Integrated Methods in Catchment Hydrology—Tracer, Remote Sensing and New Hydrometric Techniques
(Proceedings of IUGG 99 Symposium HS4, Birmingham, July 1999). IAHS Publ. no. 258, 1999.

Hydrometric and tracer approaches to investigate rainfall–runoff processes in mountainous basins with different geologies

MAKI TSUJIMURA
Department of Environmental Earth Sciences, Aichi University of Education, Kariya, Aichi 448-8542, Japan
e-mail: mktsuji@auecc.aichi-edu.ac.jp

YUICHI ONDA, JUN'ICHI FUJIWARA
School of Agricultural Sciences, Nagoya University, Nagoya, Aichi 464-8601, Japan

JUN ITO
Department of Environmental Earth Sciences, Aichi University of Education, Kariya, Aichi 448-8542, Japan

Abstract Hydrometric and tracer approaches have been applied to investigate the rainfall–runoff process in two headwater basins underlain by shale and granite. Four small basins were monitored; two in shale and two in granite. The rainfall peak was followed by the runoff peak in the shale basin, whereas peak runoff coincided with rainfall peak in the granite basin. Tensiometric data from hillslopes indicate that subsurface water percolated into the bedrock even during the rainstorm in the shale basin, whereas lateral saturated subsurface flow was often observed during heavy rainstorms in the granite basin. Considering the isotopic data from water, subsurface flow with relatively long residence times through the bedrock should be dominant so that the delayed runoff response was observed during the rainstorm in the shale basin, whereas lateral subsurface stormflow in the soil mantle should be dominant so that the quick response of runoff was observed during rainstorms in the granite basin.

INTRODUCTION

Understanding of the storm runoff water component in headwater basins has been improved by traditional methods for separating the storm hydrograph (Sklash & Farvolden, 1979; Pearce *et al.*, 1986; Sklash *et al.*, 1986; DeWalle *et al.*, 1988). In many cases, separating the storm hydrograph into event and pre-event water has been conducted using the stable isotopic composition of rainfall and stream water as a tracer. However, subsurface flow processes in the regolith and bedrock cannot be well understood using only the tracer approach, and the isotopic evolution of subsurface water during storms has not been well investigated (Stewart & McDonnell, 1991; Bazemore *et al.*, 1994; Tanaka & Ono, 1998; Tsujimura *et al.*, 1998). For a better understanding of the runoff process, hydrometric and chemical data must be combined.

Because the rainfall–runoff processes depend upon site specific conditions such as lithology of the bedrock, physical characteristics of the soil, vegetation, and climate, data concerning the relationship between runoff processes and site conditions should be collected from mountainous basins with different site conditions. However, there is a paucity of field data on rainfall–runoff processes in steep mountainous terrain. As the depth of the regolith is very thin in these areas, the physical properties of the bedrock of the basin has an important role in the rainfall–runoff process. Onda (1994) conducted a hydrological observation in two headwater basins underlain by Palaeozoic sedimentary rock and granite, and found the runoff characteristics were quite different in the two basins. He stated that the subsurface flow process in the bedrock is important in the rainfall–runoff process, though there were insufficient data to identify the different flow mechanisms.

The purpose of this study is to compare the rainfall–runoff processes in two steep mountainous basins, one underlain by shale, the other by granite, based on field data acquired from the hydrometric and tracer observations. Additionally, we seek to clarify the relationship between the runoff process and the bedrock lithology of the basin.

STUDY AREA AND METHODS

The study was conducted in a mountainous region located in the Ina district, Nagano prefecture, central Japan. Four small basins were monitored: two (K1 and K6) underlain by shale and two (Y1 and Y2) underlain by granite. The drainage areas are 7.1 ha, 0.78 ha, 3.8 ha, and 1.04 ha, respectively. Relief ratios in K1 and K6 are 0.84

