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Characteristics of Subsurface Stormflow from Forested Hillslopes in Hokkaido, Japan — Overbedrock Subsurface Flow —

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Abstract

Studied plots were selected at the forested hillslopes on the headwaters of a small basin in the outskirts of Sapporo, Hokkaido, Japan, so that the storm runoff from a hillslope to a stream channel were examined. It was revealed that the Hortonian overland flow was absent there, as was reported in humid and forested regions by many investigators. The classic concept of the Hortonian overland flow is, as a matter of fact, giving way in recent years to the new concept that a rapid response to rainfall or snowmelt is mainly caused by the subsurface flow except arid regions, as noted in detailed reviews by Ward (1984), and Chorley (1978).

The characteristics of the subsurface flow are closely related to the structure of a soil mantle overlying the bedrock ; for example, thickness, anisotropic and granulometric properties reciprocally controlled by vegetation, climate, geology and landform. In the small experimental basins of Bankei River and Hiyamizu River, it was clear that the quick runoff from a forested hillslopes mainly excels in the overbedrock subsurface flow through the thin permeable layer on the surface of a bedrock in response to a rainstorm and snowmelt. The percolated water reaches quickly the bedrock surface through the vertical path accumulated inhomogeneously the angular gravels resulting from a landslide in a soil mantle.

The thin permeable layer overlying on a bedrock is become more permeable by the washing fine soil materials and as the result of a washing, it is introduced that the soil mantle become unstable. It is assumed that the repeated occurrences of a landslide on the hillslope come from the overbedrock subsurface flow during long years.

1. Introduction

It has been reported that the subsurface flows discharge through various kinds of paths in many regions of the world. In the present study the subsurface flows in the humid regions are classified into three types in the consideration of the mechanism collected the subsurface flow from hillslopes to stream channels; anisotropic subsurface flow, saturated overland flow and homogeneous groundwater flow.

a) Anisotropic subsurface flow

Overbedrock subsurface flow Generally, the hillslopes in headwaters are steep and are covered by a thin soil layer which is shallower than 1 or 2 m in depth with a soil mantle composed of superficial humus soil, weathering soil and slope deposits resulting from a landslide and a creep induced the anisotropy in soil structure.

The subsurface stormflow has frequently been observed as a predominant lateral flow through the permeable soil layer at the basal soil horizons overlying a bedrock in the rapid response to rainfall or snowmelt on two experimental plots of hillslopes in a humid forested region, Hokkaido. We call the stormflow; overbedrock subsurface flow which is inherent in a kind of throughflow, as noted by Kirkby and Chorley (1967), Troendle et al. (1971), Nakao et al. (1987) and Ishii (1990).

The rain percolated from the ground surface rapidly concentrates on the interface between a soil mantle and a bedrock, increasing discontinuously the hydraulic conductivity with an increase in depth, then it makes up a saturated flow there and becomes increasingly permeable there by eluviation and forms a quick flow path on the lateral movement to the stream channels.

Furthermore, our field studies clarified the evidence that the quick paths percolating vertically to the surface of bedrock were built in the collapsed soil with the anisotropic accumulation of angular gravels. And it is expected that the sliding of the soil mantle overlying on the bedrock is repeatedly occurred by the washing out of fine soil materials and the eluviation with the overbedrock subsurface flow during long years.

Pipe flow Pipings are found in the soil mantle of the hillslopes where they are formed by such fine sediments as aeolian soil and marine deposits (Fletcher et al., 1954; Tanaka et al., 1982). The permeable varieties in an impermeable sedimentary structure generate the pipings by eluviation.

b) Saturated overland flow and homogeneous groundwater flow

The concept of saturated overland flow was suggested by Hewlett (1961a and 1961b), who found the occurrences in the valley floor and floodplain adjacent to a river. The saturation to a ground surface is caused by the lateral flow of percolated water on the hillslope such as the overbedrock subsurface flow. In our opinion, the saturated overland flow is insignificant proportion for the total process of the runoff discharging to stream channels in headwaters, beause the valley floor is narrow and hillslope is steep. Meanwhile, in the wide floodplain

