

## **Effect of a permeable bedrock on runoff generation in steep mountainous catchments in the Kanto Mountains, Japan**

**KUNIHIDE MIYAOKA**

*Faculty of Education, Bunkyo University, 3337 Minami-Ogishima, Koshigaya, Saitama 343, Japan*

e-mail: miyaoka@koshigaya.bunkyo.ac.jp

**SHINICHI ONODERA**

*Faculty of Integrated Science, Hiroshima University, 1-7-1 Kagamiyama, Higashihiroshima, Hiroshima 739, Japan*

**TAKASHI HIROSE**

*Faculty of Law and Literature, University of Ryukyus, 1 Senhara, Nishiharamachi, Chuto-gun, Okinawa 903-01, Japan*

**Abstract** We estimated the effect of the permeable bedrock on the runoff generation in two steep mountainous catchments west of Tokyo, using hydrological observation and hydrogeological surveys. Two small catchments, one underlain by granite bedrock, and the other with sedimentary bedrock were studied. Runoff decreased after the first peak in the granite catchment, while it reached 5 times the initial peak value after 6 h in the sedimentary catchment. Runoff ratios were 12% in the granite catchment and 65% in the sedimentary rock catchment. Because the regolith layer is thinner in the sedimentary catchment than in the granite catchment, this observed secondary peak of runoff suggests the existence of significant flow-through fissures. Event water amounts in both catchments were estimated to be very low, using the natural tracers Cl<sup>-</sup> or δ<sup>18</sup>O. These results indicate the contribution of pre-event water to storm runoff. The electrical sounding and infiltration experiments suggest that rainwater percolates into the fractured bedrock, mixes with soil water in the regolith, and discharges quickly in the sedimentary rock catchment.

### **INTRODUCTION**

In order to evaluate storm runoff processes in steep mountainous catchments, it is necessary to estimate the thickness and hydraulic characteristics of the weathered or fractured permeable bedrock. Furthermore, it is necessary to confirm the effect of permeable bedrock on runoff in catchments underlain by different bedrock in terms of understanding the streamflow generation (Montgomery *et al.*, 1997). Because of several inconveniences such as measurement techniques and costs, it is very difficult to determine the hydrogeological structure, especially the bedrock conditions. Miyaoka (1995) constructed a contour map of the bedrock surface in an alluvial fan using electric sounding and existing borehole data, but there are few previous studies which provide a three-dimensional illustration of the bedrock in a mountainous catchment.

Many studies showed contrasting runoff processes, regolith thickness, and topography underlain by different types of bedrock geology in Japan; i.e. Tanaka *et al.*

(1993), Onda (1994), Komatsu & Onda (1996) and Hirose *et al.* (1994). Becker & McDonnell (1998) suggested the role of bedrock topography in runoff generation. Based on these previous studies, it is necessary to consider the geological structure of bedrock, especially weathered and fractured permeable bedrock, and the contribution of groundwater flow in the permeable bedrock to storm runoff in steep mountainous catchments.

In this study, we estimated the effect of a permeable bedrock layer on runoff generation in steep mountainous catchments using physical surveys and tracer methods.

## EXPERIMENTAL SITE AND METHODS

The experimental small catchments are located in the Kanto Mountains west of Tokyo (Fig. 1). They are source areas of the Tama River, which flows into Tokyo Bay and supplies the metropolitan city.

Runoff was measured in two experimental small catchments; one is underlain by granites with a slope of above  $40^\circ$  (G-cat.), and the other is underlain by sedimentary rocks with above  $50^\circ$  (S-cat.) slopes (Fig. 2). The areas of G-cat. and S-cat. are about  $0.2 \text{ km}^2$ . Rainwater and runoff water were collected. Stream water and rainwater were collected intensively during the storms on 20 June and 26 July 1997. Chemical components or isotopic compositions of water samples were analysed. In this study,  $\text{Cl}^-$  or  $\delta^{18}\text{O}$  was used as the tracer. Amount of event water was estimated by the two component separation method using  $\text{Cl}^-$  concentration (Onodera, 1993).

Penetration tests and electrical sounding were carried out at seven plots in each catchment by the dynamic cone penetrometer and four poles method, respectively (Fig. 2). The values for the basement rocks were estimated by electrical sounding by the measurements at the plots in front of the outcrops in as well as at the outcrop. In addition, infiltration capacity experiments on the permeable bedrock of the outcrop were conducted.

