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Effects of weathered granitic bedrock on runoff processes in a small headwater catchment

Ken'ichirou KOSUGI[1]

1 Department of Forest Science, Graduate School of Agriculture, Kyoto University, Kyoto, Japan: kos@kais.kyoto-u.ac.jp

Abstract Recent studies have suggested large influences of bedrock groundwater on runoff generation, water chemistry, and landslides occurrences in headwater catchments. In order to clarify physical water flow process between soil and shallow bedrock, and its effect on storm and base-flow discharge processes in a small headwater catchment underlain by weathered granite, this study conducted hydrometric observations using soil and bedrock tensiometers combined with numerical simulation analyses. Results showed that, in an unchanneled 0.024-ha headwater catchment, saturated and unsaturated infiltration from soil to bedrock is a main hydrological process at the soil-bedrock interface. Annual bedrock infiltration ranged 35 to 55% of annual precipitation and increased as precipitation increased, suggesting a large potential of bedrock infiltration, which was partly explained by a large buffer capacity of soil layer overlying the bedrock. Physical property of soil layer was an important factor to control generations of bedrock infiltration and saturated lateral flow over the bedrock.

Key words storm runoff, baseflow, forest soil, bedrock, numerical simulation, granite

INTRODUCTION

Recent researches have demonstrated the importance of shallow bedrock flow in headwater catchments with any kinds of geologic characteristics. These studies have indicated great contribution of bedrock groundwater to storm runoff generation [e.g., *Wilson et al.*, 1993] as well as base flow discharge [e.g., *Mulholland*, 1993]. Many studies have pointed out that bedrock groundwater flow plays a significant role in occurrence of landslides [e.g., *Montgomery et al.*, 2002]. Moreover, water flow through bedrock is closely related to solute transport and water chemistry in headwater catchments [e.g., *Katsuyama et al.*, 2004]. Thus, it is essential to clarify hydrological interaction between soil and shallow bedrock and water flow processes in the bedrock for modeling runoff generation and water chemistry, and predicting time and location of landslide initiation.

The objective of this study is to clarify the physical water flow process between soil and shallow bedrock and within the bedrock, and its effect on storm and base-flow discharge processes in a small headwater catchment underlain by weathered granite. For this purpose, hydrometric observations using soil and bedrock tensiometers are combined with numerical simulation analyses. Based on the results, we examine the importance of soil-bedrock interaction on hydrological processes in head water catchment.

METHOD

Study Site

Field observations were conducted at the Kiryu Experimental Watershed (WK; 5.99 ha; Fig. 1a), located in the southern part of Shiga prefecture, central Japan (34º58'N, 136º00'E). The climate is warm temperate, with rainfall distributed year round, peaking in summer, but producing little snowfall in winter. The mean annual precipitation from 1972 to 2002 was 1630.0 mm. The mean annual air temperature from 1997 to 2002 was 13.9ºC. We selected a 0.086-ha catchment named Akakabe Watershed (WA) within WK for discharge measurements (Figs. 1a and 1b), and an unchanneled 0.024-ha headwater catchment (WS) in WA for an intensive monitoring (Fig. 1b).

WK is covered with a closed forest mainly consisting of Japanese cypress (*Chamaecyparis obtusa*) and oak (*Quercus serrata*). Whole WK is underlain by granitic bedrock called Tanakami Granite. WA is predominantly covered with Japanese cypress planted in 1959. A stonemasonry dam exists in the catchment, which was constructed about 75 to 95 yeas ago for preventing sediment discharge (Fig. 1b). A spring outflow points, existing below the dam, recharges a perennial stream channel. Sediment had deposited in the upslope area from the dam, with a thickness up to 175 cm. A perennial groundwater exists in this sedimentation area. The area upstream from the sedimentation area consists of two unchanneled head water catchments, one of which is WS. Below the outlet of WS, a pit was excavated to observe a profile from soil through the weathered bedrock, and to take soil and rock samples for hydraulic property measurements (Fig. 1b).