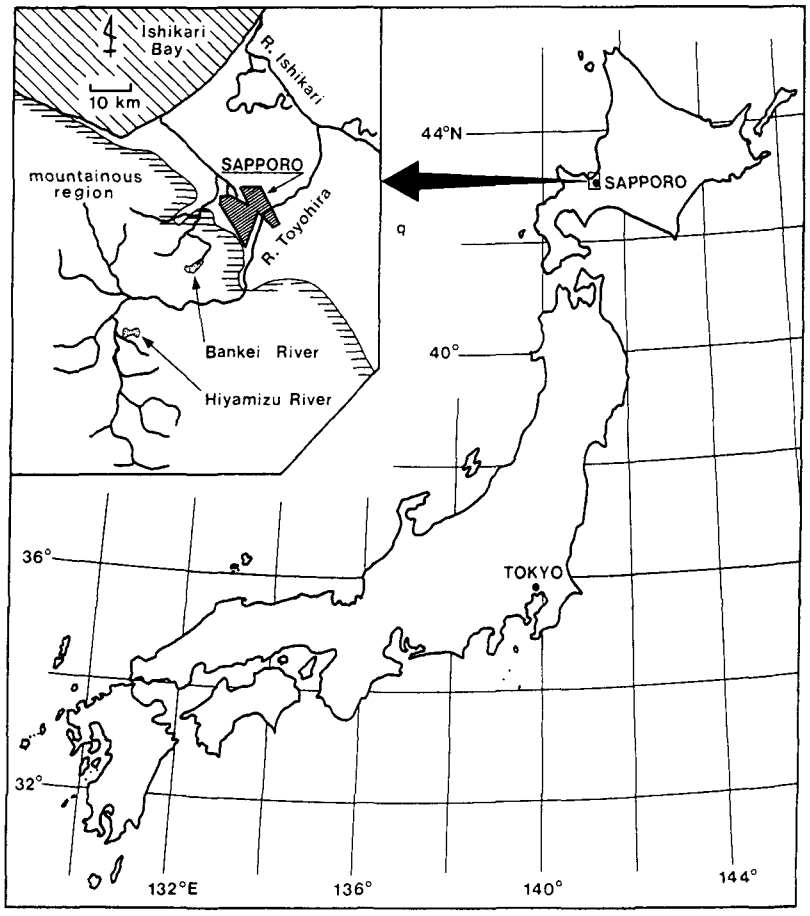

Fig. 1. Locations of Bankei River and Hiyamizu River in the outskirts of Sapporo, Hokkaido.

the homogeneous groundwater flow is generated commonly through deep alluvial sediments rather than the saturated overland flow (Ishii and Nakao, 1981).

The homogeneous groundwater flow is predominant in the drainage basin covered thick with fluvioglacial sediments and volcanic products, commonly in well-developed floodplains or alluvial fans in many parts of the world (Toth, 1962; Freeze, 1967).

Subsurface flow was observed to examine a quick flow through a soil mantle at experimental plots of hillslopes in small basins of Bankei River and Hiyamizu River in Toyohira River Basin situated in the outskirts of Sapporo; latitude 40°03′N and longitude 141°20′E, Hokkaido, Japan, as shown in Fig. 1. The mean annual air temperature and the annual precipitation are respectively 7.8°C and 1141 mm in Sapporo, based on the meteorological record during the period from 1941 to 1970. The annual amount of potential evaporation calculated by using the Penman's method (Penman, 1956; Nakao, 1971) is 726 mm, based on the meteorological records during the period from 1955 to 1964; and in humid vegetated regions, the ratio of evapotranspiration to potential evaporation was estimated by Nakao (1971) as 0.65 in the Ishikari River, Hokkaido.

2. Subsurface flow measured on forested hillslopes; Experimental hillslope plot of Bankei River

The drainage basin is situated at the distance of about 7 km from the center of Sapporo to the westward; the basin is 0.68 km^2 in area, 27 degrees in the mean incline of hillslopes and is covered with the soil mantles of 1 to 2 m thickness overlying the bedrock composed mainly of andesite. The forest trees are formed by a Japanese spruce, a white birch and an alder and the common undergrowth is formed by low striped bamboo.

Response to rainfall The observation results of the subsurface stormflow were made as follows; the pit of 1 m depth was dug at the experimental plot of a hillslope with 38 degrees in incline and 100 m in slope length, sited about 100 m upstream from the gauging site of a river stage (Fig. 2). Then three troughs were constructed respectively at the depths of 10, 50 and 100 cm in this pit, so that the first trough was used to collect the lateral flow called superficial subsurface flow on the base of fumus soil, the second one to collect the middle subsurface flow and the third one to collect the flow called overbedrock subsurface flow discharging from the base of a soil mantle overlying the bedrock. The trough was 70 cm long and an iron plate was attached to it, inserting the plate into the soil mantle so that the discharged water was led to the tipped