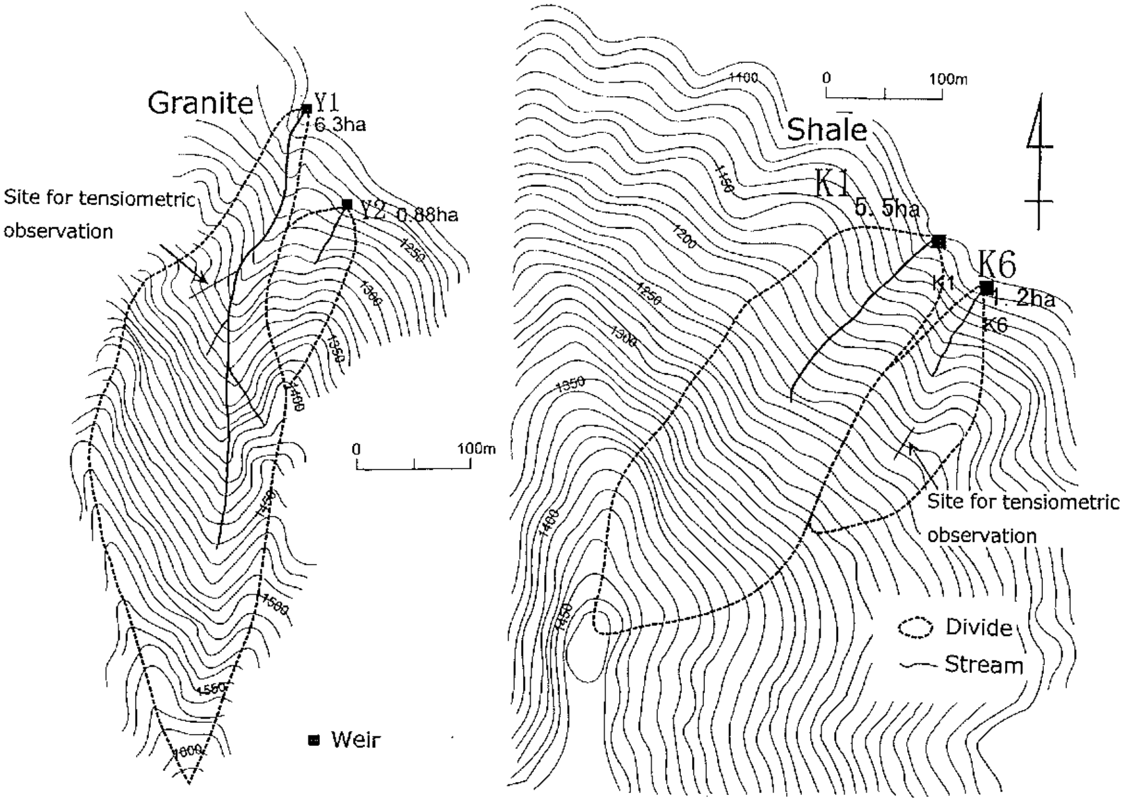

Fig. 1 Topographical map of each basin.

and 0.97 and those in Y1 and Y2 are 0.67 and 0.73. There are no riparian zones in either basin. The catchments are steep (>40°) and forested, and are covered by a 0.6–1.5 m mantle of soil as revealed by sounding tests. Laboratory measurements of saturated hydraulic conductivity of field cores (volume of 100 cm^3) is of the order of 10^{-2} to 10^{-3} cm s^{-1} for those basins.

Intensive hydrometric observations were performed in these basins from 1995 to 1997. The discharge in the stream and the spring was measured continuously (Fig. 1). Soil water tension was recorded at 10-minute interval by tensiometers installed on the hillslope.

Throughfall was collected approximately every one to four weeks. Subsurface water was sampled using suction lysimeters installed at multiple depths and sites in the hillslope at intervals of one to four weeks. Stream water and spring water were sampled manually at the weir at intervals of one to four weeks, and the stream water in the K1 and Y1 catchments was sampled hourly during rainstorms using an automatic water sampler. The stable isotopic compositions of deuterium (D) and oxygen-18 (^{18}O), and concentrations of the solute inorganic ions were determined for all water samples. The hydrometric measurements and water sampling were conducted from 1995 to 1996.

