韓國水資源學會論文集
第30卷 第6號 · 1997年 12月
pp. 777~785

산지 사면에서 토양체와 대공극을 통해 발생하는 지표하 호우류의 수문학적 특성

Hydrological Characteristics of Subsurface Stormflow through Soil Matrix and Macropores on Forested Hillslopes

김 경 하*
Kim, Kyong Ha

Abstract

This study was conducted to clarify the hydrological characteristics of subsurface flow through a soil matrix and macropores. The research facility was set up in a 20m-long trench excavated down to bedrock at the base of a hillslope in the Panola catchment under USGS Georgia district. 13 macropores were found on the trench face and 6 major macropores were monitored. Matrix and macropore flow were measured during 95.5mm rainfall on March, 6 to 7, 1996. Macropore flow had great influence on formation of peak flow because the delivery time to peak flow of macropore flow were faster about 10hrs than those of matrix flow. Matrix flow continued to recess for 3 days. On the other hand, macropore flow stopped within 12hrs after the event ceased. This means that matrix flow controls the recession part. The spatial variations of matrix and macropore flow between each trough and collector were very large by a wide range of 8,655.3 ℓ to 17.8 ℓ. The bed rock surface topography relates closer with the spatial variations of the flow than the surface one.

Keywords: forested hillslope, subsurface stormflow, matrix flow, macropore flow

요 지

이 연구는 강우시 산지사면의 토양체와 대공극에서 발생하는 지표하 호우류를 구분하여 측정한 후 이들의 수문학적 특성을 밝히고자 수행하였다. 측정 시설은 미국 Georgia주에 위치한 지질국 산하 Panola시험유역의 상류 산지사면에 약 20 m 길이의 조사구를 암반 깊이까지 파고 2 m간격으로 집수구를 설치하였다. 대공극류는 조사구 토양단면에 있는 13개의 대공극 중 유출이 발생한 6개의 대공극에 집수통을 설치하여 측정하였다. 1996년 3월 6일부터 7일까지 95.5 mm의 강우가 내렸으며 이 때 발생한 대공극류와 기질류를 측정하여 분석하였다. 대공극류는 기질류보다 약 10시간 앞서 첨두유출이 발생하므로 유역의 첨두유출을 형성하는데 보다 큰 영향을 미쳤다. 강우가 종료된 후 대공극류는 약 12시간 이내에 멈춘 반면 기질류는 약 3일 이상 지속되어 감수부를 형성하는데 보다 큰 영향을 미쳤다. 기질류와 대공극류의 유출량은 집수구에 따라 최대 8,655.3 ℓ에서 최소 17.8 ℓ로 공간적 변이가 매우 크게 나타났으며 이 변이는 지표 지형보다 기반암 표면의 지형과 밀접한 관계가 있었다.

핵심용어: 산지사면, 지표하 호우류, 기질류, 대공극류

---

* 산림수자원연구실 연구사 임업연구원

1. Introduction

Stormflow in a forested catchment plays an important role in non-point source pollution such as solute movement and soil erosion etc.. Until now, there have been various mechanisms explaining rapid stormflow generation on a forested hillside i.e. Hortonian overland flow, saturation overland flow and subsurface flow(Buttle, 1994).

It is well known that there is rare overland flow on the soil surface and most of the discharge occurs through subsurface at humid, steep, forested catchments. The mechanisms explaining rapid delivery of subsurface flow are groundwater ridging, translatory flow and macropore flow etc.. Subsurface flow often begins shortly after rain events even when there is neither saturation at the point of outflow nor high antecedent soil moisture. The hydrologic characteristics of subsurface stormflow was referred to rapid delivery and large spatial variability (Mosley, 1982; Wilson et al., 1990; Jabro et al., 1991).