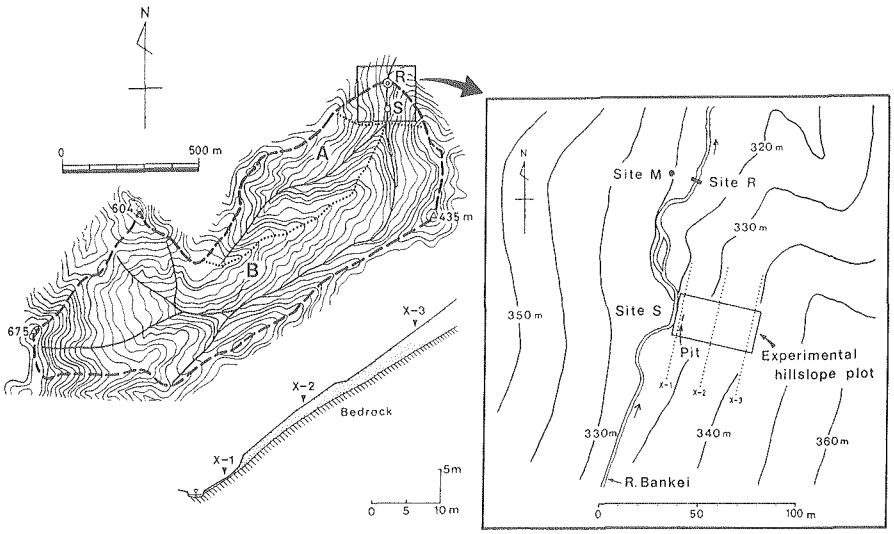

Fig. 2. General views of the topography and experimental plot of hillslope in Bankei River Basin, selfrecorded the river stage, the water temperature in the stream and the rainfall at site R, the air temperature and groud temperature at site M, and made the electrical depth soundings at sites x-1, 2, 3.

bucket of a rain gauge which recorded automatically the amount of the leding water.

Measurements were made for two rainstorms in September and October, 1982, the total rainfall being 125 mm and 124 mm respectively. A rapid response to rainfall is characterized as follows; the subsurface flows through the superficial and the middle soil layer discharge to the troughs immediately after the rainfall, but the overbedrock subsurface flow discharges with 2 or 3 hours delay, the discharged amount is most abundant in comparison with the other subsurface flows as shown by Fig. 3.

Moreover, a rainstorm was simulated artificially in August 1982 to examine the flowing process of the overbedrock subsurface flow on the hillslope. The intensity of the artificial rain was 6.1 cm per hour, the period of a rainfall was 33 minutes and the rain water was sprinkled over an area of 1 m width at the distance of 1.8 m upward from the pit on the hillslope. Tensiometers were set up to measure the hydraulic head, respectively at the depths of 25, 50 and 100 cm and they were sited at the distnce of 1.3 m upward from the pit.

The hydrographs of the subsurface flows measured by the trough and the variations of hydraulic head in response to the artificial rainstorm show that the

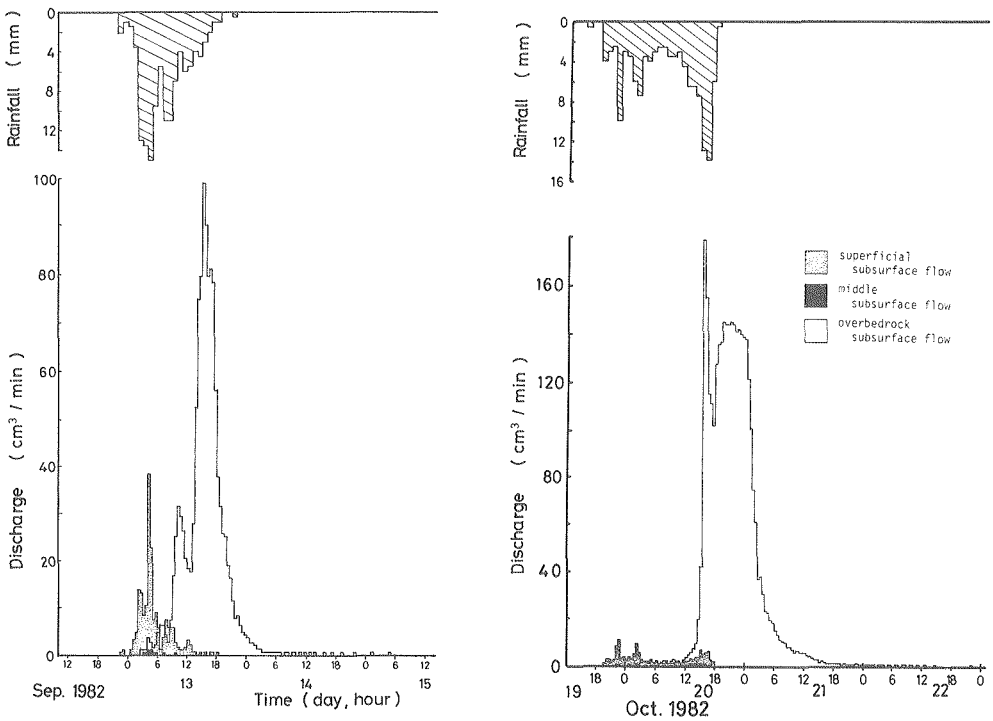

Fig. 3. Runoff responses of the subsurface flows to rainfall measured by the troughs constructed in the pit on the experimental plot of hillslope.

subsurface flows are nearly similar to those of natural events, except that the overbedrock subsurface flow is rapid in response; that the superficial subsurface flow is a little abundant to reflect the high intensity of artificial rainfall and after the rainfall the hydraulic heads at the depths of 25 and 100 cm increase to saturate, in spite of unsaturation at the depth of 50 cm (Fig. 4). It is very important that the evidence suggests the existence of vertical quick paths percolating to the surface of the bedrock.

Meanwhile, the examination of delay time for the overbedrock subsurface flow shows that the hydraulic conductivity is roughly esimated to be 0.095 cm sec^{-1} in the soil layer at the boudary between the soil mantle and the bedrock and that the values is about 30 times permeable as compared with that of the soil mantle under the humus soil.