RUNOFF CHARACTERISTICS

The hydrographs of the shale (K1) and granite (Y1) basins during rainstorms are shown in Fig. 2. The runoff response to rainfall in the shale basin was characterized by

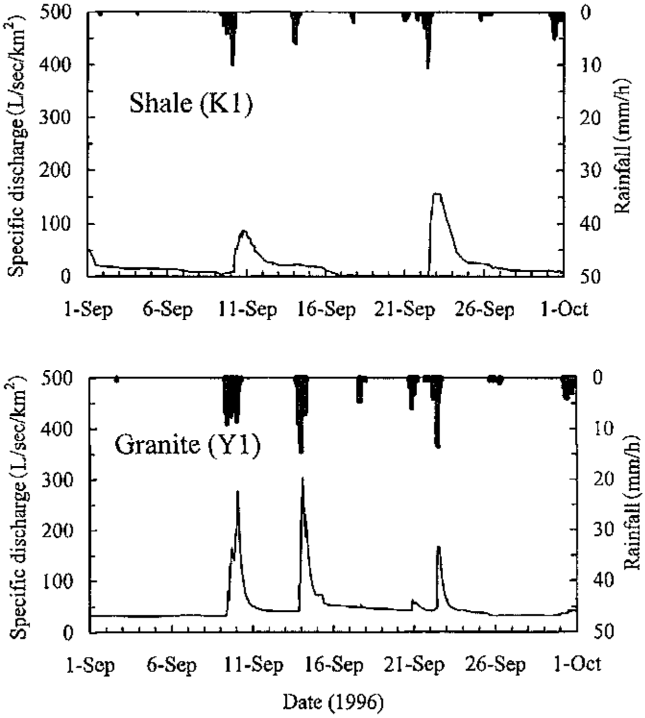

Fig. 2 Hydrographs of shale and granite basins during rainstorms.

a peak discharge lag of approximately 12 h behind peak rainfall. The hydrograph has a convex recession limb. In the granite basin, peak discharge coincided with the rainfall peak, and exhibited very rapid increases and decreases in discharge over a rainfall event.

The relationship between the ratio of quick flow defined by Hewlett & Hibbert (1967) to the storm rainfall rate and the antecedent precipitation index (API) is shown in Fig. 3. The antecedent soil moisture condition is represented by API defined by Mosley (1979).

The ratio of quick flow to rainfall (*QF/P*) increases remarkably above an API of 30–50 in the shale basin, whereas no clear relationships are seen between *QF/P* and API in the granite basin. The antecedent subsurface moisture condition would affect the storm runoff rate in the shale basin. Relatively deep subsurface flow through the bedrock would have an important role in the rainfall–runoff process in the shale basin. On the other hand, the antecedent moisture condition would not be so important in the storm runoff rate in the granite basin. Figure 4 shows the relationship between accumulated rainfall and *QF/P*. This figure suggests the rainfall rate would affect the runoff rate in the granite basin.

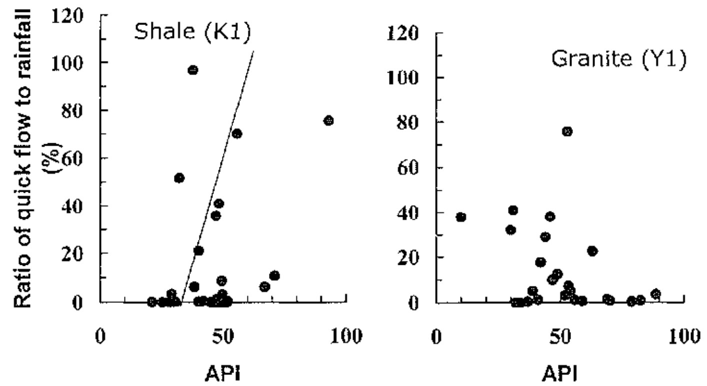

Fig. 3 Relationship between antecedent precipitation index and ratio of quick flow to rainfall.

