much more permeable than the underlying rocks, so that the ground water in this area can be treated as phreatic water except those parts where the soil mass is heavily disturbed or fractured.

Annual variation of the water level in the boreholes obtained with the water level recorder in 1969 is shown in Fig. 7. An example of short term variations is shown in Fig. 8. In the borehole 4004, the annual variation of the water level is relatively small because the water in a crack intersecting the borehole in the ground determines the water level in the borehole. At the beginning of the rainfall, the rain water entering the crack caused a rapid rise of the water level followed by a slow rise due to percolation through the unsaturated zone (Fig. 8). In the borehole 4238, the response of the water level to the rainfall is slow but large. It is suggested that a considerable amount of ground water is stored in the region around the borehole. The water level in the borehole 4242 shows a similar variation though the response to the rainfall is more rapid and smaller, probably because the water surface is nearer to the ground surface. In the borehole 4239, the response to the rainfall is considerable and as rapid as in the borehole 4242, in spite of the fact that the water surface is much further below the ground surface. This cannot be

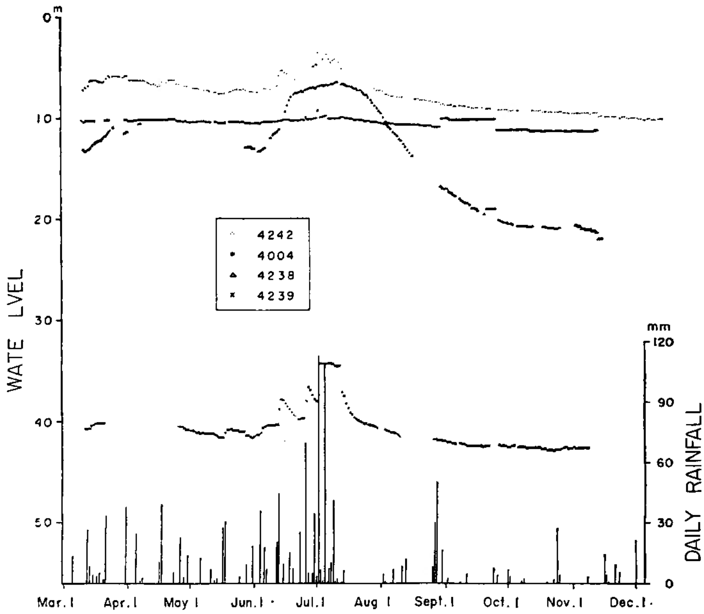

Fig. 7. The annual variation of the water level in the boreholes.

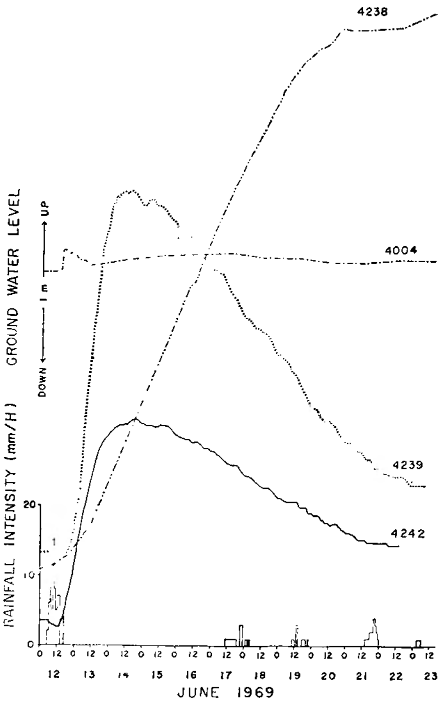

Fig. 8. An example of the response of the ground water level to the rainfall.

explained by the percolation of rain water. There are some boreholes (3901, 3904, 3905, 3908, 4002, 4208, 4211, 4212, 4213, and 4223) which also show a jump in the water level of more than 5 m at times of heavy rainfall. Occurrence of temporary perched water, or the inflow of the subsurface water into the borehole is probably the cause. It is certain in any case that the water level in these boreholes does not represent the level of the water table correctly.

The contour map of the water table estimated through the water level in boreholes and wells, and the altitude of springs observed between 24th and 26th in 1969 is shown in Fig. 9, where the broken lines are supplemented according to the data in the other periods. It is remarkable that the configuration of the water table corresponds to the upper surface of the impermeable bed whose contour map has been given by Fujita [1967], more than to the ground surface. There are two zones where the water table is extraordinarily steep. The vertical cross section along the line A-A in Fig. 9 is shown in Fig. 10. The geological structure is shown according to the investigation by Kinki Regional Construction Bureau [1969]. Kawamoto and Oba [1967] found that an underground ridge of tuff breccia in the Shimizudani district dammed up the ground water flow and made a step in the water table. This is connected to the one in the Toge district shown in the left part of Fig. 10, where there is a thin layer of tuff instead of the ridge. It is probable that the water above the thin layer of tuff is perched water and that the water table to be connected to the ones in the upstream and the downstream regions stays below the layer of tuff. Some troughs of the water table are seen in Fig. 9. The collector wells W4 and W6 were dug in one of the troughs, but drained little ground water. Therefore the troughs of the water table do not necessarily mean the concentration of the ground water flow.

