

CHENG Jinhua, ZHANG Hongjiang, ZHANG Youyan, SHI Yuhu, HE Fan, QI Shenglin, SUN Yanhong

Affecting factors of preferential flow in the forest of the Three Gorges area, Yangtze River

© Higher Education Press and Springer-Verlag 2007

Abstract In order to study the factors affecting preferential flow, a 2.9 m-long, 2.6 m-deep soil profile was dug in the Quxi watershed, Yangtze River. To analyze the influence of rainfall on preferential flow, the preferential flow process was observed when the rainfalls were recorded. Soil physical and infiltration characteristics were also measured to study their effect on preferential flow. The results showed that the rainfall amount that could cause preferential flow was over 26 mm. There are four types of rainfall in the Three Gorges area, namely gradually dropping rain, even rain, sudden rain and peak rain. Preferential flow process was found to be relevant to the rainfall process. It was determined that with different rainfall types, preferential flow appeared at different times, occurring first in peak rain, followed by sudden rain, gradually dropping rain, and then even rain. Preferential flow would appear when the rainfall intensity was over 0.075 mm/min. In the studied area, the coarse soil particles increased with the soil depth, and for the deeper soil layer, the coarse particles promote the formation of preferential flow. Preferential flow accelerates the steady infiltration rate in the 83–110 cm soil horizon, and the quickly moving water in this horizon also enhanced the further formation and development of preferential flow.

Keywords Three Gorges of Yangtze River, preferential flow, rainfall types, soil physical characteristics, soil infiltration characteristics

Translated from *Journal of Soil and Water Conservation*, 2006, 20(5): 28–33 [译自: 水土保持学报]

CHENG Jinhua (✉), ZHANG Hongjiang, HE Fan, QI Shenglin, SUN Yanhong
School of Soil and Water Conservation, Beijing Forestry University,
Beijing 100083, China
E-mail: jinhua_cheng@126.com

ZHANG Youyan
Research Institute of Forestry, Chinese Academy of Forestry, Beijing
100091, China

SHI Yuhu
Forestry Academy of Hubei Province, Wuhan 430075, China

1 Introduction

Soil water movement is influenced by soil texture, the connection degree of soil pores, and the diameter of soil pores. The highly connected soil pores can become paths for water's quick movement and the carrying of soil particles. The quick movement of water in soil macropores is called preferential flow. Preferential flow exists in different kinds of soil and matrix (Landon et al., 1999; Gautom et al., 2000). Studies on preferential flow are concentrated in the fields of agricultural soil, forest hydrology, and soil physics. Aubertin and Jones (1971) put forward that preferential flow was influenced by types of preferential flow paths, the roughness coefficient n , the shape of preferential flow paths, and the soil water situation, so its velocity and flux are much faster than those that follow the Darcy Law. Many studies in Japan showed that lateral water flow in soil is non-linear with fast velocity and have great influence on forest hydrological process (Hikaru, 1989, 1994, 1996). Qin and Hu (1998) explored the effect of macropores on the saturated hydrologic conductivity of arable layer. Hao (Hao and Feng, 2002) obtained the moving rule of water flow and solute in macroporous farmland soil. The studies of Zhang et al. (2000, 2001, 2002, 2003) showed that preferential flow was common in the granite area of Yangtze River and they have done preliminary studies on the characteristics of preferential flow paths and preferential flow process in the forestland of the Yangtze River.

According to the previous studies, the factors affecting preferential flow mainly include two kinds: internal factors and external factors. Internal factors include soil characteristics such as soil particle constitution and soil types. External factors include farming methods, irrigation methods, and precipitation characteristics. In this paper, the influence of soil and precipitation characteristics on preferential flow is studied.

2 Research area and methods

2.1 Site description

The field site is the Quxi watershed, located in Zigui County, Hubei Province, China, 8 km away from the Three Gorges

Dam on the Yangtze River (111°57'20" N, 30°51'15" E). The major bedrock is granite, with a 10-meter thick weathering layer. The soil is mainly paddy soil.

The tree species in the research site are mainly *Cunninghamia lanceolata* and *Pinus massoniana*, with stand age of 24–26 years, tree height of 10–14 m, and a canopy coverage of approximately 0.6. There are also some bushes such as *Vitex negundo* sp., *Cotinus coggygria* var. *pubescens*, *Lespedeza* sp. and *Coriaria nepalensis*, grasses such as *Cymbidium faberi*, *Imperata cylindrica*, *Pteridium* sp., *Carex* sp. and *Erigeron acer*. The soil surface is also covered by moss, with a coverage of 0.5. The total coverage of vegetation on the experimental site is 0.9.