To clarify the runoff ratios of each subsurface flows from the hillslopes to the river, it is carried out the following procedures that the drainage basin is divided into two simplified rectangular basins as shown in Fig. 5 and the lateral

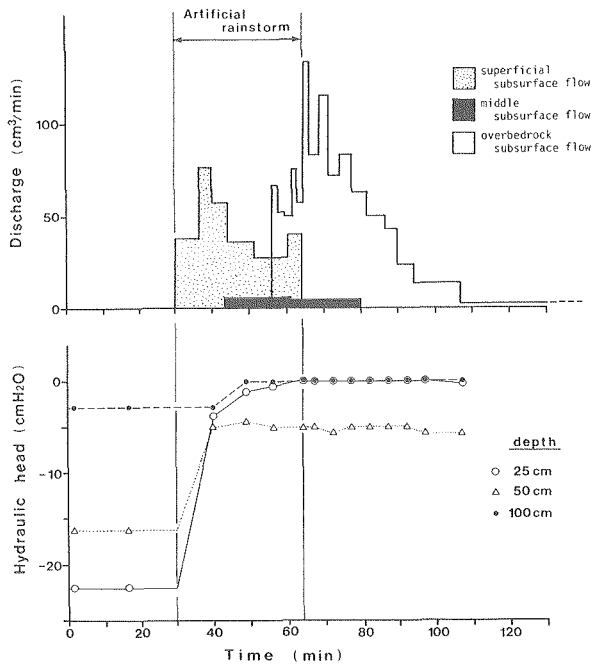

Fig. 4. Hydrographs of the subsurface flows and the variations of hydraulic head in response to the artificial rainstorm.

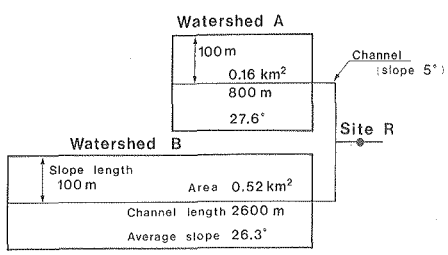

Fig. 5. Drainage basin model simplified two rectangular basins, divided into the basins of A and B as shown in Fig. 2.

inflows from the hillslopes to the collecting channels are given as shown in Fig. 6 with the hydrograph measured on the experimental plot of the hillslope and the total discharges are finally decided by trial and error, in so far as their resultant hydrograph agrees well with the hydrograph measured at the gauging site (Site R) of the river stage.

The resultant hydrograph is fundamentally estimated from the following

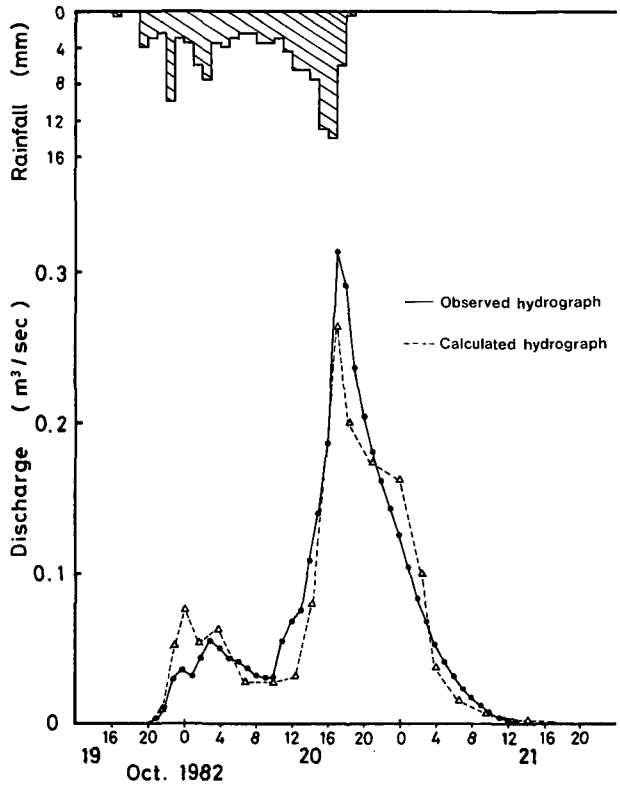

Fig. 6. Hydrograph estimated by collecting the lateral inflows of subsurface flow from the hillslope and the direct rainfall along channel from the headwaters of a stream to site R, and hydrograph observed at site R.

equations proposed by Iwagaki and Sueishi (1954), Sueishi (1955) and Kishi and Nakao (1962).

On the assumption of uniform flow, the basic equations for a channel flow are expressed as

$$A = \alpha Q^{P} \tag{1}$$

and

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q(t) \tag{2}$$

where A is the cross-sectional area of a stream, Q and q are the discharges in the channel and the lateral inflow for the unit length of the channel respectively,

x is the distance from the headwaters of a stream to downstream and t is the time. If the flow conforms to the Manning equation, the channel has a rectangular cross section and the breadth of the channel is wide as compared with the water depth, α and P are shown as

$$\alpha = n/\left\{\left(\frac{1}{B}\right)^{\frac{2}{3}} i^{\frac{1}{2}}\right\}, \quad P=0.6 \tag{3}$$

where n is roughness coefficient and B and i are respectively the width and the slope of a channel.