The influence of the drainage of the ground water through the collector wells on the ground water level can be seen in the regions near the collector wells W1, W2, W3, W7, and W8 in Fig. 9. The difference in the water level in the boreholes between October 1967 and October 1968 is shown in Fig. 9 with small figures in units of meters. The collector wells (except W7) were dug in the period between the above times. The change in the water level in the boreholes far from the collector wells is between -2 m and $+2$ m except for the boreholes 4238 and 4243. Therefore the change in the water level shown in Fig. 9 can be thought to show the influence of the drainage through the collector wells with an error within ± 2 m. The drawdown of the water level exceeds 10 m just near the collector wells, but the boreholes more than 50 m apart from the collector wells show no significant drawdown of water level,

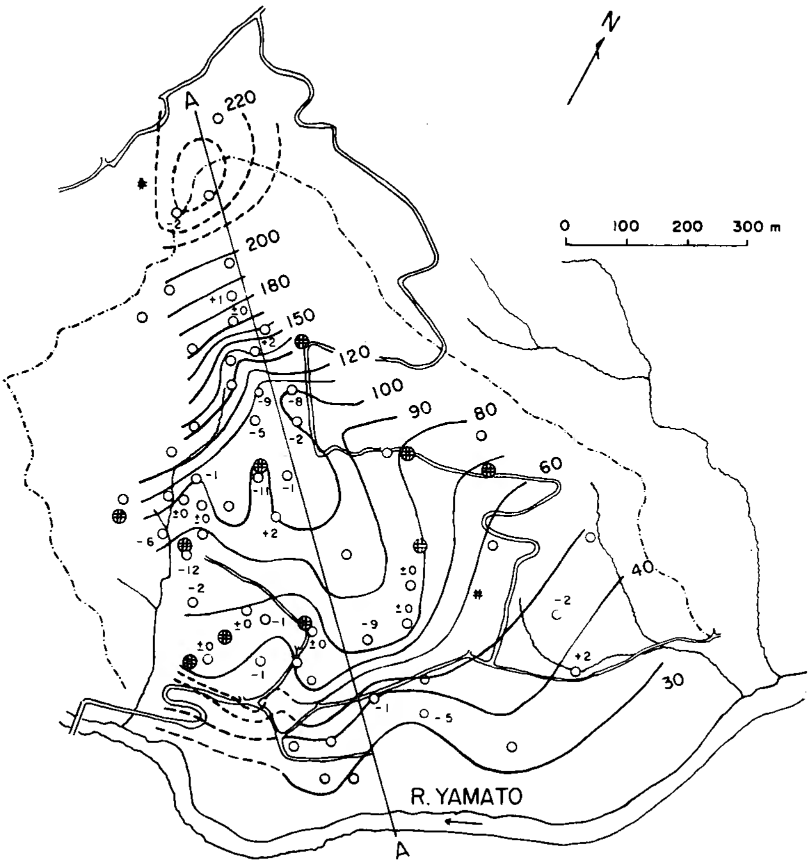

Fig. 9. A contour map of the water table. The change of the ground water level due to the pumping at the collector wells is shown with small figures.

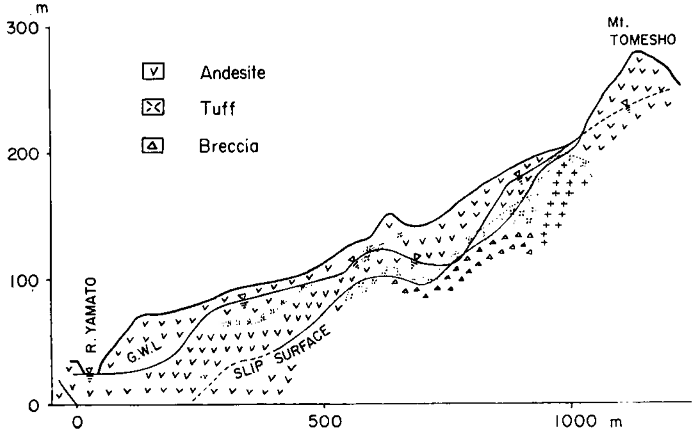

Fig. 10. A cross section of the landslide area along the line A-A in Fig. 9.

except for the region to the south of W1. A large drawdown of water level in the boreholes 4238 and 4243 may be due to the change in some local conditions such as the expansion of cracks intersecting the boreholes.

Construction of drainage tunnels was started in 1968 in order to remove the ground water in all the landslide area through line sinks and also in order to drain the collector wells without pumping. The three tunnels constructed by 1970 (among which the first one constructed in 1968 is shown in Fig. 2) are draining constantly a large quantity of ground water, though the effect on the ground water level has not yet been well confirmed.