Figure 1c shows the longitudinal section along the hollow of WS indicated by the line A–B in Fig. 1b. A penetration test was conducted at 5 points along the hollow, by using a cone-penetrometer with a 60º bit, a cone diameter of 30 mm, a weight of 5 kg, and a fall distance of 50 cm. From the results of the penetration test, we computed N_c value which represents the number of blows required for a 10-cm penetration. Based on investigations in granite mountains, previous studies [e.g., *Okunishi and Iida*, 1978] have found that N_c of 50 can be a rough index for the boundary between soil and bedrock. The penetration test produced a sudden increase in N_c, indicating the depth of soil-bedrock interface (Fig. 1c). The soil thickness was small in crest, large in middle slope part, and very small around the outlet of WS.

Laboratory tests using the soil samples (100 cc in volume) collected at the pit showed that soils 15- and 30-cm deep from soil surface have the saturated hydraulic conductivity of 0.0507 cm/s with a standard deviation of 0.0216 cm/s (n = 4). Water retention curves observed for the soil samples had large changes in the volumetric water content θ in the region where the pore water pressure head, ψ, was greater than about -50 cmH_2O, suggesting large water holding capacities of soils near saturation.

Hydrological Observations

Precipitation was measured using a 0.5-mm tipping bucket rain gauge at the meteorological station located at the center of WK (the open square in Fig. 1a). The discharge rate at the outlets of WK and WA were measured by using weirs with 90- and 30-degree triangular notches, respectively (Figs. 1a and 1b). At the outlet of WS, the soil thickness was less than 20 cm (Fig. 1c), and we dug a trench over the weathered bedrock and installed an impermeable wall 20 cm high and 160 cm wide for collecting discharge from the soil layer (Figs. 1b and 1c). The collected water flows through a PCV pipe to a 200-cc tipping bucket gauge situated in the sedimentation area in WA (Fig. 1b).

Pore water pressures in soil profiles were measured at seven points (T1 through T7 in Fig. 1c) by using tensiometers (DIK-3150, Daiki Rika Kogyo, Tokyo, Japan). At each point, the deepest tensiometer measured the pressure over the weathered bedrock. At T3, T5, and a point between T6 and T7 (T6a in Fig. 1c), tensiometers (DIK-3151, Daiki Rika Kogyo, Tokyo, Japan) were installed in the weathered bedrock. Electric hammer drills (GBH 3-28FE, BOSCH, Yokohama, Japan) equipped with a drill bit (HEX 190 100, Miyanaga, Hyogo, Japan) were used to make holes in the bedrock, since the bedrock was too hard to be drilled with a hand auger penetration. After the tensiometers were inserted in the drill holes, space between the rock and tensiometer pipes was filled with epoxy resin or impermeable cement. Whole of the 32 tensiometers were automatically measured. The recording interval of all meteorological and hydrometric data was 10 minutes.

RESULTS

Hyetograph and Hydrographs

The total precipitation in the discharge observation period (i.e., May 10, 2002 through Dec. 31, 2003) was 2778 mm. In the same period, total discharge from WK and WA were 1352 and 1205 mm, respectively. That is, the total discharge from WA was about 89% of that from WK. During the summer in 2003, we had more precipitation than we did during the summer in 2002 (Fig. 2a), which resulted in the large base flow discharge of both WK and WA (Figs. 2b and 2c, respectively). The base flow discharge of both WK and WA never disappeared even in the dry summer in 2002 nor during the dry winter season. On the other hand, we never observed base flow discharge from WS. Hydrographs of WS were peaky corresponding to the rainfall peaks (Fig. 2d), and the discharge always disappeared within 12 hours after the rainfall stopped.

Figure 3a shows the relationship between total rainfall and total storm discharge from WS for each storm event. In this study, we assumed that storm events are separated by no-rain period of 12 consecutive hours, and defined the end of each storm as the time point 12-hours after the rain stopped. In Fig. 3a, the total storm discharge is equal to the whole discharge from WS, since the discharge always disappeared within 12 hours after the rainfall stopped as mentioned above. The figure indicates that the total discharge was always smaller than about 5% of the total rainfall. This result contrasts to the results in Fig. 3b which shows the relationships between total rainfall and total storm discharge from WK and WA. For these watersheds, the total storm discharge were greater than 5% of total rainfall for many storm events, and increased up to about 30%. It is noted that the storm discharge for WK and WA was assumed as the increment of discharge from the initial discharge, since the both watersheds had consecutive base flow discharge. As a result of Fig. 3, WS had much less storm discharge than WA and WK, suggesting a large water loss in WS caused by infiltration into the weathered bedrock.