Flow into the subsoil constitutes two domains such as Darcian and non-Darcian flow. Darcian flow, like soil matrix flow is subjected to capillarity and controlled by the hydraulic conductivity. Soil matrix flow can generate subsurface stormflow provided that the hydraulic conductivity of the upper soil horizon is high. On the other hand, macropore flow is primarily driven by gravity and is obstructed only faintly by capillary forces. Macropore flow can speed up soil drainge to rates comparable with and even exceeding that of overland flow(Anderson and Burt, 1990). Most hydrologic models have used Darcian equation to simulate saturated and unsaturated soil moisture but failed to predict the runoff hydrograph successfully where subsurface flow is dominant.

Despite the large number of field researches about subsurface flow had been carried out in the 1970s, hydrological pathways for subsurface flow were not identified exactly. For example, Mosley(1979) emphasized the importance of macropore flow in a forested catchment in New Zealand. However, further work by Pearce et al.(1986) suggested that some translatory flow through the soil matrix must be involved since the outflow is old water of long residence time. For this occur, water infiltrating at soil surface must cause a rapid rise in the water table. This could occur if the unsaturated hydraulic conductivity of the soil is high or if macropore flow bypasses the soil matrix. Subsurface stormflow through soil macropores has important implications for the movement of pollutants and the use of field soils to filter waste water. Macropore flow has been studied in detail at the scale of small pits and soil samples(Jabro et al., 1991 ; Tsuboyama et al., 1994) but it is difficult to find evidence on the role of macropores in water transport in field soils.

Initiation and maintenance of flows in the macropore system requires a supply of water exceeding all losses to the matrix. Generating local saturation caused by stemflow and micro-relief may be important in occurring macropore flow. Antecedent soil moisture and rainfall intensity have the particular importance for the thresholds controlling macropore flow. Macropore flow is not responsible only for recharging the water table through bypassing the soil matrix but also for providing a direct connection from source area to the stream. The aims of this study are to 1) monitor the hydrological characteristics of matrix and macropore flow on forested hillslope, 2) clarify how martix and macropore flow contribute to produce subsurface stormflow, and 3) find which area i.e. surface or subsurface controls the volume of subsurface stormflow. 2. Methods and Materials

2.1 Experimental site

The study area is 25 km southeast of Atlanta, Georgia in USA. The experimental catchment is located in Panola conservation state park. The Panola Mountain research catchment is one of the five Water, Energy and Biogeochemical Budgets(WEBB) sites operated by the U.S. Geological Survey where researchers are identifying subsurface flow paths of associated soil water, groundwater, and stream flow using chemical and isotopic compositoins. The catchment has an area of 41 ha at lower gaging station and 10 ha at upper one(Fig. 1). Forests consist of a second-growth oak, hickory, tulip popular and loblolly pine. Bedrock is dominated by Panola Granite (granodiorite composition) and soils arepredominately Ultisols. The study hillslope is southwestern part of upper gaging station in a dimension of 20 m × 48 m. The upper part of hillslope is located on a large bedrock.

2.2 Field survey and instrumentation

A 20 m-long trench was excavated down to weathered bedrock(0.4-1.8 m) at the base of the study hillslope. Trench can prevent water flow line from modification by producing flow line convergence and the buildup of a saturated wedge immediately upslope. Subsurface flow on the bedrock was collected by using 10 sections of 2 m-long plastic troughs. Troughs were constructed using epoxy on the soil-bedrock interface(Fig. 2). 6 major macropores among 13 macropores found at trench face during heavy rainfall were monitored using plastic collectors. 10 troughsfor matrix flow and 6 collectors for macropore flow were connected through plastic hose to 13 small (0.3 ℓ/tips) and 3 large tipping buckets(0.7 ℓ/tips) res-