(*d*) *Water quality*

Chemical investigation of the land water was carried out by Okuda and Okunishi [1969] from 1964 to 1969, and by Kinki Regional Construction Bureau [1969] in 1967. The main result is shown in Tables 1 and 2. The contents of Na^+ and Cl^- are higher in the surface water and the shallow ground waters than in the deep ground waters[3]. The contents in the deep ground water can be explained by the salts contained in the rain water and by the dry fallout of the sea salt. The high contents in the shallow waters suggest their contamination by the fertilizer used in the orchards and by domestic waste water. The high contents in some boreholes are due to the grouting chemicals remaining since the time of drilling. The increase of the content of Na^+ due to the deterioration of rock minerals as reported in some landslide area (Umezaki and Misawa [1970]) is not obvious. Ca^{++} and Mg^{++} dissolved in the land waters originate from the rock minerals. The contents of these ions are lower in the waters of some streams and of shallow wells than in the other waters. The regional distribution of these contents is very complicated. In many waters the ratio Mg^{++}/Ca^{++} is relatively large because the rocks are of volcanic origin. The content of HCO_3^- (BCP alkalinity as HCO_3^-) is higher in the deep ground waters than in the others, though the regional distribution is very complicated. Except a small amount of CO_2 gas from root zone, the origin of HCO_3^- is the CO_2 gas from great depths (Kitano *et al.* [1967]). On the contrary the content of SO_4^{--} is higher in the shallow waters than in the deep ground waters. Natural origins of SO_4^{--} are mainly volcanic waters and fossil water, both of which would enrich the deeper waters with SO_4^{--} rather than the shallower waters. Therefore the origins in the Kamenose landslide area must be considered to be artificial, among which the fertilizer in the orchards is the most probable in this area. The content of soluble silica (determined with a

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[3] In this section the word 'deep ground water' means the ground water below the water table as shown in Figs. 9 and 10. The word 'shallow ground water' means the local and shallower ground water (probably perched water).

Table 1. Quality of land waters in the Kamenose landslide area according to Okuda and Okunishi [1969]

Location	Date of sampling	pH	Temp. (°C)	Na^+ (mg/l)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	Cl^- (mg/l)	HCO_3^- (mg/l)	SO_4^{--} (mg/l)	Soluble silica (mg/l)	SO_4^{--}/HCO_3^- (ratio of weight)
(A) Stream waters											
R1	Feb. 7, 1967	7.2	9.3	26.0	27.5	4.9	30.0	112.2		19.9	
R2†	Mar. 25, 1967	7.6		11.1	27.2	9.6	12.7	39.8		30.0	
R2††	Feb. 7, 1967	7.4	8.5	12.4	19.7	6.8	12.4	43.6		16.8	
R3	Apr. 5, 1967	7.0		9.4	28.5	9.8	18.8	10.8			
R4	May 18, 1967	7.0		8.7	9.7	5.4	7.9	29.6			
R5	Aug. 26, 1969	6.9	20.0	7.7	10.0	3.8	11.8	16.4	19.0	25.8	1.16
R6	May 19, 1967	6.8	15.0	24.1	19.7	5.0	10.4	8.0			
R7	Apr. 3, 1967	7.0		6.9	6.1	4.3	3.2	10.2			
R8	Aug. 26, 1969	6.9	18.0	7.4	6.3	0.8	5.0	27.1	8.3	35.2	0.31
R9	Aug. 26, 1969	7.5	18.6	9.4	8.1	1.7	5.2	33.1	16.2	54.8	0.49
(B) Spring waters											
SP1	Jul. 12, 1969			9.8	27.8	10.5	7.8	63.2	36.8	32.7	0.58
SP2	Feb. 7, 1967	7.6	15.5	10.1	22.9	9.0	10.9	51.9		21.5	
SP3	Mar. 25, 1967	7.6		9.4	24.4	10.1	9.5	45.4		21.4	
SP4	Mar. 29, 1967	7.4		11.8	31.6	14.0	14.1	85.7		37.2	
SP5	Mar. 29, 1967			9.8	37.9	8.3	11.1	24.5		46.8	
(C) Waters from shallow wells											
SW1	May 19, 1967	6.5	22.5	11.0	19.2	9.4	12.8	21.1			
SW2	Jul. 25, 1966	7.4	16.6		22.4	8.4	7.8	79.4			
SW3	May 18, 1967	5.0		4.0	0.7	1.2	3.8	3.4			
SW5	May 18, 1967	5.7		6.6	3.8	3.4	4.8	5.7			
SW6	Aug. 26, 1969	6.2	16.3	22.9	25.1	6.4	21.1	45.1	46.8	32.7	1.04
SW7	Aug. 26, 1969	6.4	20.2	37.7	25.4	4.7	23.4	37.8	50.1	27.6	1.33
SW8	Aug. 26, 1969	6.6	17.7	26.5	22.8	7.5	31.8	36.3	41.5	32.4	1.14
(D) Waters of deep wells (collector wells)											
WA	Jul. 25, 1966	8.6	15.4		21.7	1.1	6.4	168.7			
WB	Mar. 12, 1969	7.8	10.8		27.2*		3.1	74.8	24.8		0.33
W1	Aug. 26, 1969		15.3	9.4	24.8	15.2	5.4	171.3	6.5	59.6	0.38
W2	Aug. 26, 1969		16.7	9.1	26.6	11.2	9.9	72.9	30.0	32.7	0.41
W3	Aug. 26, 1969	7.6	17.9	10.1	31.5	11.7	8.8	123.6	21.0	22.4	0.17
W4	Mar. 10, 1969	8.2	9.0		54.5*		16.7	41.5	38.4		0.93
W5	Mar. 11, 1969	8.1	8.7		78.4*		11.2	126.7	43.6		0.34
W7	Aug. 26, 1969	7.7	20.6	9.3	27.9	14.2	7.5	119.0	27.1	29.1	0.23
W8	Aug. 26, 1969		15.5	13.3	21.2	7.0	16.1	94.6	18.4	84.8	0.19
(E) Waters of boreholes											
3704	Mar. 12, 1969	6.2-6.4	11.2		50.6*		11.0	49.6	26.3		0.53