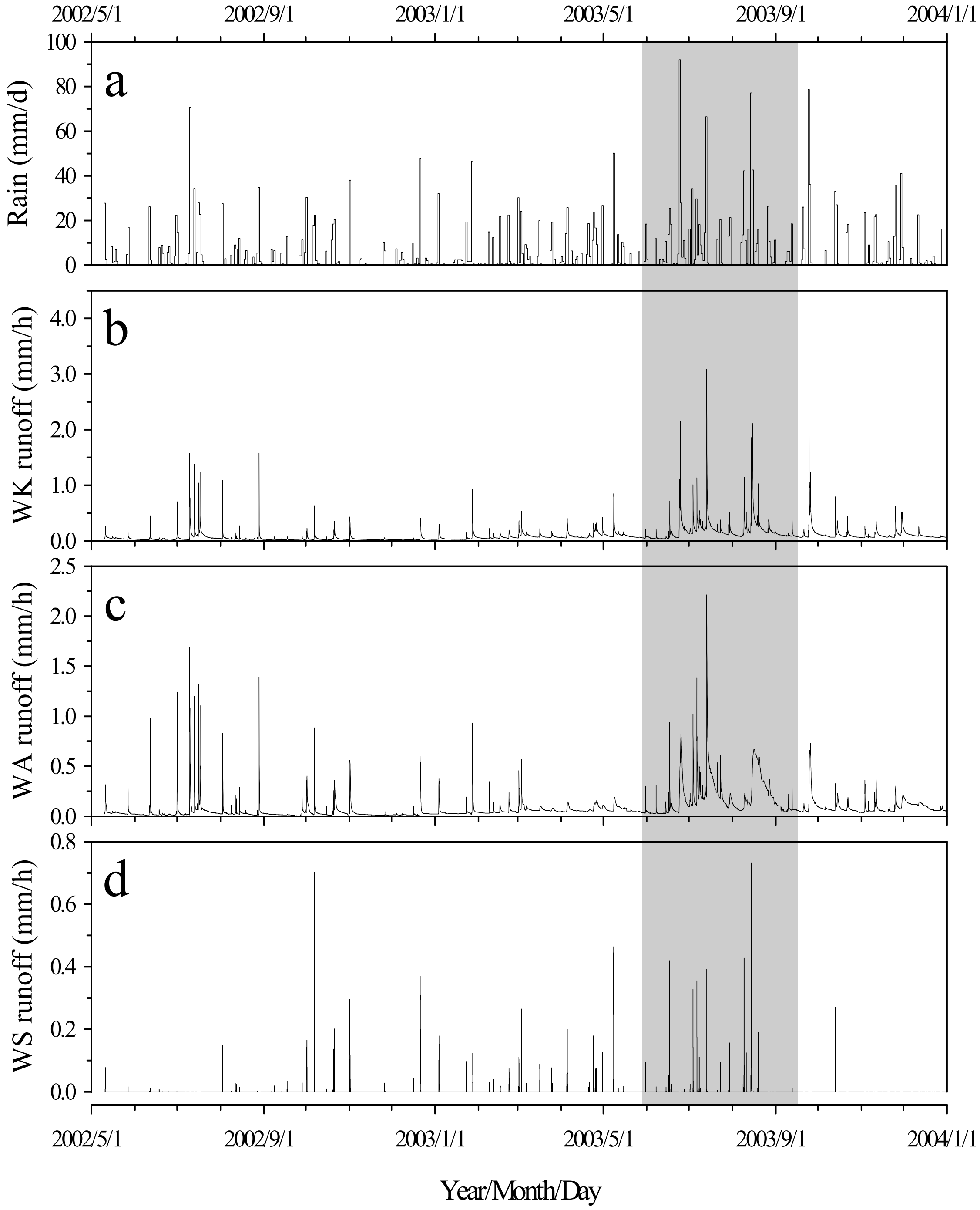

Fig. 2 (a) Hyetograph and hydrographs from (b) WK, (c) WA, and (d) WS. The shaded period corresponds to the tensiometric observation periods shown in Fig. 4.