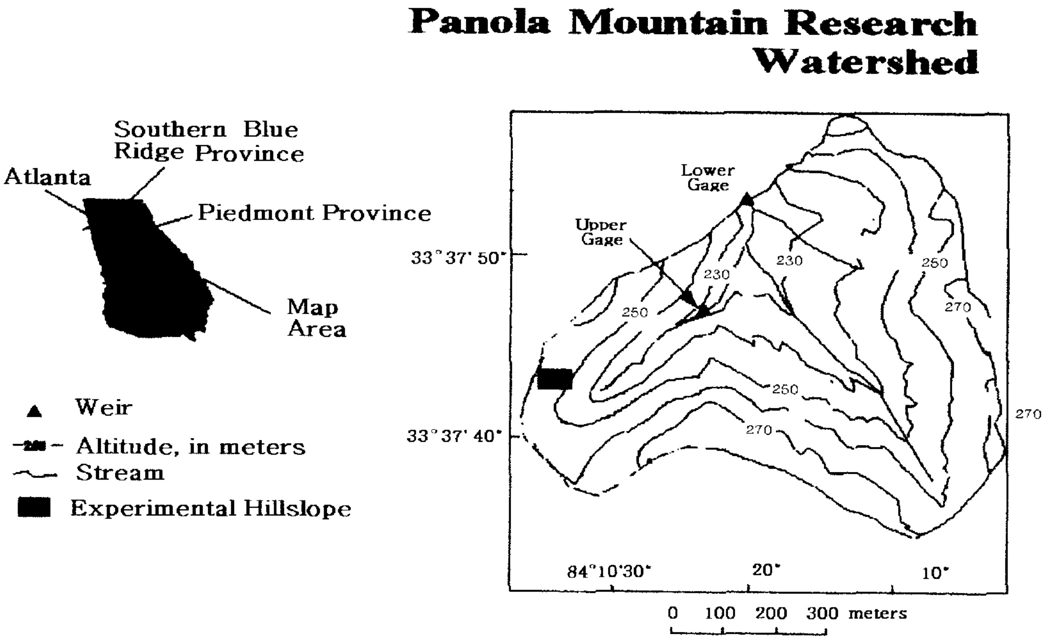


Fig. 1. Location of the Experimental Hillslope at the Panola Research Watershed, Georgia, U.S.A.

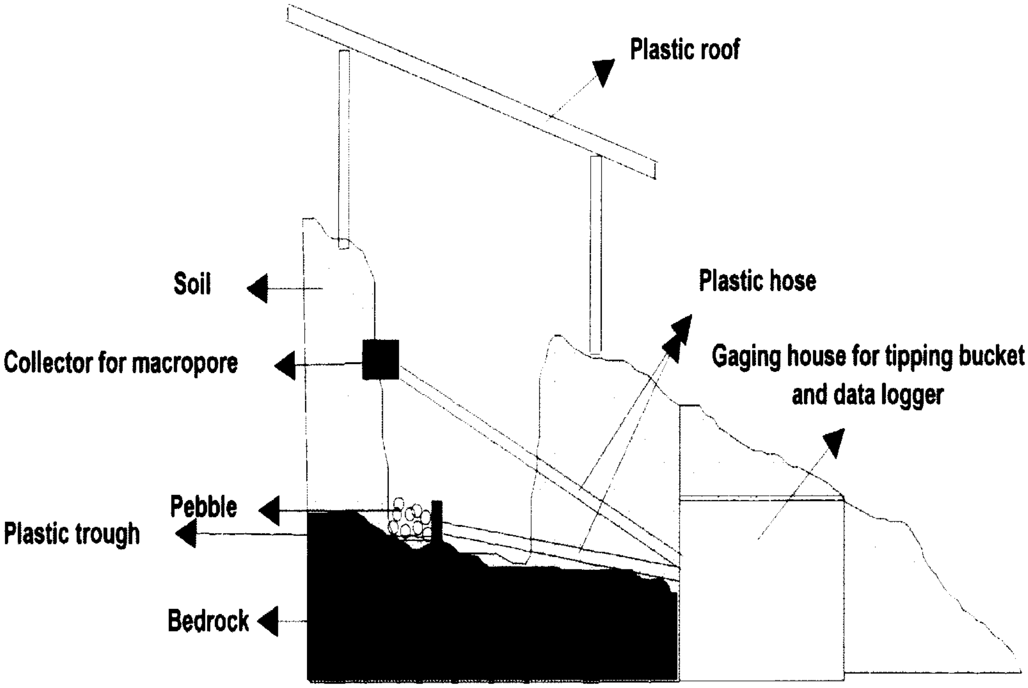


Fig. 2. Schematic Side View of Trench

pectively. Tipping counts of bucket were recorded on a Campbell Science SDM-SW8A module and CR10 data logger at an interval of one minute. Data logger were directly connected to the computer monitoring system using Campbell multi-drop module. Custom-made tipping buckets were dynamically calibrated at the laboratory to derive the relationship between steady state flow rate and tipping rate. Elevations of 2 m × 2 m grids in the study hillslope was surveyed using total station level. Depths to bed rock at each grid were measured using the soil auger. Rainfall was continuously recorded by tipping bucket raingage.