3902	Jul. 25, 1966	8.3			35.5	16.2	8.2	207.2			
3903	Jul. 15, 1965	>9	18.7		34*		8.8	51**			
3904	Jul. 15, 1965		17.3		26*		7.1				
3905	Jul. 25, 1966	8.9	17.7		23.5	4.3	20.6	129.0			
3907	Jul. 25, 1966	7.1	19.4		73.5	6.9	42.4	225.2			
3908	Jul. 25, 1966	7.2	22.3		44.5	20.6	67.6	76.4			
3910	Jul. 25, 1966	7.2			29.0	8.6	13.6	86.8			
3911	May 19, 1967	6.6	17.0	12.5	18.9	7.4	4.0	110.0			
3912	Jul. 15, 1965	7.6	18.8		48*		10.7	81**			
3914	Mar. 11, 1969	<7.0	15.5		58.3*		12.0	31.7	74.6		2.83
3915	May 19, 1967	7.3	19.0	11.4	33.4	18.5	9.5	176.1			
4001	Jul. 25, 1966	7.6-8.0	19.1		49.5	17.0	19.0	217.1			
4002	May 18, 1967	8.6		21.2	41.9	7.2	14.6	121.5			
4003	Jul. 25, 1966	7.4	19.5		25.6	13.5	10.0	176.1			
4004	Jul. 25, 1966	9.0	19.2		68.9	8.8	46.0	121.6			
4006	May 19, 1967	7.1	19.0	19.1	28.1	11.1	10.2	67.2			
4007	May 19, 1967	6.9	18.0	10.6	28.5	10.5	13.5	33.9			
4101	Jul. 25, 1966	7.2			17.0	4.2	12.6	226.4			
4102	Jul. 25, 1966	6.4	17.4		26.9	11.0	21.6	176.8			
4103	Jul. 25, 1966	>9.0			23.8	4.1	12.0	166.3			
4105	Jul. 25, 1966	7.6	17.8		43.7	17.5	27.8	186.1			
4106	Jul. 25, 1966	7.4	18.5		48.2	15.7	49.0	230.1			
4107	Mar. 11, 1969	>9.8	15.4								
4108	May 18, 1967	8.8		20.8	33.1	8.5	46.5	101.2			
4110	May 18, 1967	>9.8		34.8	38.8	2.2	8.6	193.3			
4202	Aug. 26, 1969	5.6-5.8	15.9	20.7	30.3	4.9	14.9	6.3	68.5	26.4	10.87
4215	Aug. 26, 1969	6.7	18.3	10.2	4.8	1.4	12.0	0	11.7	16.5	—
4238	Oct. 25, 1967	7.7	16.7	39.3	88.2	4.8	25.5	106.0			
4239	Oct. 25, 1967	7.7	18.5	16.5	60.2	13.0	18.3	137.3			
4240	Oct. 25, 1967	8.6	22.8	26.9	25.8	8.1	10.5	186.3			
4241	Oct. 25, 1967	8.6	20.3	45.2	12.8	1.7	9.2	155.4			
4242	Oct. 25, 1967	8.7	15.6	39.3	17.0	2.8	17.9	116.4			
4243	Oct. 25, 1967	9.8	16.6	43.0	9.9	0.6	10.7	119.4			
4244	Oct. 25, 1967	8.0	16.5	123.9	22.4	6.8	60.0	291.2			
4301	Aug. 26, 1969	9.6-9.8	16.8	61.0	18.6	2.3	17.9	171.9	41.3	62.8	0.24
4302	Aug. 26, 1969	9.6-9.8	18.0	40.0	25.5	0.9	25.0	54.9	68.0	40.1	1.24
4303	Aug. 26, 1969	6.8	20.0	8.4	31.4	10.8	13.3	140.8	19.6	36.8	0.14
4304	Aug. 26, 1969	7.3	17.9	65.0	18.4	5.6	26.4	176.2	32.7	37.8	0.19
4305	Aug. 26, 1969	6.7	19.8	16.1	18.6	5.0	22.5	91.3	16.4	5.4	0.18
4307	Aug. 26, 1969	7.1	17.6	15.3	15.5	4.3	3.8	116.3	5.0	85.2	0.04
4308	Aug. 26, 1969	7.3	17.5	31.9	13.0	3.0	11.4	122.2	6.7	28.7	0.05
4401	Aug. 26, 1969	6.9	16.2	52.0	13.0	3.8	8.0	168.4	22.8	28.1	0.14