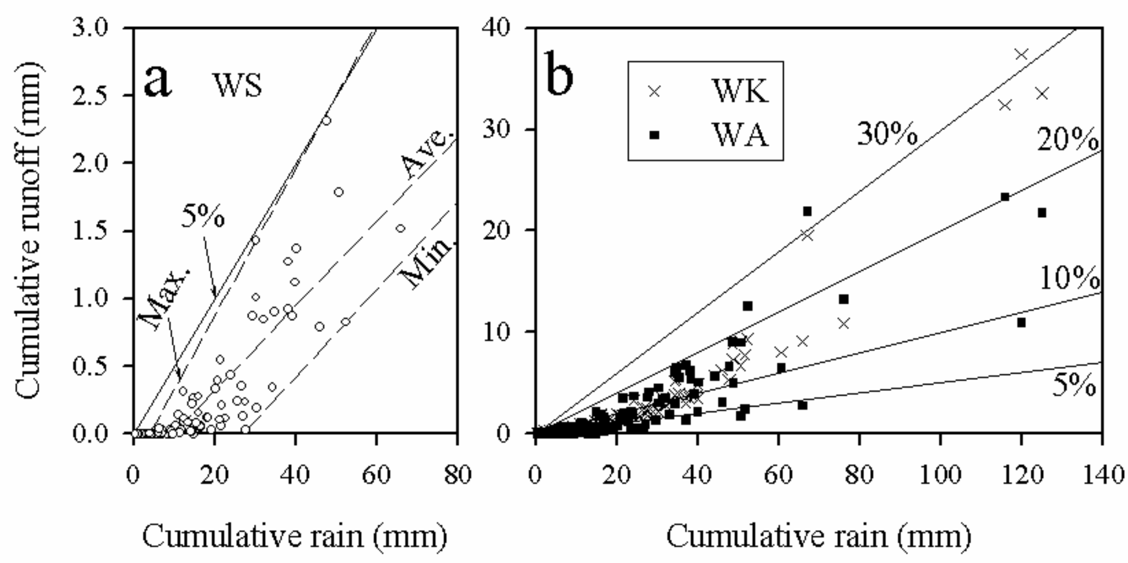

Fig. 3 Relationships between total rainfall and total storm runoff for (a) WS and (b) WK and WA. Solid lines indicates runoff ratios.

Tensiometer Responses

Figure 4c shows rapid and peaky responses of pore water pressures over the weathered bedrock at the points T1 through T3, which can be attributable to the small soil thicknesses at these points (Fig. 1c). The tensiometers frequently observed positive pressures indicating generations of tentative saturation zones. On the other hand, the points T4 through T7 had relatively large soil thicknesses (Fig. 1c), and Fig. 4d shows gentler responses of pore water pressures over the weathered bedrock at these points than those shown in Fig. 4c. Especially at the points T5 and T6, the soil thicknesses were the largest, and the pore water pressures did not took positive values during the whole observation period.

At all depths and all observation points, pore water pressures in the weathered bedrock exhibited substantial changes corresponding to storm events (Figs. 4e through 4g). While some pressures took positive values under heavy storm events, pressures at some points decreased below -200 cm under dry conditions. These results support the finding in Fig. 3 that WS has large water loss by infiltration into the weathered bedrock. Moreover, Figs. 4e through 4g indicate occurrences of both saturated and unsaturated water flow in the weathered bedrock.

At each point of T3, T5, and T6a, the pore water pressures in the shallow bedrock (i.e., 10 to 40 cm deep from the soil-bedrock boundary) generally had similar responses to the pore water pressure over the weathered bedrock (indicated by the gray lines in Figs. 4e through 4g). That is, the time series of pore water pressure in the weathered bedrock is greatly affected by infiltration processes in the overlying soil layer.