3. Results and discussion

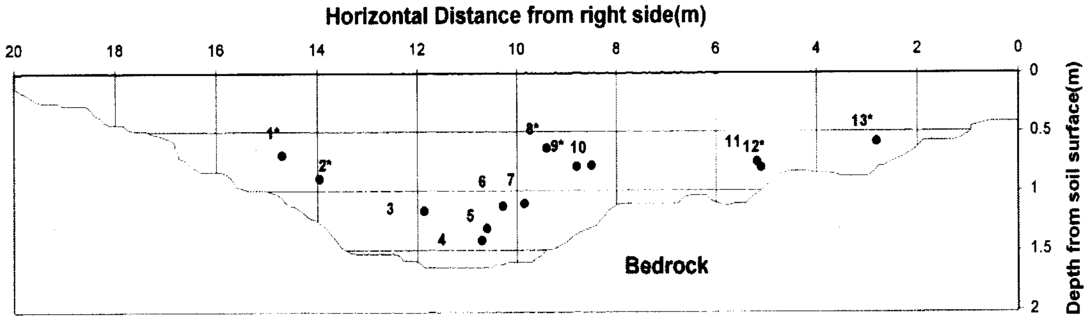
3.1 Description of macropores

13 macropores were found at the trench face during the heavy storm of about 100 mm on February 4, 1996. Water significantly gushed out from the 6 major macropores but water flowing was negligible at the others. The plastic collectors were set up to the 6 macropores for monitoring. Table 1 and Fig. 3.

Table 1. Descriptions of the Macropores at the Trench Face

No	Location at trench face(m)		Opening size(cm)	
	Distance from right side	Depth from soil surface	Horizontal	Vertical
1	14.7	0.7	6.2	4.1
2	14.0	0.9	2.7	3.9
3	11.9	1.2	-*	-
4	10.7	1.4	-	-
5	10.6	1.3	-	-
6	10.3	1.1	-	-
7	9.9	1.1	-	-
8	9.4	0.6	1.4	1.2
9	8.8	0.8	6.3	5.9
10	8.5	0.8	-	-
11	5.2	0.8	-	-
12	5.1	0.8	3.1	4.1
13	2.8	0.6	3.2	2.4

* Minor macropores were not measured.



* on the number means macropores monitored.

Fig. 3. Schematic View of Macropores' Position on the Trench Face.

describe the sizes and positions of macropores at the trench face. Diameter of macropores ranges from 1.3 cm(No. 8) to 6.1 cm(No. 10). Depth from soil surface ranges from 0.59 m(No. 13) to 1.42 m(No. 4). Most macropores were made from decayed roots.

3.2 Hydrological characteristics of matrix and macropore flow

Fig. 4, 5 and 6 show the hyeto-hydrographs of matrix and macropore flow produced by 10 troughs and 6 macropores during 5 days from March 6, 1996. The first rainfall precipitated 48.5 mm for 4 hrs and maximum intensity was recorded as 5.3 mm/10 min. The second one fell 47.0 mm for 10 hrs and recorded 8.6 mm/10 min of the maximum intensity. For the first rainfall, the hydrographs in all troughs did not show peak. This means the first rainfall was used to fill up the soil storage