(F) Spring waters in the tunnel

TS1	Aug. 26, 1969	7.0	17.0	8.6	18.4	14.6	4.8	138.3	4.2	74.0	0.03
TS2	Aug. 26, 1969	7.1	17.8	10.8	26.1	15.7	4.4	184.0	7.3	70.4	0.04

TS3	Aug. 26, 1969	7.3	17.6	13.3	27.6	12.7	6.9	181.5	3.1	59.6	0.02

(G) Ground waters drained to the tunnel

T1	Aug. 26, 1969	6.9	17.1	8.8	25.4	11.1	9.2	74.3	26.8	33.2	0.36
T2	Aug. 26, 1969	6.8	17.0	9.9	32.2	10.2	9.5	114.6	16.7	38.0	0.15
T3	Mar. 10, 1969	8.1	16.5		45.6*		9.1	109.2	23.0		0.21
T4	Mar. 10, 1969	8.1	16.1		36.2*		6.7	80.0	24.5		0.31
T5	Mar. 10, 1969	8.0	15.4		40.3*		7.1	96.9	21.5		0.22
T6	Mar. 10, 1969	8.0	15.9		44.0*		7.5	107.2	20.8		0.19

† (upstream), †† (downstream), * $Ca^{++}+Mg^{++}$ as Ca^{++}, ** M-alkakinity as HCO_3^-

Table 2. Ground water quality in the Kamenose landslide area according to Kinki Regional Construction Bureau [1969]

Location	Date of sampling	Temp. (°C)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	Cl^- (mg/l)	HCO_3^-* (mg/l)	SO_4^{--} (mg/l)	soluble silica (mg/l)	SO_4^{--}/HCO_3^- (ratioof weight)
4201	May 16, 1967		8.4	1.3	29.4	6.2	15.8	84.2	4.3	26.5	0.05
4204	May 26, 1967		48.8	5.4	25.8	1.0	78.1	54.9	12.0	37.4	0.22
4205	Jul. 1, 1967	19.0	178.0	6.5	51.5	2.9	284.0	334.3	30.3	36.6	0.09
4209	May 26, 1967		15.1	1.5	24.8	6.5	22.4	110.4	6.7	25.0	0.06
4210	May 26, 1967		31.0	2.4	22.4	5.9	32.2	136.6	13.4	19.6	0.10
4211	May 26, 1967	15.5	7.8	1.9	29.8	9.8	11.2	93.3	13.9	27.7	0.15
4213	May 26, 1967		200.0	3.7	15.2	1.9	300.3	81.7	18.2	36.6	0.22
4217	May 26, 1967		27.4	4.4	29.4	4.8	46.4	62.8	39.4	22.0	0.63
4219	Jul. 1, 1967	17.5	10.8	2.0	19.0	26.6	10.6	20.4	28.3	35.6	1.39
4221	Jul. 1, 1967	18.0	16.7	2.1	35.3	9.2	16.0	200.7	30.3	15.2	0.15
4222	May 26, 1967		413.0	9.1	79.6	21.0	871.5	78.7	25.0	18.8	0.32
4224	May 26, 1967		39.5	9.5	46.7	1.3	14.0	300.1	20.2	39.5	0.07
4225	Jun. 30, 1967	19.0	8.4	0.6	30.5	5.8	16.0	75.6	53.8	14.4	0.71
4233	Jul. 1, 1967	17.0	5.5	7.3	28.3	9.5	10.6	162.3	33.6	16.1	0.21
4232	Jul. 1, 1967	17.5	13.0	5.2	25.1	13.9	14.2	114.7	38.9	34.8	0.34
4231	Jul. 1, 1967	17.5	19.0	2.0	19.0	0.4	14.5	92.1	34.1	22.6	0.37

* BCG alkalinity as HCO_3^-.

photometric method) in most of the waters in this area is larger than the normal values in Japan reflecting the volcanic rocks.