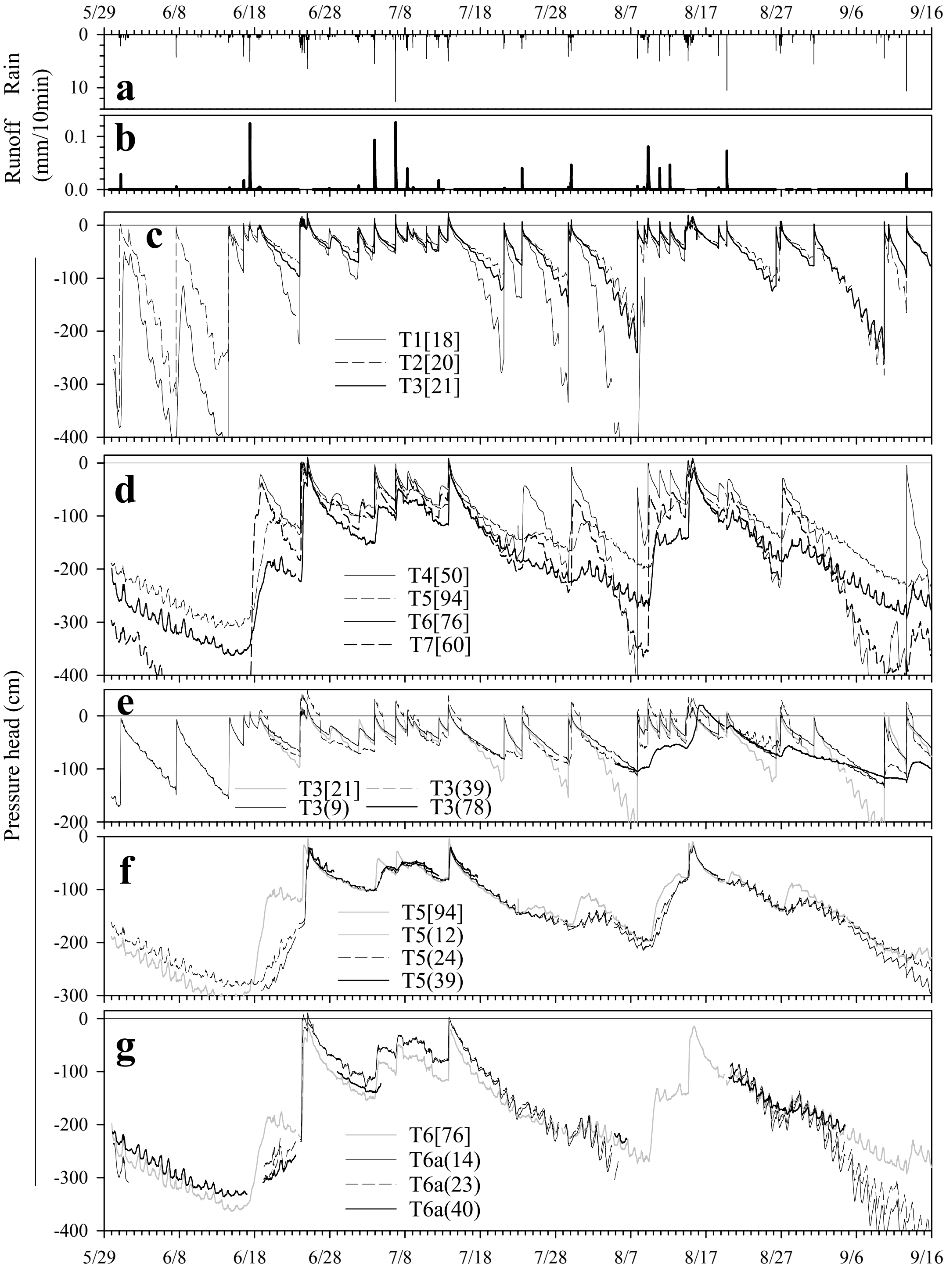

Fig. 4 (a) Hyetograph, (b) hydrograph from WS, pore water pressures over weathered bedrock at points (c) T1 through T3 and (d) T4 through T7, and pore water pressures in weathered bedrock at points (e) T3, (f) T5, and (g) T6a. Points and depths for tensiometer installation are summarized in Fig. 1c. Gray lines in Figs. 4e through 4g represent pore water pressures over the weathered bedrock. In Figs. 4c through 4g, square-bracketed numbers represent depths of soil tensiometers measured from soil surface(in cm). In Figs. 4e through 4g, parenthesized numbers represent depths of bedrock tensiometers measured from soil-bedrock interface (in cm).