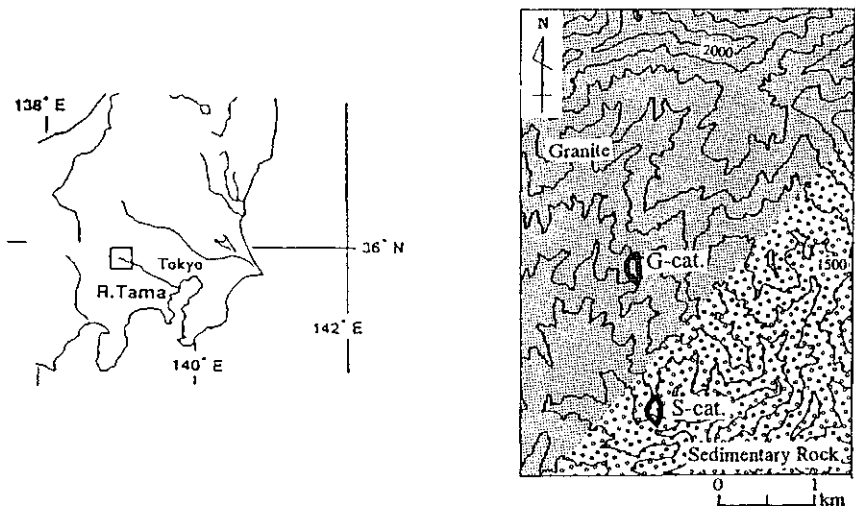


Fig. 1 Location of small experimental catchments and distribution of bedrock geology.

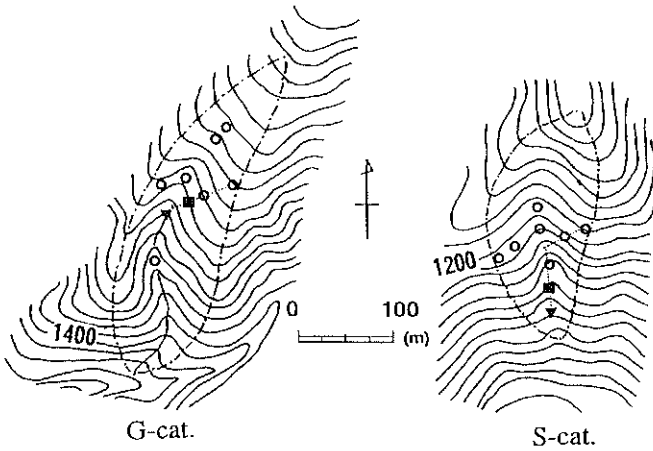


Fig. 2 Location of measurement points in each catchment.  $\nabla$ : weir,  $\blacksquare$ : observation site,  $\circ$ : electrical sounding point.

## RESULTS AND DISCUSSION

### Runoff characteristics

Figure 3 shows temporal variations in rainfall amount and stream runoff at the G-cat. and S-cat. during the 85-mm rainfall event on 26 July 1997. Peak runoff occurred at each catchment just after peak rainfall intensity. Runoff amount decreased after the peak in the granite catchment, while in the sedimentary catchment reached it the maximum 6 h since the first peak. The amount of the secondary peak is 5 times the value of the first peak, and the duration of the secondary peak is longer than the first peak in S-cat. Runoff ratios in each catchment were 12% in G-cat. and 75% in S-cat.

Figures 4 and 5 show the variations in Cl<sup>-</sup> concentration in July 1997 and of  $\delta^{18}\text{O}$  at the 120-mm rainfall event on 20 June 1997 for rainwater and stream water, respectively.

The Cl<sup>-</sup> concentration of rainwater ranges from 0.05 to 0.15 mg l<sup>-1</sup>, whereas the Cl<sup>-</sup> concentration of stream water is approximately constant at 0.54 mg l<sup>-1</sup> in S-cat. The  $\delta^{18}\text{O}$  of rainwater ranges from -12.1 to -8.4‰, while the value for stream water is constant at -10.7‰ in G-cat. The observed results indicate that the contribution rate of

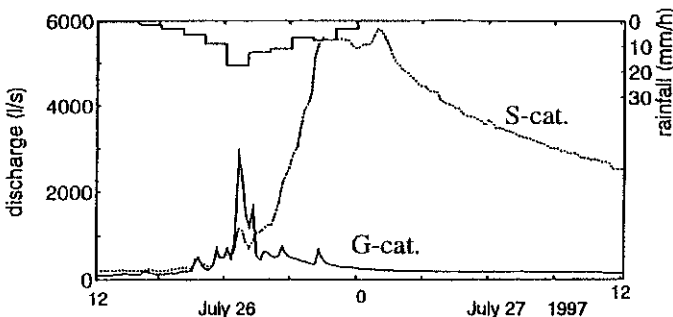


Fig. 3 Hydrographs for G-cat. and S-cat.