The waters of the streams in the landslide area contain more ions of rock mineral origin than the ones outside the landslide area. This suggests that the landslide area is richer in ground water than the neighboring areas. The water of the Yamato River is heavily polluted by waste waters in the upstream region. The water quality of the spring waters sited in Table 1 is similar to that of the waters in the collector wells and the tunnel. It means that these spring waters represent the seepage of the deep ground water. The contour map of the water table in Fig. 9 is based on this fact. Other temporary springs showed water quality similar to that of shallow wells. The waters of the shallow wells SW1, SW3, and SW5 contain a poor quantity of dissolved matter. This fact means that the water of the shallow wells belongs to a hydrologic cycle other than that of the deep ground water. The waters in the boreholes show a great variety in their quality, though the greater part is similar to those in the collector wells and the tunnel. It is thought that the waters in the boreholes 4007, 4202, and 4215 are essentially the same as the ones in the shallow wells.

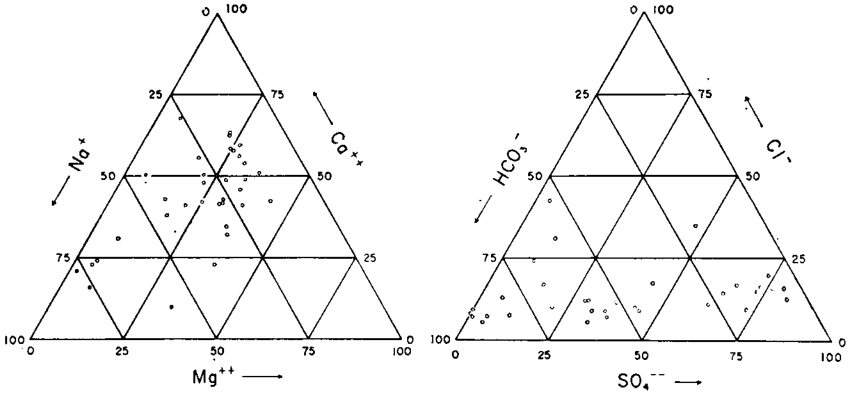

Fig. 11. The triangle diagrams of the major ions in the land waters.

The triangle diagrams of the major ions are shown in Fig. 11. If the content of SO_4^{--} had not been analyzed, it was calculated from the equation,

$$[SO_4^{--}]=[Na^+]+[Ca^{++}]+[Mg^{++}]-[Cl^-]-[HCO_3^-], \qquad (2)$$

where the contents are given in meq/l. In the diagram of cations, the dots are spread around the point (Ca^{++}: 50%, Mg^{++}: 25%, Na^+: 25%) except those showing an extremely high proportion of Na^+ due to contamination by grouting chemicals. In the diagram of anions, the dots gather near the line,

$$[Cl^-]_{\%}=0.07\times[SO_4^{--}]_{\%}+9\%, \qquad (3)$$

except four dots. The dots of the surface waters and the shallow ground waters are located in the righthand side (SO_4^{--} is predominant), the dots of the boreholes in which the water level is more than 30 m below the ground surface are located in the lefthand side (HCO_3^- is predominant), and the dots of the spring waters are located near the center. This diagram can be interpreted as follows. The rain water infiltrating into the top soil layer dissolves the SO_4^{--} and Cl^- near the ground surface, and then percolating to deeper layers, dissolves Ca^{++}, Mg^{++}, and HCO_3^- through the leaching of rock minerals

(Kitano *et al.* [1967]). The deeper ground waters dissolve a greater quantity of HCO_3^- than the shallower ones, if the contents of SO_4^{--} and Cl^- are the same. Equation (3) suggests that the content of Cl^- consists of a component proportional to that of SO_4^{--} which originates from the fertilizer and the constant component originating from the sea salt.

It was found that the time change of the ratio SO_4^{--}/HCO_3^- at the same location was much less than that of their absolute values. Therefore the land waters in the Kamenose landslide area can be classified according to this ratio. Let us call the land waters the 'shallow water' if the ratio (gravimetric ratio) is larger than unity, the 'circulating ground water' if the ratio is between unity and 0.1, and the 'stagnant ground water' if the ratio is less than 0.1. The