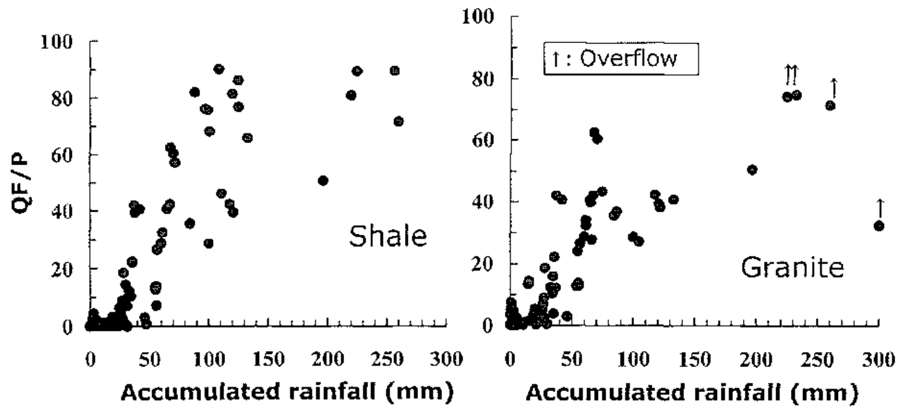

Fig. 4 Relationship between accumulated rainfall and ratio of quick flow to rainfall.

TRACER APPROACH DURING A RAINSTORM

The $\delta^{18}O$ values of rainfall, soil water (mean), and stream-water samples from 11 August to 18 October are shown in Fig. 5, and mean $\delta^{18}O$ values are summarized in Table 1. Low $\delta^{18}O$ values in rainfall occurred at the end of September, and high values occurred in August in the two basins. Both the soil water and stream water data followed the rain $\delta^{18}O$ trend in the granite basin. In the shale basin, the $\delta^{18}O$ of stream water was very stable (standard deviation was 0.06) and did not follow the $\delta^{18}O$ trend for rainfall. This suggests that the soil water in hillslopes in the granite basin contributes significantly to runoff water. The average residence time of subsurface water might therefore be longer in the shale basins than in the granite basins.

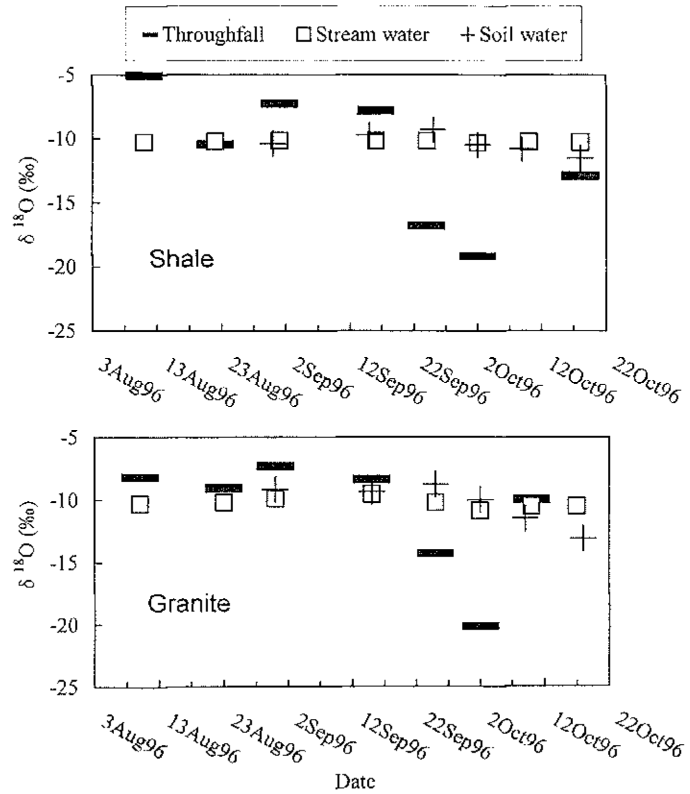

Fig. 5 Temporal change of $\delta^{18}O$ in rainwater, soil water, and stream water samples from 11 August to 18 October 1996 in the shale and granite basins.

Table 1 Mean $\delta^{18}O$ (‰) for rainfall, soil and stream waters.