By substituting equation (1) into equation (2), we obtain

$$t = \alpha x Q^{P-1} \tag{4}$$

and

$$t = \alpha Q^{P}/q \tag{5}$$

The calculated hydrograph at site R is estimated by equations (4) and (5) by using the numerical values of $n=0.03$ sec $m^{-\frac{1}{3}}$, $B=1$ m and $i=5°$. And the calculated results agree with the observed hydrograph as shown in Fig. 6. From the results of examination, the runoff ratios are expressed as follows; 62% for the overbedrock subsurface flow, 31% for the superficial subsurface flow, 3% for the middle subsurface flow and 4% for the direct rainfall to the water surface in the channel. The quick response to the rainfall on the hillslopes is schematically shown in Fig. 7.

Response to snowmelt The ground surface is almost entirely covered with

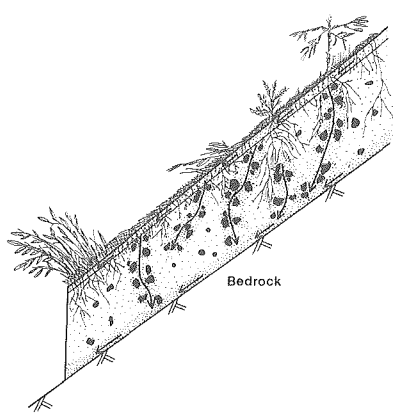

Fig. 7. Schematic feature of the paths on the quick response to rainfall.

snow from late November to early May in the drainage basin and the covered snow starts melting in late March.

Under the condition which the channels are almost entirely covered with snow in the early snowmelt season, if the advective heat flux in the flowing water is negligibly small, the heat budget equation for the flowing water in the channel is expressed as

$$c\rho DB\frac{d\theta}{dt}=c\rho q_g(\theta_g-\theta)+c\rho q_s(\theta_s-\theta)+BH_0 \tag{6}$$

where c and ρ are respectively the specific heat and the density of river water, D is the water depth in the channel, θ is the water temperature in the channel,

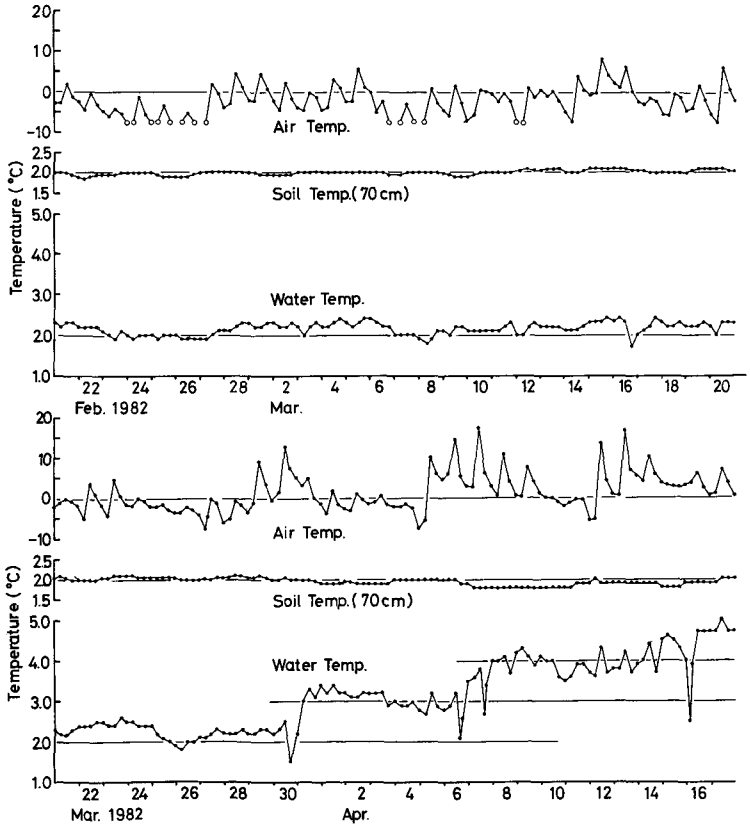

Fig. 8. Air temperature and ground temperature measured at the depth of 70 cm and water temperature of stream measured at site R during the observation period from late February to April, 1982.

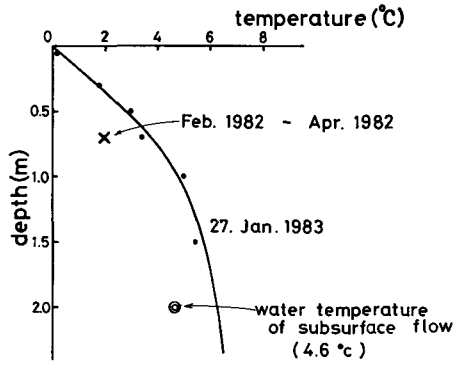

Fig. 9. Vertical profiles of ground temperature in the soil mantle.