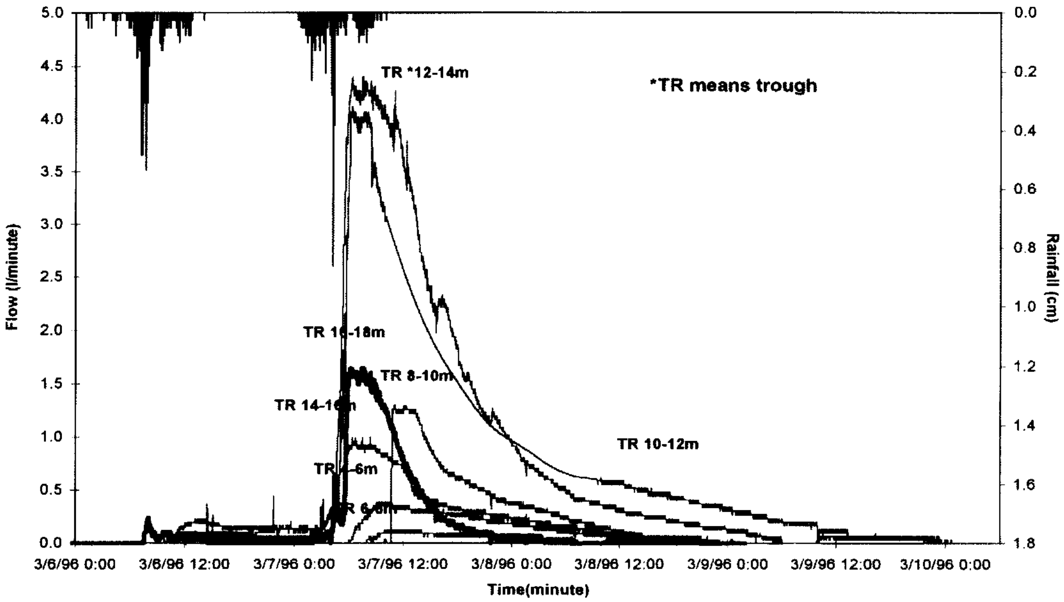


Fig. 4. Hyeto-Hydrograph of Matrix Flow at 7 Troughs During the Rainfall for Period of March, 6 to 7, 1996.

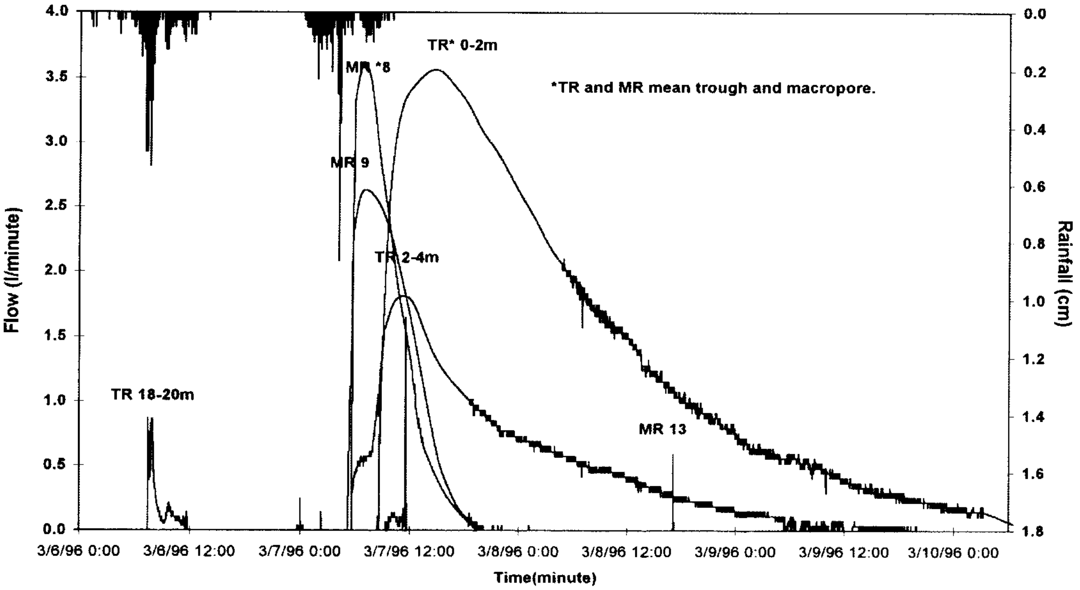


Fig. 5. Hyeto-Hydrograph of Matrix and Macropore Flow at 3 Troughs and 3 Collectors During the Rainfall for Period of March, 6 to 7, 1996.