NUMERICAL SIMULATION

Method of Simulation

Based on the results of the field hydrological measurements, numerical simulations for saturated and unsaturated water flow were conducted for analyzing rainwater infiltration and discharge processes at a forested hillslope underlain by permeable bedrock. Two-dimensional Richards' equation was solved numerically by using the finite element method assuming triangle elements. The entire calculation domain is shown in Fig. 5. An observed storm hyetograph was supplied to the soil surface. The hyetograph was observed at Nagoya Japan, on 11 to 12 September 2000, having the total precipitation of 566.5 mm. We also examined the case that the observed rainfall intensities were decreased to one-fourth. The soil thickness was fixed at 0, 1, or 2 m. Then, the seepage from bedrock, saturated through flow from soil, and overland flow were computed. The hydraulic properties of the soil and bedrock layers were fixed at the observed characteristics as described in Katsura et al. [2006].

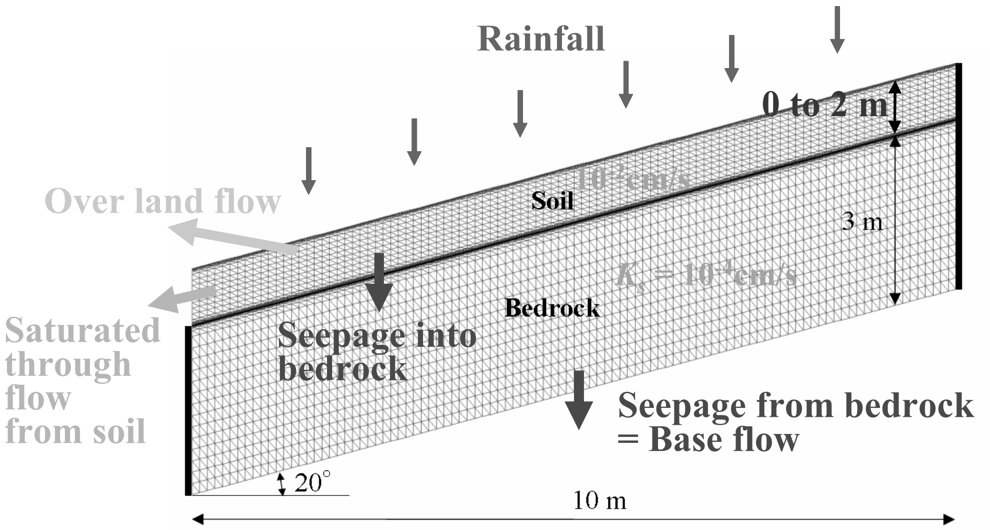

Fig. 5 Slope and triangle elements assumed for numerical simulations (case of 1-m soil thickness).

Results of Numerical Simulation

Figure 6 shows how the spatial distribution of matric pressure changed during the storm event. The figure showed the results when the soil thickness was 1 m and the observed hyetograph was applied. Just after the peak rainfall occurred, the soil layer was unsaturated and had large matric pressure heads (Fig. 6b). Then, 20 minutes after, a saturated zone was formed above the bedrock and the saturated through flow was formed (Fig. 6c). The saturated zone gradually expanded into the bedrock layer (Figs. 6d and 6e).

Figure 7 summarized how the storm water was separated into the overland flow, saturated through flow from soil layer, and seepage from bedrock that was supposed to recharge baseflow. When the rainfall magnification was one-fourth, most of the storm rainfall fed baseflow discharge if a soil layer had a thickness greater than 1 m. Without the soil layer, about 40% of the storm water discharged as the overland flow. When the rainfall magnification coefficient was increased to one, every simulation run produced flood discharge consisting of overland flow and saturated through flow from soil layer. As the soil thickness increased, the flood discharge decreased and baseflow increased. Thus, we conclude that, as the thickness of soil layer increases, the buffer function of the soil layer is enlarged, resulting in increased amount of rainwater infiltration into the permeable bedrock.