θ_g is the water temperature of the subsurface flow and θ_s is the water temperature of the overland flow on the ground surface under a snow mantle which contains partially the superficial subsurface flow; $\theta_s=0°C$, q_g and q_s are the lateral inflow per unit length of the channel by the subsurface flow and that by the overland flow, respectively and H_0 is the net heat flux to the water surface in the channel. And in this case, the channel is covered by the snow having the space between a water surface and the bottom of a snow cover. If the temperature of a snow bottom in 0°C, then H_0 is expressed as

$$H_0=\varkappa(\theta_a-\theta)+\sigma\{273^4-(\theta+273)^4\} \tag{7}$$

where θ_a is the air temperature, σ is the Stefan-Boltzmann's constant; $\sigma=1.183\times10^{-7}$ cal cm^{-2} K^{-4} day^{-1} and $\varkappa$ is the cooling constant. Then, θ_g and $\varkappa$ are the unknown constants in equations (6) and (7). On the assumptions which the variations of water temperature, air temperature and streamflow were kept in the steady state during the period from 3^h to 7^h on 4th and from 15^h to 19^h on 11th in April, the numerical values of the unknown constants were estimated by using equations (6) and (7) as $\theta_g=4.6°C$ and $\varkappa=0.55$ cal cm^{-1} sec^{-1} (Fig. 8).

The estimated temperature of the subsurface runoff corresponds to the ground temperature at the depth of 2 m which fits with the average depth of the soil mantle in the drainage basin, according to the judgement based on the vertical profiles of groud temperature as shown in Fig. 9. The evidence suggests clearly that the subsurface runoff is mainly caused by the overbedrock subsurface flow also in the response to snowmelt in the same manner as the response to rainfall.

Moreover, by using the estimated values of θ_g and $\varkappa$ and unsteady equations

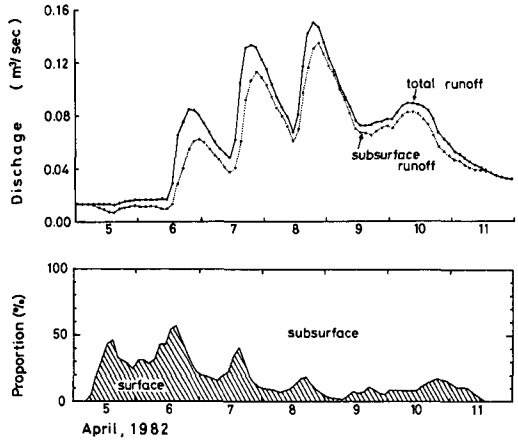

Fig. 10. Runoff ratios of the overbedrock subsurface flow and the overland flow contained partially the superficial subsurface flow to total runoff.

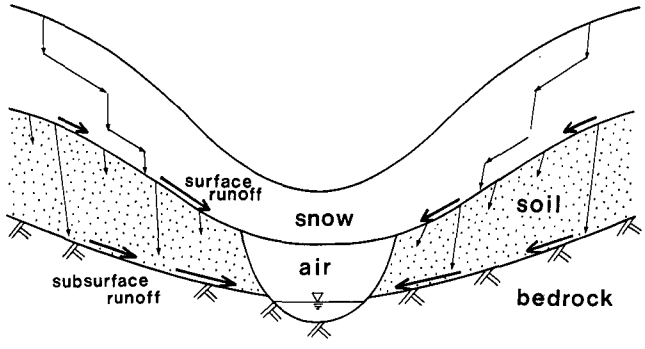

Fig. 11. Schematic illustration for the runoff paths collecting to the stream covered by snow.

(6) and (7), the runoff ratios of the overland flow and the subsurface runoff were decided for the measured hydrograph during the early snowmelt season as shown in Fig. 10. The average values of runoff ratios were estimated to be about 80% for the subsurface runoff caused by the overbedrock subsurface flow and 20% for the overland flow and their paths are schematically illustrated in Fig. 11.

3. Subsurface flow measured on forested hillslopes ; Experimental hillslope plot of Hiyamizu River

The drainage basin is situated southwestward about 21 km from the center of Sapporo City and the basin is 0.93 km^2 in area, 26 degrees in the mean incline of hillslopes and is covered with soil mantles thinner than 1 m overlying the bedrock composed of quartz porphyry. The forest trees are formed by Japanese spruce, fir, white birch, alder and walnut and the common undergrowth is formed by low striped bamboo similarly to Bankei River Basin.

The discharge of the subsurface flow was measured by the troughs of 80 cm long which set respectively at the depths of 20, 60 and 80 cm in a pit of 1 m depth at an experimental plot of a hillslope with 45 degrees in incline and 110 m in slope length and the pit sited adjacently to the river channel at the distance of about 70 m upstream from the site gauging a river stage. Tensiometers were set up to measure the hydraulic head, each one at the depths of 20, 40 and 60 cm and they were sited at the distance of 3.5 m upward from the pit. And thermister probes were also laid to measure ground temperature each one at the depths of 20 and 60 cm at the same site (Fig. 12).