	Shale: Mean	Standard deviation	Granite: Mean	Standard deviation
Rainfall	−11.3	4.82	−10.7	4.09
Soil water	−10.3	0.72	−10.3	1.52
Stream water	−10.2	0.06	−10.3	0.38

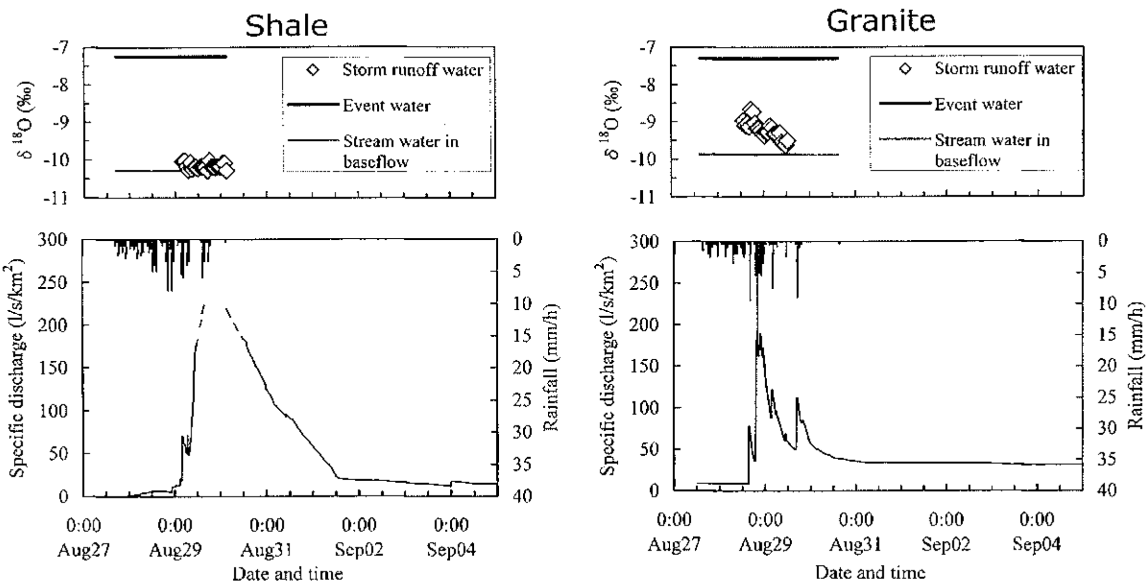

Fig. 6 Storm response of runoff and $\delta^{18}O$ in stream water during a rainstorm in the shale and granite basins, 27 August–1 September 1996.

The storm hydrograph and temporal change of $\delta^{18}O$ in runoff water during a rainstorm are shown in Fig. 6. In the shale basin, the $\delta^{18}O$ of storm runoff agreed well with mean $\delta^{18}O$ of stream water in baseflow (pre-event water) and the ratio of the pre-storm water component to the total discharge at the peak discharge was estimated to be 98% (Table 2). Conversely, in the granite basin $\delta^{18}O$ of storm runoff is affected by that of event rainfall water particularly at the beginning of a storm. The ratio of the pre-storm water component to the total discharge at the peak discharge was estimated to be 64% (Table 2).

The results of the tracer approach shows that the role of the pre-event water with long residence times is very important in the storm runoff in the shale basin, whereas the event water (including subsurface stormflow on the hillslope) contributes much to the storm runoff in the granite basins.

Table 2 Ratio of pre-event water to total runoff water in the study area.

	This study	Ichiyanagi *et al.* (1994)
Shale	98%	98%
Granite	64%	85%

BEHAVIOUR OF SUBSURFACE WATER DURING A RAINSTORM

Figure 7 shows the typical hydraulic head distribution of subsurface water on hillslopes in the shale and granite basins during a storm event on 14–15 August 1996. The vertical percolation of subsurface water is predominant in the soil layer in the shale basin, whereas the lateral saturated subsurface flow is observed throughout the soil layer in the granite basin. The hydraulic head distribution data from 1995 to 1997 show that vertical subsurface flow was observed even during heavy rainstorms in the shale basin. Because the shale has a lot of fissures on its surface (Chigira, 1992), the water might flow along fissures throughout the bedrock and discharge out to the stream at the outlet of the fissures. Saturated lateral subsurface flow occurred