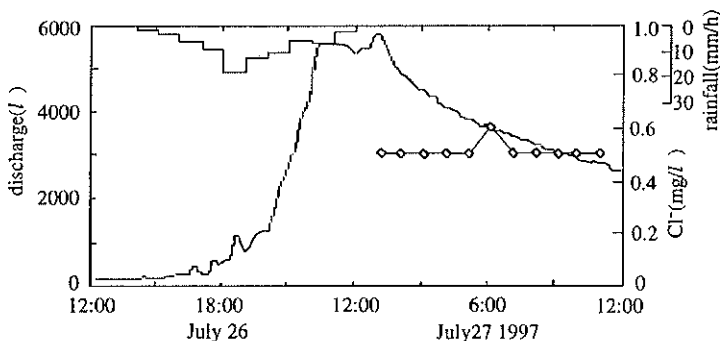


Fig. 4 Variation in  $\text{Cl}^-$  concentration of rainwater and stream water in S-cat for the 85-mm rainfall event on 26 July 1997.

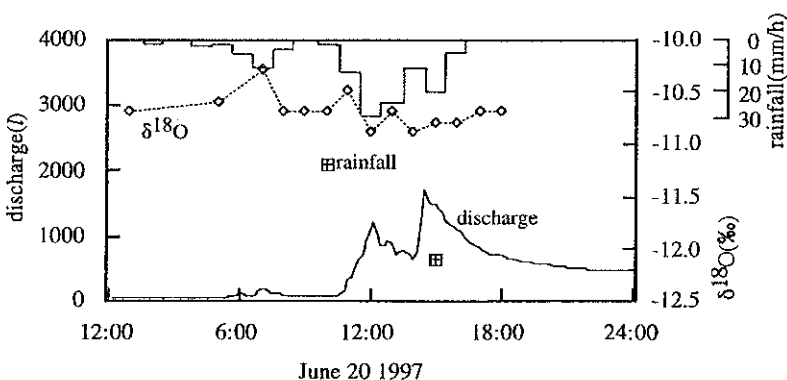


Fig. 5 Variation in  $\delta^{18}\text{O}$  of rainwater and stream water in G-cat for the 120-mm rainfall event on 20 June 1997.

rainwater (new water) to storm runoff is extremely low in both S-cat. and G-cat. Furthermore, these results suggest that rainwater constantly mixes with subsurface water, and subsurface water contributes to storm runoff.

### Subsurface hydrogeological structure

The results of infiltration capacity experiments and penetration tests on the nose slope in each catchment are shown in Fig. 6. The regolith layers in each catchment are separated into A, B, and C layers. The depth to the bedrock surface estimated by a penetration test is about 200 cm in S-cat., and about 330 cm in G-cat. The longitudinal profiles of the depth to the bedrock surface in each catchment show a thickness of less than 2 m at the middle of the slope in G-cat., and less than 1 m in S-cat., and less than 0.5 m at the foot of the slope. The regolith layer is thinner in the sedimentary catchment than in the granite catchment. The infiltration capacity of the regolith layer ranges from  $10^{-2}$  to  $10^{-1}$   $\text{cm s}^{-1}$ , and it is relatively better in the granite catchment than in the sedimentary catchment. Furthermore, the values of the bedrock estimated by the penetration test in each catchment are around  $10^{-1}$   $\text{cm s}^{-1}$ . According to observations of the outcrops and soil profiles in the trenches, the bedrock is confirmed to be weathered in G-cat. and fractured in S-cat.