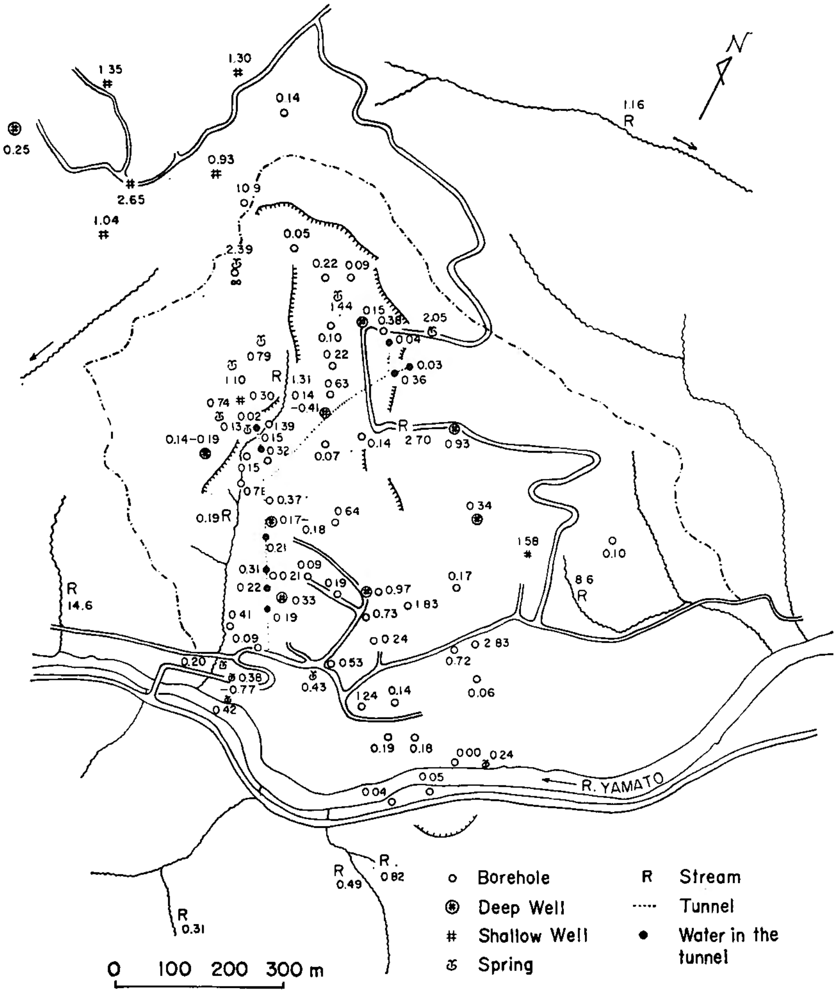

Fig. 12. The distribution of the ratio SO_4^{--}/HCO_3^-

regional distribution of this ratio is shown in Fig. 12. The water of the Shimizudani Brook (R2) is classified as 'circulating ground water' because it drains the ground water of the Shimizudani district. The waters of the brooks to the south of the Yamato River cannot be classified by this method, because these brooks drain the natural forest area. The waters of the other brooks, and all the waters in the shallow wells are of 'shallow water' type. All the waters in the collector wells and all the spring waters are of 'circulating ground water' type. The waters from the pitfaces of the tunnel are considered to be of deep origin, though they are classified as 'stagnant ground waters'. The other waters in the tunnel are of 'circulating ground water' type. The waters in the boreholes near the Yamato River (4101, 4243, 4307, and 4308) are really stagnant ground water because the water surface stays in the impermeable layers.

The content of Hg in the land waters was investigated by Okuda and Okunishi [1969], in order to determine the effect of rice fields in the Shimizudani district on the ground water regime of the landslide area. Since agricultural medicines containing Hg had been used in the rice fields, the water containing Hg is supposed to have once infiltrated the rice fields. The result of the analysis

Table 3. The content of Hg in the land waters of the Kamenose landslide area

Location	Date of sampling	Hg (ppb)
SP1	May 9, 1967	1.1-1.2
SP5	May 9, 1967	2.5-3.2
R2 (upstream)	Jun. 23, 1967	<1.0
SP1	Jun. 23, 1967	<1.0
SP2	Jun. 23, 1967	<1.0
SP4	Jun. 23, 1967	2.1-2.3

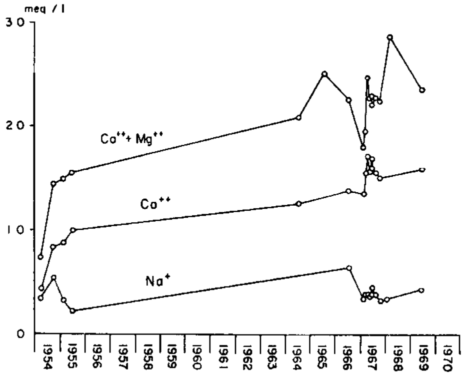

Fig. 13. A secular variation of the water quality at SP1.

shown in Table 3 suggests that the water of SP4 has flowed from the upstream region of the Shimizudani Brook across a ridge in the Shimizudani district.

Fig. 13 shows a secular variation of the quality of the spring water at SP1, according to the data by Ichihara [1955], and Okuda and Okunishi [1969]. Besides the short term variation corresponding to the variation in the hydrologic conditions, there is seen a steady increase in the contents of Ca^{++} and Mg^{++}, whereas the content of Na^{+} stays at the level accounted for by the sea salt. This secular variation suggests that the chemical weathering process is being accelerated in this landslide area.