A typical concave slope was selected to collect soil samples and observe the preferential flow. The altitude of this slope is 250–271.4 m; the direction is NW33°, and the mean gradient 33.3°, the total area 328.4 m².

2.2 Measurement of preferential flow

In the foot part of the slope, a soil profile, 2.23–2.60 m long and 2.9 m deep, was dug. Through observations of the soil profile, it was found that preferential flow paths concentrated on the horizontal strip range of 0.65–1.5 m deep in the soil, which was a transitional horizon from B horizon (the granite highly weathered) to C horizon (the granite lowly weathered). The number of preferential flow paths observed obviously was eight, and diameters were 4–8 mm. Limited by the number of apparatus, only four preferential flow paths were measured. The locations of the four preferential flow paths are shown in Table 1.

Table 1 Vertical distribution of the pipes

Preferential flow path	A	B	C	G
Vertical distance to land surface /cm	65.0	69.0	78.5	107.5
Lateral distance to path A /cm	0.0	22.0	95.0	225.0

Preferential flow was measured by reformed flowmeter (B-432Z, made in Japan). Water that flowed from four preferential flow paths was transported into the four apparatus through airtight soft plastic pipes. The water flow was measured continuously.

2.3 Measurement of precipitation

Precipitation was measured by digital flowmeter (CR2, made in Chengdu, China). The record interval was one hour and the measured maximum precipitation intensity was 33.6 mm/min. Based on the measured data, the precipitation duration, precipitation amount, and precipitation intensity in different rainfalls were calculated.

Table 2 Average rainfall and distribute proportion of 1993–2000 in Duanfanxi small valley

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Precipitation/mm	24.08	22.06	55.03	72.31	137.89	152.24	255.68	228.38	132.9	119.09	49.1	17.64	1,266.4
Proportion/%	1.9	1.74	4.34	5.71	10.89	12.03	20.19	18.03	10.49	9.4	3.89	1.39	100

2.4 Measurement of soil characteristics

A 110-cm-deep profile was dug in the upper, middle and lower position of the selected slope, respectively. The characteristics of each soil profile were observed and recorded. Based on the soil color and soil texture, the profile was divided into five horizons: 0–15 cm, 16–43 cm, 44–82 cm, 83–110 cm and below 110 cm. In each layer, samples in each soil profile were collected in cylinders for the measurement of water holding capacity of the capillary, soil bulk density, and capillary porosity.

Another two soil samples of each horizon were collected in cylinders to measure the size of soil particles. The soil texture was determined using the pipette method.

2.5 Measurement of soil infiltration

To simulate the natural soil infiltration situation, a double-ring was used to measure the soil infiltration of the field site. The double-ring consists of an outer loop and an inner loop. The diameter of the outer loop is 15 cm, and that of the inner loop is 8.5 cm. The height of both loops is 30 cm. During the experimental period, the depth of the outer loop into soil was the same as that of the inner loop, and the water level in the inner loop was kept 3 cm lower than that in the outer loop. The infiltration count was recorded every 10 minutes.

In the selected slope, the soil profile was divided into five horizons with the same method used in the measurement of soil physical characteristics. The granite below 110 cm was not weathered, and its infiltration ability was very weak, so it can be regarded as a staunch layer. The infiltration experiment in each layer was repeated twice.

3 Results and analysis

3.1 Precipitation characteristics and its influence on preferential flow

3.1.1 Precipitation characteristics

The monthly mean precipitation and their proportion in the whole year are shown in Table 2 on the basis of precipitation from the year 1993 to 2000. From Table 2, it can be seen that the mean precipitation of the Quxi watershed is 1,266.4 mm. Precipitation in July is the maximum, with 20.19% of the whole year. Precipitation during flood season (from May to October) accounts for 81.09%, which is also the main season producing preferential flow.

3.1.2 Influence of rainfall amount on preferential flow

We use experimental results from 2002–2004 to analyze the influence of rainfall amount on preferential flow. We defined the rainfall lasting 24 h without interruption as one rainfall process. Within the 78 rainfalls observed, preferential flow occurred 13 times. In Table 3, it was shown that the rainfall amount that can influence preferential flow occurrence is 26–151.4 mm. That is to say, preferential flow can occur when rainfall amount is bigger than 26 mm.