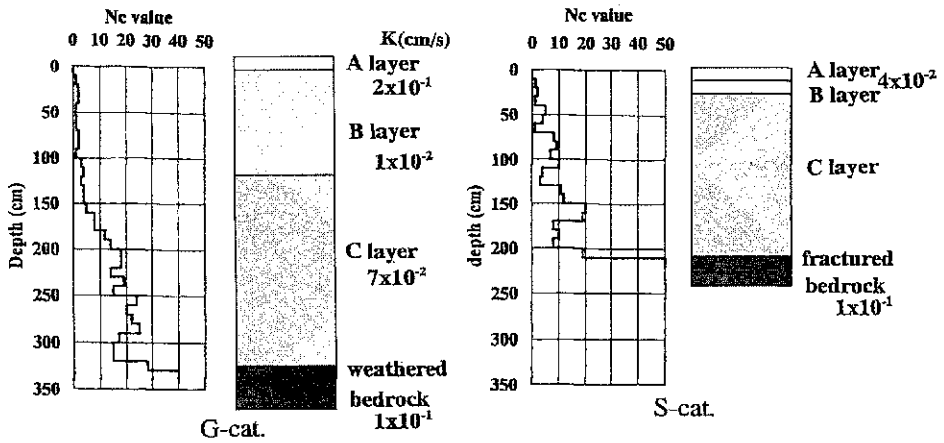


Fig. 6 The results of infiltration capacity experiments and penetration tests in each catchment.

The subsurface hydrogeological structure in each catchment estimated by penetration tests and electrical soundings are shown in Fig. 7. The electrical soundings could reach the deeper geological boundary, which is suggested to be the hydrological

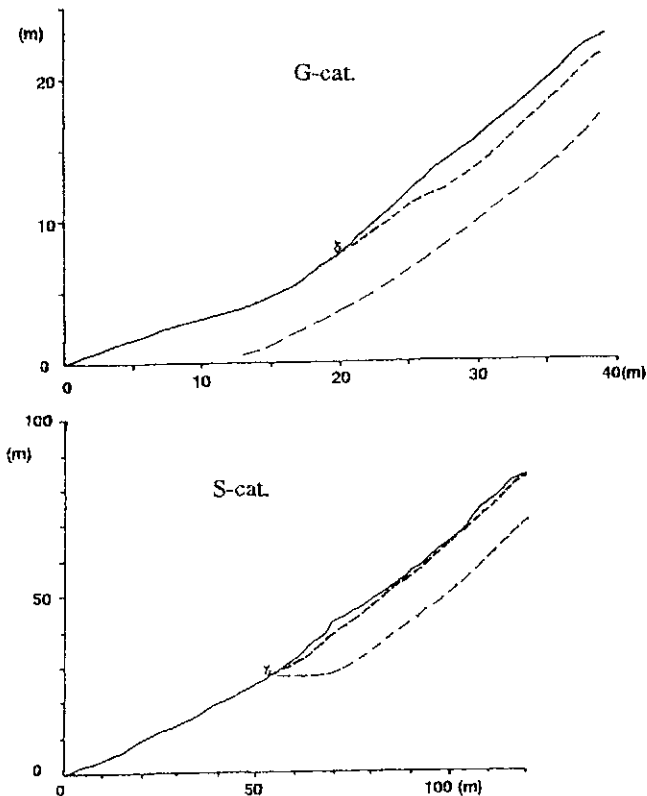


Fig. 7 The subsurface hydrogeological structure. ----- boundary of A, B layer and C layer, - - - - - boundary of C layer and basement rock.

basement by the electrical soundings at the outcrops. The thickness of the permeable bedrock was around 10 m on the slope of each catchment. These results suggest that rainwater percolates into the permeable bedrock after mixing with soil water in the regolith, then it mixes with groundwater in the permeable bedrock. The permeable bedrock in G-cat. is the porous medium, and more water is retained and stored than in S-cat. In addition, the thickness of the regolith layer is deeper in G-cat. than it is in S-cat. These facts suggest that after rainwater mixes with groundwater, the groundwater seeps out gradually in G-cat., whereas it discharges quickly in S-cat.

## CONCLUSIONS

The results of this study are summarized as follows:

- (a) Runoff ratios were 12% in G-cat. and 75% in S-cat. The event water rates in both G-cat. and S-cat. were very low. These results indicated contrasting runoff processes influenced by the different bedrocks and the contribution of subsurface water to storm runoff.
- (b) The thickness of the permeable bedrock was around 10 m on the slopes of each catchment. Furthermore, the permeability of both the fractured bedrock in S-cat and the weathered bedrock in G-cat. were  $10^{-1} \text{ cm s}^{-1}$ . These results suggested that rainwater mixed with groundwater in the permeable bedrock after percolating into the permeable bedrock with mixing with soil water in the regolith, and groundwater discharged quickly in S-cat. in contrast with gradual discharge in G-cat., in which the permeable bedrock is a porous medium.

**Acknowledgement** We give special thanks to Mr T. Noda and Mr T. Naruoka for cooperation concerning the field observations and to Mr M. Mashima for support concerning the observation station. This research was funded by the Tokyo Environmental Foundation, Japan.

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