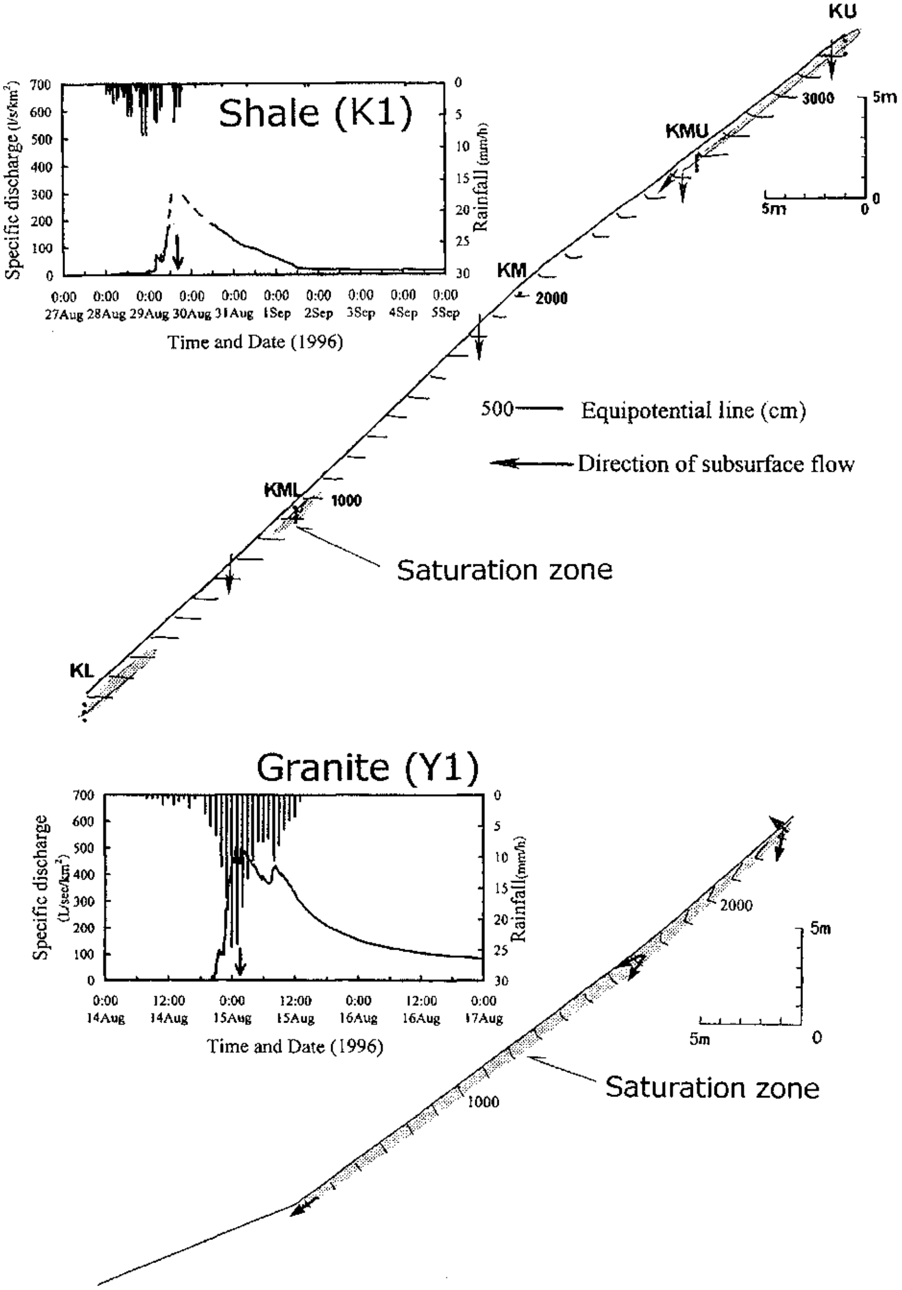

Fig. 7 Distribution of hydraulic head and subsurface flow direction in hillslopes during a rainstorm at the shale and granite basins.

frequently during heavy rainstorms with high antecedent soil moisture conditions in the granite basin. This near-surface lateral deflection results in very rapid runoff generation during rainstorms. The different hydrograph characteristics of the shale and granite basins might be explained by the different subsurface flow processes in the regolith and bedrock of the two basins.