3.1.3 Influence of precipitation process on preferential flow

According to the measured precipitation curve, the precipitation in the granite area of the Three Gorges may be divided into four types: gradually dropping (Fig. 1), even raining (Fig. 2), suddenly raining (Fig. 3) and peak raining (Fig. 4) (Shi et al., 2003; Wang and Wang, 1995). The preferential flow process under different rainfall is consistent with their rainfall type.

According to the rainfall that occurred on May 18, 2002 and the occurring time of preferential flow, it can be found that rainfall began at 14:50, peaked at 18:05, then decreased and stopped at 2:00 of May 19. The decreasing time was 6 h. After 22 h stopping, the rainfall began again and peaked at 4:00 of May 20, and then decreased. The decreasing time was 43 h. Therefore, this rainfall was of the gradually dropping type. Preferential flow appeared 67 h after rainfall, began at 20:00 of May 23 and got peak value at 21:00, and then decreased. The process is shown in Fig. 1.

The rainfall that occurred on August 20, 2002 was of the peak rain type. It began at 4:00 of August 25, got peak value at 10:00. Preferential flow occurred at 13:00 of August 25 and got its peak value at 19:00. The process is shown in Fig. 4.

According to the start times of rainfall and preferential flow, preferential flow appeared 8.5–95 h later than rainfall (Table 3). For peak rain (20020825), preferential flow appeared earlier, 9 h later than rainfall, and for even rain (20020528), preferential flow appeared 95.5 h later than rainfall. In the type of gradually dropping rain (20020518), preferential flow appeared 67 h later, and in sudden rain (20020622), preferential flow appeared 44.5 h later than rainfall. Therefore, preferential flow had the earliest occurrence when the rainfall type is peak rain, then occurred in sudden rain, gradually dropping rain and even rain at increasingly later times.

3.1.4 Influence of rainfall intensity on preferential flow

In Table 3, it can be seen that the rainfall intensity influencing preferential flow occurrence was 0.075–0.936 mm/min. That is to say, preferential flow can occur when the rainfall intensity is higher than 0.075 mm/min.

Taking the rainfall process, rainfall intensity and preferential flow process of August 25, 2002 as an example, the influence of rainfall intensity on preferential flow was explored. Rainfall began at 4:00 and rainfall intensity was 0.208 mm/min. Then two intensive peaks occurred at 8:00 and 10:00, the rainfall intensities being 0.093,3 mm/min and 0.251,3 mm/min, respectively. Preferential flow occurred 8 h after rainfall and got its peak value, 0.005,28 m³/h, at 19:00. The preferential flow amount increased from 0.003,32 m³/h to 0.003,52 m³/h because of the appearance of a shower at 8:00. The shower at 10:00 resulted in the slowly decreasing process of preferential flow and the increase of 0.000,2 m³/h at 15:00 (Fig. 4). Therefore it can be concluded that after preferential flow occurred, even a little change in rainfall intensity could affect preferential flow's hydrological curve.

Table 3 Characteristics of typical rainfall and preferential flow

Precipitation time	Rainfall amount /mm	Rainfall duration /h	Max rainfall intensity /(g·kg ⁻¹)	Occurring time of preferential flow	Duration of preferential flow /h	Lagging time of preferential flow /h	Amount of preferential flow /cm ³
2002							
05-18–05-21	37.7	81	0.088,3	05-23 17:30	16	63.5	3,100
05-28–05-29	26.5	29	0.075,0	05-30 9:00	9	26	48,700
06-05–06-10	148.4	107	0.561,7	06-05 22:30	170	8.5	749,700
06-22–06-27	83.4	126	0.266,7	06-24 13:30	143	44.5	110,900
08-19–08-21	151.4	47	0.843,3	08-20 23:00	92	31	200,500
08-25–08-26	40.5	20	0.936,0	08-25 12:00	66	8	103,300
2003							
06-25–06-26	45.76	28	0.138,7	06-27 14:45	25	69.25	3,160
07-04–07-05	41.6	20	0.242,6	07-04 22:20	65	7.25	27,430
07-08–07-10	57.2	59	0.173,3	07-10 06:00	89.5	47.5	58,340
07-19–07-21	37.3	48	0.178,3	07-21 04:00	25	39.6	113,620
08-03–08-04	28.6	23	0.223,3	08-04 02:00	50.83	26.17	38,470
2004							
05-27–05-30	63.5	71.63	0.190,7	05-30 13:00	38	70	21,020
06-03–06-05	56.16	34	0.121,3	06-04 19:00	69	29	60,720