The hydrographs for 12 events of rainstorms are obtained during the period from July 1984 to October 1985. Quick responses to rainfall were consisted nearly in the overbedrock subsurface flow as the storm runoffs characterized by Bankei River and the discharges of the superficial subsurface flow measured

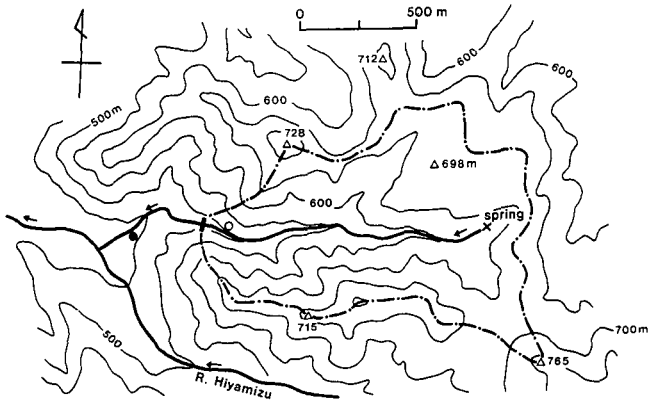

Fig. 12. Topography of the subjected drainage basin and experimental plot of hillslope in Hiyamizu River, open circle and solid circle indicated respectively the sites of pit and recording rainfall and chain line shown the divide on measured site of river discharge.

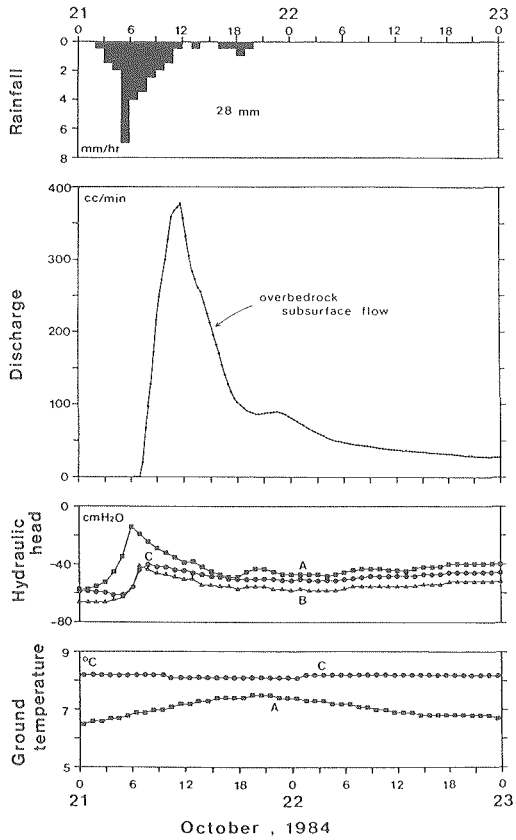

Fig. 13. Quick response of subsurface flow to rainfall under wet condition in the soil mantle and the variations of hydraulic head and ground temperature.

were slight or sometimes little, but no the middle subsurface flow was observed. The typical examples indicating the difference between wet and dry conditions in the soil mantle are shown in Figs. 13 and 14. It is noted that in case of the storm event in October 1984 under a wet condition, only the overbedrock subsurface flow occurs in a rapid response because the vertical path become more permeable as the result of the wet conditions of the soil mantle. And for the dry condition in the soil mantle, the superficial subsurface flow was occurred in advance of the overbedrock subsurface flow in July 1985 as shown in Fig. 14.

Meanwhile, the base flow for a river runoff is supported only by the rock matrix flow discharged through the joints in a bedrock after the overbedrock subsurface flow of quick response to a rainstorm.

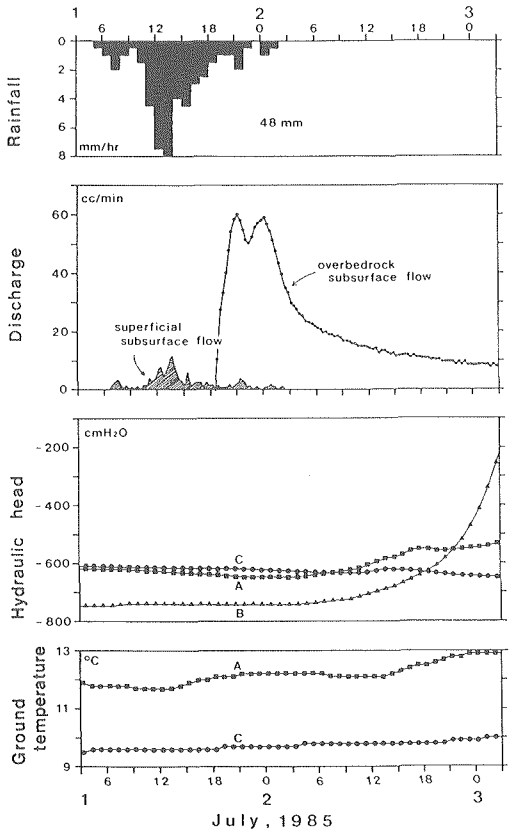

Fig. 14. Quick response of subsurface flow to rainfall under dry condition in the soil mantle and the variations of hydraulic head and ground temperature.