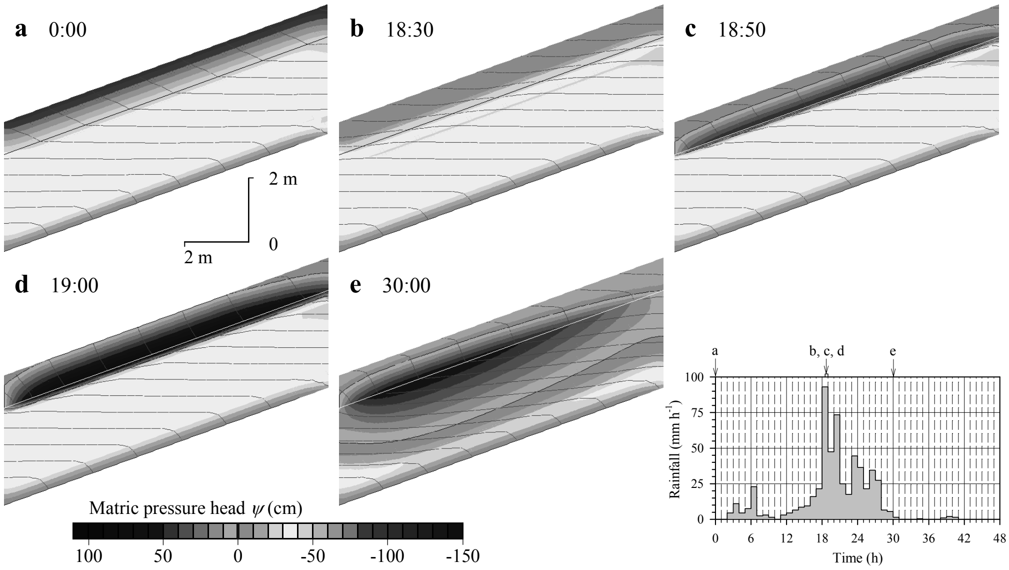

Fig. 6 Simulated matric pressure head for cases of 1-m soil thickness. Black or white line indicates boundary between soil and bedrock. Grey lines are equi-hydraulic head lines with 50-cm intervals.

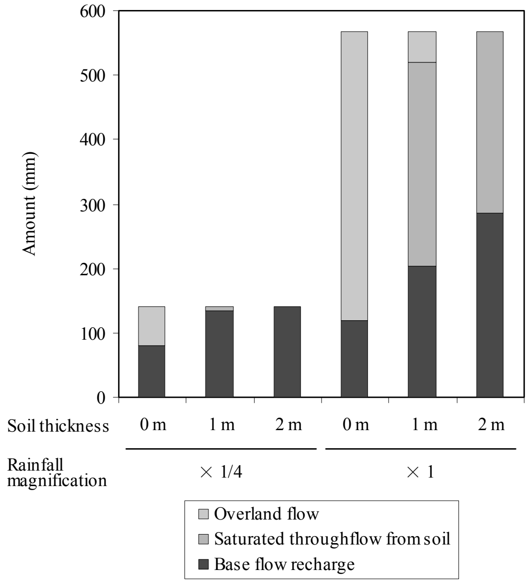

Fig. 7 Separation of input rainfall into overland flow, saturated throughflow from soil, and base flow recharge.

CONCLUSIONS

This study conducted intensive hydrometric observations at watersheds underlain by weathered granite, and numerical simulations on rainwater discharge at a hillslope underlain by a permeable bedrock, revealing the followings:

(1) Base flow discharge both from a watershed of 5.99 ha (WK) and a sub-watershed in WK (WA; 0.086 ha) never disappeared even in dry periods. On the other hand, we never observed base flow discharge from a 0.024-ha headwater catchment (WS) in WA.

(2) The total storm discharge from WS was always smaller than about 5% of the total rainfall, indicating a large water loss in WS caused by infiltration into the weathered bedrock.

(3) Around the outlet of WS, all of rainwater infiltrated into the bedrock by forming unsaturated flows for small storms. Under medium and large storm conditions, the small water-holding capacity of soil layer, which stems from the shallow soil depth, lets the infiltration intensity at the soil-bedrock interface increase, resulting in a formation of saturated zone in the soil layer, causing saturated lateral flow over the bedrock and expansion of the saturated zone into the bedrock, simultaneously. After storms, the saturated zone in bedrock gradually shrinks from the surface, and unsaturated infiltration flux becomes dominant.

(4) In the middle- and up- slope regions in WS, large water-holding capacity of soil layer, which stems from a large soil thickness, results in the large ability as a buffer to reduce infiltration intensity at the soil-bedrock interface. Consequently, whole rainwater infiltrates into the bedrock. Thus, middle- and up- slope regions never become contribution areas for WS discharge, but contribute to the large potential of water loss by bedrock infiltration.

(5) Results of numerical simulation showed that, while an exfiltration from the bedrock sustains base flow discharge, soil layer behaves as a buffer, moderating the infiltration intensity relative to the rainfall intensity and permitting large amount of rainwater to infiltrate into the bedrock.

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