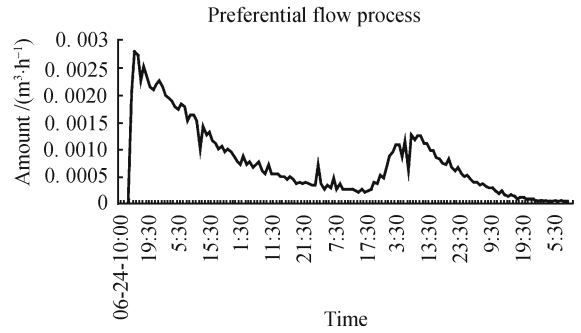
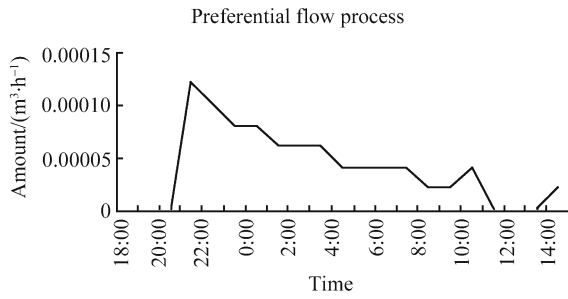
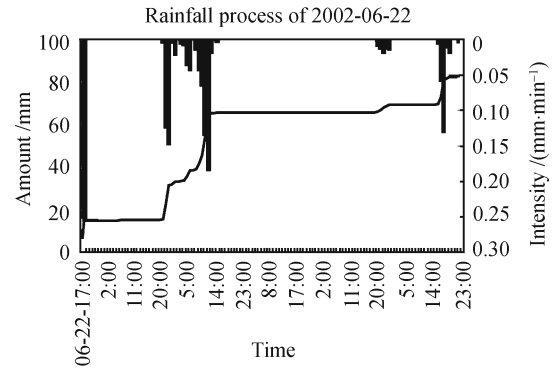
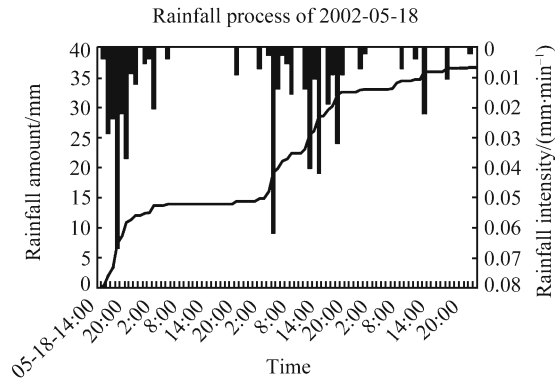


Fig. 1 Gradually dropping rain type and its preferential flow's process

Fig. 3 Sudden rain type and its preferential flow's process

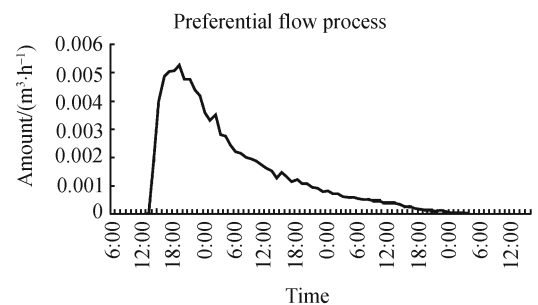
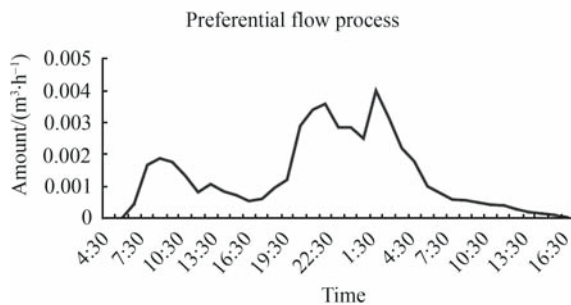
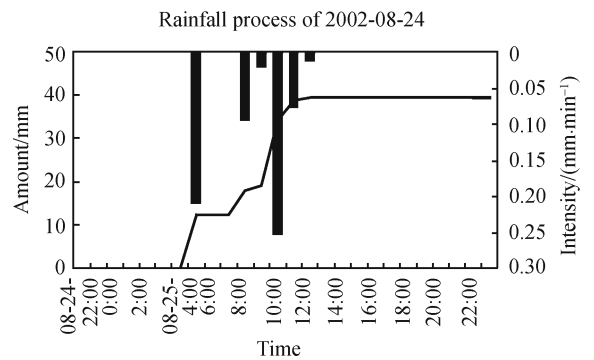
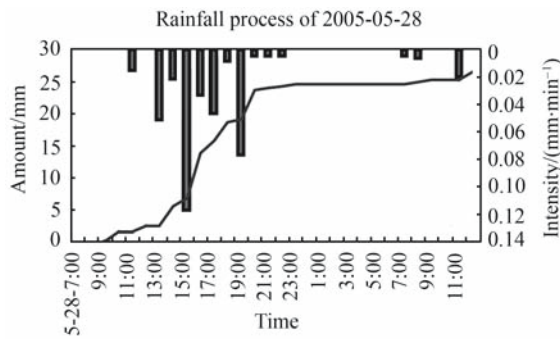