4. Conclusions

In the response to a rainstorm, the quick runoff from forested hillslopes was found to be mainly the overbedrock subsurface flow on the surface of a bedrock in the drainage basins convered by the soil mantle thinner than 2 m thickness. The characteristics of the overbedrock subsurface flow are summarized as follows ; the percolated water flows vertically through the quick path with the angular gravels resulting from a landslide accumulated inhomogeneously in a soil mantle and the lateral subsurface flow discharges to a stream channel through the thin permeable layer on the surface of a bedrock.

While, during the early snowmelt season the ground surface was almost

entirely covered with a snow in the basin. Then, the average runoff ratio of the overbedrock subsurface flow was estimated with 80% and that of the saturated overland flow under a snow cover was 20% for the total quick runoff. Considering the steep depression curve of a hydrograph, the overbedrock subsurface flow is judged to be phreatic and saturated gravity flow.

The thin permeable layer overlying on a bedrock is become more permeable by washing fine soil materials and it is suggested that the landslide is occurred by the unstable condition of the soil mantle during long years.

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References

Chorley, R.J., 1978. The hillslope hydrological cycle. In: M.J. Kirkby (Editor), Hillslope Hydrology, Wiley, New York, N.Y., 1-42.

Fletcher, J.E., K. Harris, H.B. Peterson, and Y.N. Chandler, 1954. Piping. Trans. Am. Geophys. Union, **35**, 258-262.

Freeze, R.A., 1967. Quantitative interpretation of regional groundwater flow patterns as an aid to water balance studies. Int. Assoc. Sci. Hydrol., Publ. No. **76**, 154-173.

Hewlett, J.D., 1961a. Watershed management. In: Report for 1961 Southeastern Forest Experiment Station, U.S. For. Serv., Asheville, N.C.

Hewlett, J.D., 1961b. Soil moisture as a source of baseflow from steep mountain watersheds. U.S. For. Serv., Asheville, N.C., Southe. For. Exp. Stn., Pap. No. **132**.

Ishii, Y. and K. Nakao, 1981. Control of groundwater runoff by a seasonal variation in the river stage. Geophys. Bull. Hokkaido Univ., **40**, 31-45 (in Japanese with English abstract).

Ishii, Y., 1990. Runoff characteristics of subsurface flow from forested hillslopes in headwaters, Geophys. Bull. Hokkaido Univ., **53**, 1-24 (in Japanese with English abstract).

Iwagaki, Y. and T. Sueishi, 1954. On the unsteady flow in open channels with uniform lateral inflow — hydraulic studies on the run-off phenomena of rain water, 1st report —. J. Japan Soc. Civ. Eng., **39**, 575-583 (in Japanese with English abstract).

Kirkby, M.J. and R.J. Chorley, 1967. Throughflow, overland flow and erosion. Bull. Int.

Assoc. Sci. Hydrol., **12**, 5-21.

Kishi, T. and K. Nakao, 1962. Run-off from rainfall for the Toyohira River. Bull. Fac. Eng., Hokkaido Univ., **28**, 45-77 (in Japanese with English abstract).

Nakao, K., 1971. A hydrological study on the stability of water-level of a lake or a swamp. Geophys. Bull. Hokkaido Univ., **25**, 25-87 (in Japanese with English abstract).

Nakao, K., Y. Ishii, and H. Nishida, 1987. Characteristics of subsurface stormflow from forested hillslopes in Hokkaido, Japan — Overbedrock subsurface flow —. In: T. Kishi (Organizer), Comparative Hydrology of Rivers in Japan, Final Report, Grant-In-Aid for Scientific Research, 31-50.

Penman, H.L., 1956. Estimating evaporation. Trans. Am. Geophys. Union, **37**, 43-50.

Sueishi, T., 1955. On the run-off analysis by the method of characteristics — hydraulic studies on the run-off phenomena of rain water, 2nd report —. Proc. Japan Soc. Civ. Eng., **29**, 74-87 (in Japanese with English abstract).

Tanaka, T., M. Yasuhara, and A. Marui, 1982. Pulsating flow phenomenon in soil pipe. Ann. Rep., Inst. Geosci., Univ. Tsukuba, No. **8**, 33-36.

Toth, J., 1962. A theory of groundwater motion in small drainage basins in central Alberta, Canada. J. Geophys. Res., **67**, 4375-4387.

Troendle, C.A. and J.W. Homeyer, 1971. Stormflow related to measured physical parameters on small forested watersheds in West Virginia. Trans. Am. Geophys. Union, **52**, 204 (abstract).

Ward, R.C., 1984. On the response to precipitation of headwater streams in humid areas. J. Hydrol., **74**, 171-189.