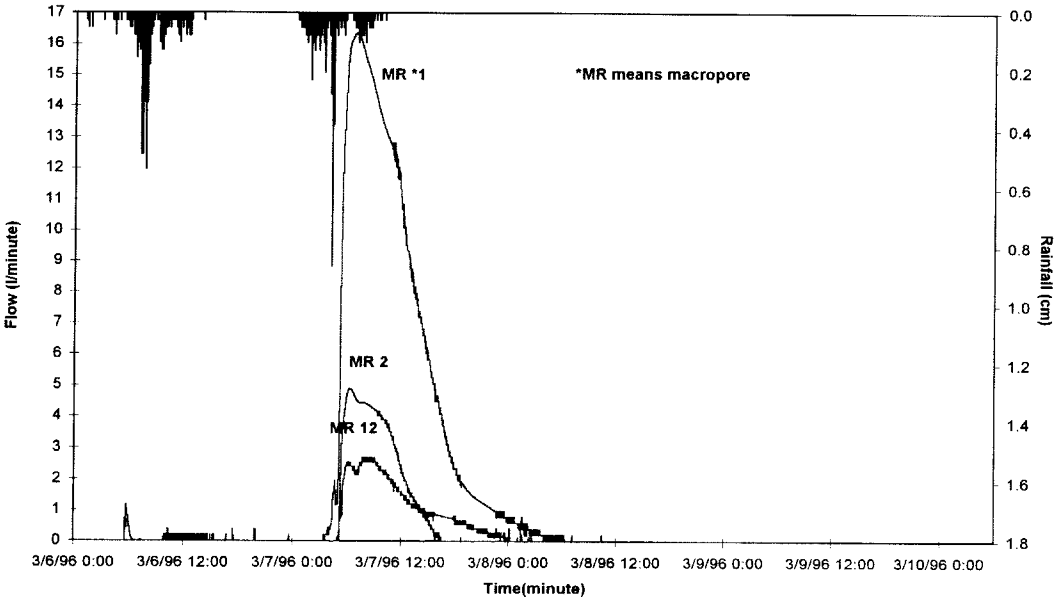


Fig. 6. Hyeto-Hydrograph of Macropore Flow at 3 Collectors During the Rainfall for the Period of March, 6 to 7, 1996.

deficiency. As shown in Fig. 5, the hydrograph feature of matrix and macropore flow shows big difference. Macropore flow produced peak faster than matrix flow and flowing suddenly stops after rain. This suggests that macropore flow is rather controlled by kinematic energy just only influenced by the hydraulic gradient than the Darcian flow. Germann(1990) made the simple equation to estimate non-Darcian flow. This equation comprises the height of water and the slope angle. The velocity of macropore flow is often faster than that of saturated or infiltration-excess overland flow(Jones, 1978). Hydrograph of matrix flow such as in trough 0-2 m shows peak flow happened later about 10 hrs than that of macropore flow. Matrix flow continued to recess for 3 days after event ceased. From these results, it can be deduced that macropore flow mainly contributes to produce direct flow, while the matrix flow has great influence on the recession of discharge.

3.3 Discharge variability of matrix and macropore flow in each trough

Fig. 7 represents total runoff volume and peak flow rates both in each trough and macropore. As shown in the figure, the discharge variations between 10 troughs and macropore flow are large. Total discharge volume and peak flow rate were measured as 8,655.3 l and 16.3 ℓ/min respectively at No. 1, which is the biggest amount among those from the 6 macropores. The least of total discharge volume and peak flow from macropores occurs in No. 13 (17.8 ℓ) and No. 12 (0.4 ℓ/min) respectively. Total discharge volumes from 10 troughs without macropore flow also vary large range of 5,658.1 ℓ (trough 0-2 m) to 52.4 ℓ (trough 18-20 m). The amount of peak flow also show the range from 4.4 ℓ/min (trough 12-14 m) to 0.1 ℓ/min (trough 6-8 m). What does actually control the spatial variation of matrix and macropore flow? Theoretically runoff contributing area of each trough may have influence on discharge volume. Until now the hypothesis that land surface contributing area plays great role in producing runoff has prevailed. This hypothesis assumes that the surface and subsurface topography may be similar.