Fig. 2 Even rain type and its preferential flow's process

Fig. 4 Peak rain type and its preferential flow's process

The appearance of a peak could slow the preferential flow's decreasing process and induce little increase of preferential flow amount.

3.2 Influence of soil physical characteristics on preferential flow

The parameters that physically characterize the soil as a function of soil depth are shown in Table 4.

Table 4 Parameters of soil physical characteristics

Soil depth /cm	Soil bulk density /($\text{g}\cdot\text{cm}^{-3}$)	Capillary porosity /%	Total porosity /%	Non-capillary porosity /%
0–15	1.491	47.0	55.6	8.6
16–43	1.505	51.1	55.2	4.1
44–82	1.560	51.2	53.2	2.0
83–110	1.464	46.6	56.7	10.1
>110	1.647	49.2	50.3	1.1

Table 4 shows that soil bulk density increased with soil depth in the depth range of 0–83 cm, but decreased in the depth range of 83–110 cm, and increased again below 110 cm. It is known that soil bulk density is related to the soil texture and the degree of compaction. That the lowest soil bulk density was found in the depth range of 83–110 cm, and the highest below 110 cm may indicate that there are more pores existing in the 183–110 cm horizon. The capillary porosity and non-capillary porosity of the different soil horizons are shown in Fig. 5.

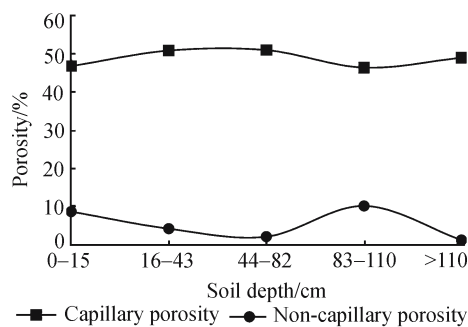


Fig. 5 Pores distribution in different soil horizons

The lowest capillary porosity (or the highest non-capillary porosity) was found in the 83–110 cm soil horizon where the non-capillary pore has more important influence on the soil physical characteristic.

From the experiment of soil pipes in the soil profile, the number of soil pipes was higher in the 80–100 cm soil horizon. It can be deduced that most of the non-capillary pores that existed in the 80–100 cm soil horizon were soil pipes caused by different reasons. Soil pipe is the basic condition for forming preferential flow, so the experiment showed that preferential flow is more easily formed in soil with more non-capillary pores.

3.3 Influence of soil particle size on preferential flow

The sieved soil particle diameter (D_i) is the average diameter between two sieve sizes. The geometric mean soil particle diameter (D_s) represents the average soil particle diameter within a given range (Zhang and Wang, 1999). In Table 4, $D_s = \sqrt{D_i D_{i+1}}$, where D_i is the lower limit value within a certain range of soil particle diameter (mm), and D_{i+1} is the upper limit value within a certain range of soil particle diameter (mm).

By screening the soil samples, the particle size weight percent distribution of the different layers was obtained (Table 5).

The accumulative curves about the distribution of soil particles of different soil layers are shown in Fig. 6.