(*e*) *Ground water tracing*

Ground water tracing with sodium fluorescene and sodium chloride was carried out by Okuda, Fukuo, and Okunishi [1965] and by Okuda and Okunishi [1969] in the downstream part of the Shimizudani district. Tracing with manganese sulphate, sodium fluorescene, and rhodamine B was carried out by Kinki Regional Construction Bureau [1969] in the upstream part. The result of these investigations shown in Fig. 14 indicates that there is a ground water vein from the upstream part to the downstream part of the left bank of the Shimizudani Brook, corresponding to the righthand branch of the landslide flow shown in Fig. 1.

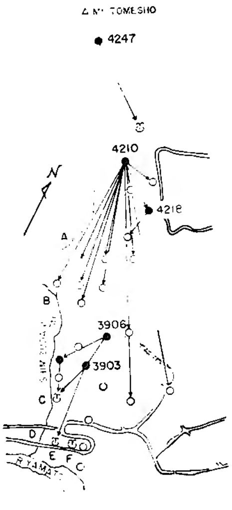

Fig. 14. The result of ground water tracing in Shimizudani district.

The change of the discharge of the Shimizudani Brook along its reach was estimated with the dilution method in February 1967, in order to investigate the exchange of water between the brook and the ground water vein (Okuda and Okunishi [1969]). It was found that the water of the upstream reach of the Shimizudani Brook leaks into the ground, and that the water of the downstream reach increases its discharge due to the confluence of tributaries and the inflow of the ground water from the left bank. From the above results, the distribution of the discharge in the brook and the ground water vein in the downstream part of Shimizudani district is estimated as shown in Fig. 15,

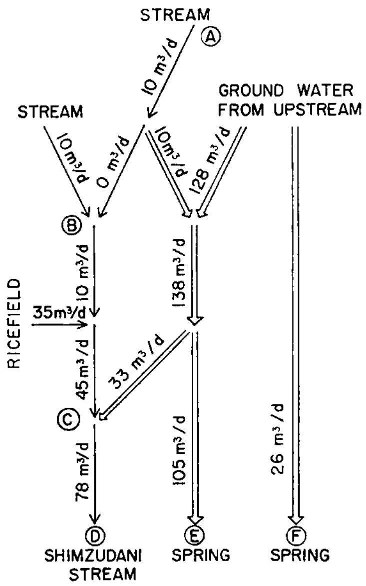

Fig. 15. The flow regime of the surface water and the ground water in the downstream region of Shimizudani district.

where the marks A~F indicate the point in Fig. 14. The single and double arrows indicate the surface flow and the underground flow respectively. According to the water balance of the drainage area of the Shimizudani Brook, however, there are unknown ground water veins with a discharge much greater than the one shown in Fig. 15.

(*f*) *Other investigations*

In order to find the vertical distribution of the ground water flow, sounding of active permeable layers (Okunishi and Okuda [1965], and Watari and Sakai [1965]) was carried out at some boreholes. It was found that the flow of the ground water exists only in the weathered andesite in many boreholes.

Electric prospecting was carried out many times (Kinki Regional Construction Bureau [1969]). The ground water flow predicted according to this result only did not coincide with the result by other methods.

4. Conclusion

The geological structure of the Kamenose landslide area has been determined in detail through test boring, seismic and electric prospectings, and other geological observations by the research group of the Kamenose landslide. Permeability of each stratum was estimated through the sounding of the active permeable layers, and the measurement of the infiltration capacity of the ground surface at different locality, as well as through the observation of core samples. It was found that the sliding earth (mainly weathered andesite) is much more permeable than the underlying layer (tuff, breccia, and granite), and that the ground water can be treated as phreatic ground water.

The contour map of the water table was made according to the observations at boreholes, wells, and springs. It was found that the troughs and steps of the water table are closely related to the structure of the impermeable layers. It was also found that the troughs of the water table do not necessarily mean the concentration of the ground water flow.

The water balance of the landslide area was estimated according to the investigation of the infiltration characteristics with an infiltrometer and a runoff plot, and according to the comparison of the volumes of the rainfall and the direct runoff of the brook. It was found that the recharge of the ground water accounts for about sixty percent of the rainfall. The soil moisture profile observed with a neutron soil moisture meter suggested that the rain water penetrating into the ground is stored mainly as unsaturated soil moisture when the rainfall is less than 50 mm.

The direction of the ground water flow was estimated through the ground water tracing and the investigation of the water quality. The distribution of the discharge of surface flow and underground flow was determined based on a detailed observation of the discharge of streams and springs. However the water balance showed that there must exist unknown ground water veins with the discharge much larger than the known one.

The land water of the landslide area was classified according to its chemical properties, related to the different phases of the hydrologic cycle, and then identified as shallow water, circulating ground water, stagnant ground water, or upwelling water from great depths.

More detailed investigation must be carried out concerning the movement of the unsaturated soil moisture and its influence on the landslide motion. The origin and the quantity of the ground water extraordinarily rich in HCO_3^- found in the tunnel and some boreholes have not been sufficiently investigated. The effect of the drainage works with the collector wells and the drain tunnels on the ground water regime and to the landslide motion must be evaluated quantitatively through succeeding investigations.

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