Fig. 8 shows the land surface and bedrock surface topographic features measured at the 2 m × 2 m grid points. The figure represents big difference between the land surface and bed rock surface topographic features. As shown in

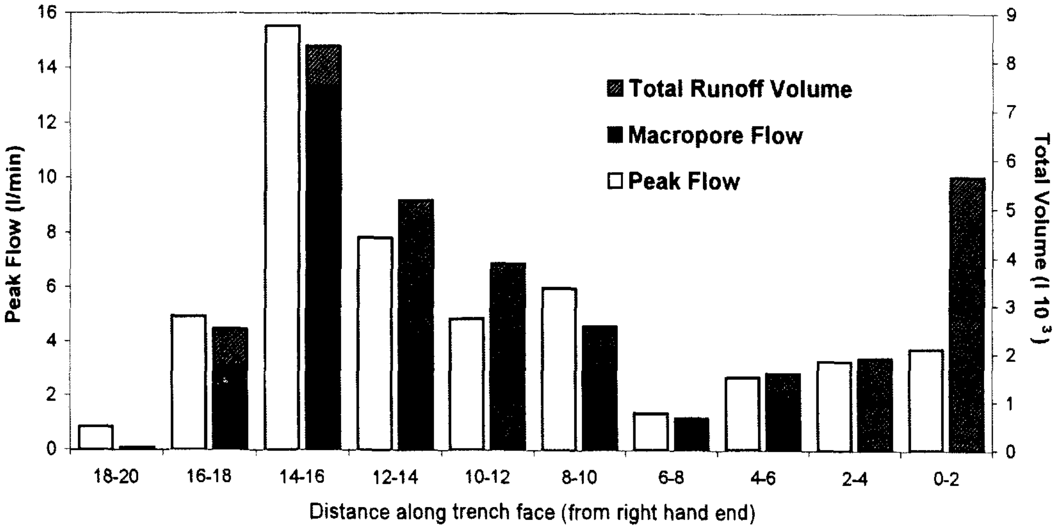
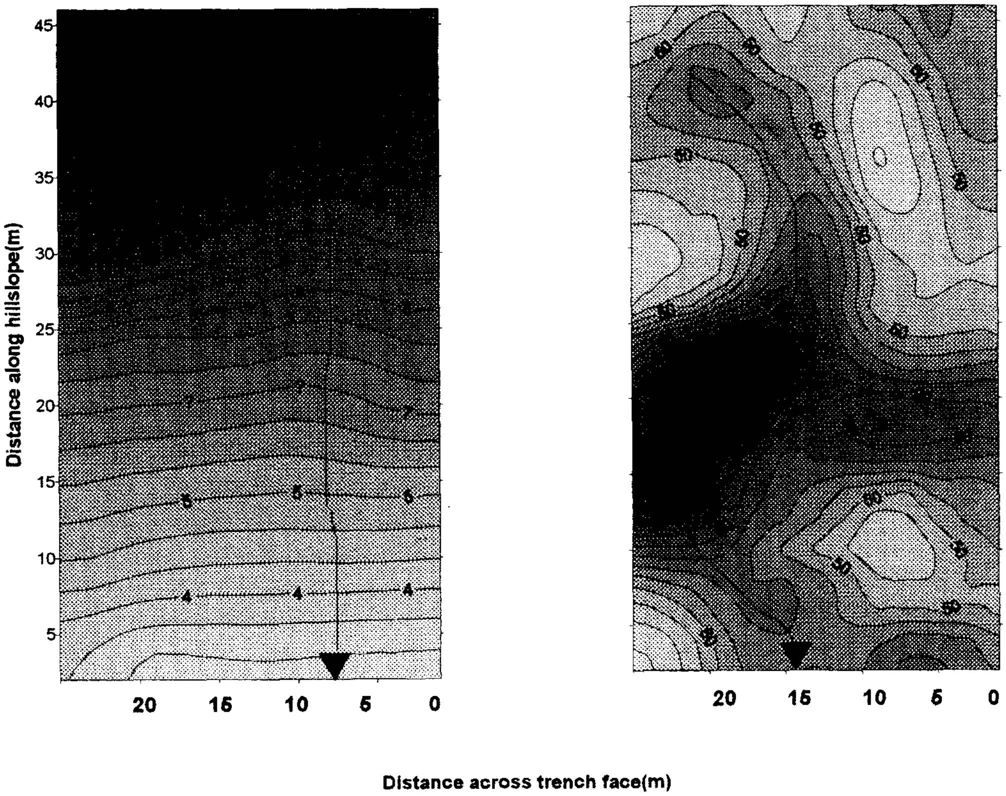