CONCLUDING REMARKS

In the shale basin, the hydrometric and isotopic data indicate that most rainfall would infiltrate and percolate vertically to the bedrock surface, accumulating a long residence time over the route to the stream. In the granite basin, the lateral saturated subsurface flow in the regolith should be important in the rainfall–runoff process. These very different flow processes probably explain the contrasting hydrograph characteristics observed in the two basins in this mountainous area.

Acknowledgements The authors thank Mr Chihiro Tanaka and Ms Nozomi Kakiuchi, Department of Environmental Earth Sciences, Aichi University of Education for their cooperation in the field research. The present study was partially supported by Nissan Science Foundation and Grants-in-aid for Scientific Research from the Ministry of Education, Science and Culture, Japan, nos 08780140 and 08408003.

REFERENCES

Bazemore, D. E., Eshleman, K. N. & Hollenbeck, K. J. (1994) The role of soil water in stormflow generation in a forested headwater catchment: synthesis of natural tracer and hydrometric evidence. *J. Hydrol.* **162**, 47–75.

Chigira, M. (1992) Long-term gravitational deformation of rocks by mass rock creep. *Engng Geol.* **32**, 157–184.

DeWalle, D. R., Swistock, B. R. & Sharpe, W. E. (1988) Three-component tracer model for stormflow on a small Appalachian forested catchment. *J. Hydrol.* **104**, 301–310.

Hewlett, J. D. & Hibbert, A. R. (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In: *International Symposium on Forest Hydrology* (ed. by W. E. Sopper & H. W. Lull), 275–290, Pergamon Press, Oxford.

Ichiyanagi, K., Onda, Y., Tomatsu, O., Iwashita, H. & Kato, K. (1994) Determination of components of stormflow using water chemistry and isotope tracers in steep forested catchments underlain by different bedrocks. In: *Proc. International Symposium on Forest Hydrology* (ed. by T. Ohta, Y. Fukushima & M. Suzuki), 569–576. Organizing Committee of the Int. Symp. on Forest Hydrol., Tokyo.

Mosley, M. P. (1979) Streamflow generation in a forested watershed, New Zealand. *Wat. Resour. Res.* **15**, 795–806.

Onda, Y. (1994) Contrasting hydrological characteristics, slope processes and topography underlain by Paleozoic sedimentary rock and granite. *Trans. Jap. Geomorph. Un.* **15-A**, 49–65.

Pearce, A. J., Stewart, M. K. & Sklash, M. G. (1986) Storm runoff generation in humid headwater catchments 1. Where does the water come from? *Wat. Resour. Res.* **22**, 1263–1272.

Sklash, M. G. & Farvolden, R. N. (1979) The role of groundwater in storm runoff. *J. Hydrol.* **43**, 45–65.

Sklash, M. G., Stewart, M. K. & Pearce, A. J. (1986) Storm runoff generation in humid headwater catchments 2. A case study of hillslope and low-order stream response. *Wat. Resour. Res.* **22**, 1273–1282.

Stewart, M. K. & McDonnell, J. J. (1991) Modeling base flow soil water residence times from deuterium concentrations. *Wat. Resour. Res.* **27**, 2681–2693.

Tanaka, T. & Ono, T. (1998) Contribution of soil water and its flow path to stormflow generation in a forested headwater catchment in central Japan. In: *Hydrology, Water Resources and Ecology in Headwaters* (ed. by K. Kovar, U. Tappeiner, N. E. Peters & R. G. Craig) (Proc. HeadWater'98 Conf., Merano, April 1998), 181–188. IAHS Publ. no. 248.

Tsujimura, M., Tanaka, T. & Onda, Y. (1998) Effect of subsurface flow on the isotopic composition of soil water in headwater basins. In: *Hydrology, Water Resources and Ecology in Headwaters* (ed. by K. Kovar, U. Tappeiner, N. E. Peters & R. G. Craig) (Proc. HeadWater'98 Conf., Merano, April 1998), 343–351. IAHS Publ. no. 248.