Fig. 7. Total Runoff Volume and the Amount of Peak Flow in Each Trough and Macropore.



(a) **Land surface topography(m)**

(b) **Bedrock surface topography(cm)**

Fig. 8. Land Surface(a) and Bedrock surface(b) Topography of the Experimental Hillslope.

the figure, water flows converging to trough 6-10 m in accordance with the main flow line of the land surface topography(Fig. 8(a)). On the other hand, the bedrock surface topography represents the main flow line is formed along the pathways to trough 14-16 m. By comparison of the observed flow at each trough, it was concluded that the amount of subsurface flow including matrix and macropore flow is influenced by bedrock surface topography rather than land surface one.

4. Conclusions

Subsurface stormflow is important in the mechanism of runoff production in a forested catchment. The hydrologic characteristics of subsurface stormflow is a rapid delivery of runoff and large spatial variability. Non-Darcian flow, like macropore flow had great influence on peak flow rate. On the other side, Darcian flow such as soil matrix flow affected a recession part. The spatial variations of matrix and macropore flow in each trough showed the wide range. The bed rock surface topography rather than the surface topography caused large spatial variability of subsurface flow.

References

Anderson, M.G. and Burt, T.P. (1990). "Subsurface runoff." *Process Studies in Hillslope Hydrology*. Anderson, M.G. and

Burt, T.P., eds., John Wiley & Sons, pp. 365-400.

Buttle, J.M. (1994). "Isotope hydrograph separations and rapid delivery of preevent water from drainage basins." *Progress in physical geography*, Vol. 18, No. 1, pp. 16-41.

Jabro, J.D., Lotse, E.G., Simmons, K.E. and Baker, D.E. (1991). "A field study of macropore flow under saturated conditions using a bromide tracer." *Journal of Soil and Water Conservation*, Vol. 46, No. 5, pp. 376-380.

Jones, J.A.A. (1978). "Soil pipe networks :distribution and discharge." Cambria, Vol. 1, pp. 1-21.

Mosley, M.P. (1972). "Streamflow generation in a forested watershed, New Zealand." *Water Resour. Res.*, Vol. 15, pp. 795-806.

Mosley, M.P. (1982). "Subsurface flow velocities through selected forest soils, South island, New Zealand." *Journal of Hydrology*, Vol. 55, pp. 65-92.

Pearce, A.J., Stewart, M.K. and Sklash, M.G. (1986). "Storm runoff generation in humid headwater catchments 1. Where does the water come from?" *Water Resour. Res.*, Vol. 22, No. 8, pp. 1263-1272.

Tsuboyama, Y., Sidle, R.C., Noguchi, S. and Hosoda, I. (1994). "Flow and solute transport through the soil matrix and macropores of a hillslope segment." *Water Resour. Res.*, Vol. 30, No. 4, pp. 879-890.

Wilson, G.V., Jardine, P.M., Luxmoore, R.J. and Jones, J.R. (1990). "Hydrology of a forested hillslope during storm events." *Geoderma*, Vol. 46, pp. 119-138.

〈최종본 접수일 : 1997년 12월 3일〉