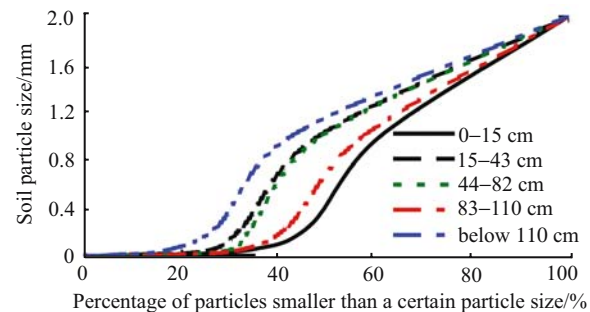


Fig. 6 Accumulative curves about the distribution of soil particles of different soil layers

Table 5 shows that when the geometric mean diameter of soil particles (D_s) is 1.414 cm, the weight percent of these soil particles is highest in the soil layer below 110 cm (57.17%)

Table 5 Soil particle distribution in different soil layers

Size of sieve holes D_i /mm	Geometrical mean diameter D_s /mm	The weight percent of different particles in different layers /%				
		0–15 cm	16–43 cm	44–82 cm	83–110 cm	>110 cm
1.00–2.00	1.414	38.88	49.55	50.97	54.33	57.17
0.25–1.00	0.500	14.79	15.81	15.45	15.67	18.40
0.05–0.25	0.112	12.33	6.64	5.57	4.01	4.23
0.01–0.05	0.022	20.00	16.00	16.00	14.00	11.20
0.005–0.01	0.007	4.00	4.00	4.00	4.00	2.00
0.001–0.005	0.002	8.00	8.00	8.00	8.00	7.00
≤ 0.001	0.001	2.00	0.00	0.00	0.00	0.00

and the least in the 0 to 15 cm soil layer (38.88 %). The highest percent of fine soil particles with D_s no larger than 0.112 mm was found in the soil layer from 0 to 15 cm, and the lowest in the soil layer of below 110 cm, which was 46.33% and 24.4%, respectively (Fig. 6). These comparisons and inspection show that the percentage of coarse soil particles was the least in the surface layer and increased with soil depth.

In the deeper soil layers, the coarser particles helped the infiltration of soil water, and with the effect of geology, the coarser particles helped to form the preferential paths, thus helping to form preferential flow.

3.4 Relationship between the characteristics of soil infiltration and preferential flow

Through the infiltration experiments, the steady infiltration velocity in differential soil layers was obtained (Table 6).

Table 6 Soil saturated infiltration rate in different layers

Soil depth /cm	0–15	16–43	44–82	83–110	>110
Steady infiltration velocity /($\text{mm}\cdot\text{min}^{-1}$)	4.51	11.01	4.55	6.14	1.08

Among the five soil layers, the steady infiltration rate in the 16–43 cm soil layer was the greatest, which may be due to the capillary porosity and the size of the soil particles. The steady infiltration rate in the 83–110 cm soil layer increased greatly after it decreased in the 44–82 cm soil layer. It can be inferred that the many preferential paths in this soil layer resulted in the great increase in the steady infiltration rate. These preferential paths largely enhanced water infiltration, and the fast moving water also accelerated the development of preferential paths in this soil layer.

4 Conclusions

The precipitation that could influence preferential flow's occurrence was not less than 26 mm (within 24 h). The precipitation in the granite area of the Three Gorges may be divided into four types: gradually dropping raining, even raining, suddenly raining and peak raining. The preferential flow process under different rainfall is consistent with their rainfall type. Preferential flow appeared at different times under different rainfall types. It occurred the earliest when the rainfall type is peak raining, then occurred in the suddenly raining, gradually dropping raining and even raining rainfall types in sequence.

The rainfall intensity that could influence preferential flow's occurrence was not less than 0.075 mm/min. After preferential flow occurred, even little changes in rainfall intensity could have an obvious effect on preferential flow's hydrological curve. The appearance of a peak could slow the

preferential flow's decreasing process and induce little increase of preferential flow amount.

The lowest soil bulk density was found in the 83–110 cm soil horizon because of more non-capillary pores there. Preferential paths existed mainly in this soil layer. Therefore, it can be derived that most non-capillary pores in this horizon were preferential paths. In the studied area, the percentage of coarse soil particles was the least in the 0–15 cm soil horizon and the highest occurred below 110 cm. The percentage of coarse soil particles increased with soil depth. In the deeper soil horizon, the coarse soil particles helped the formation of preferential flow.

The greatest steady infiltration rate was found in the 83–110 cm soil horizon where most pores were non-capillary pores. It can be inferred that it was related to the preferential flow.

In this paper, an initial study was made on the spatial distribution of preferential paths and their affecting factors. However, only the foot of the slope in the granite area was studied. The study was significant but limited to reveal the spatial distribution characteristic of preferential paths and the affecting factors in this area only. Therefore, it is recommended that the scope of the study area be extended.

Acknowledgements The paper was jointly supported by National Natural Science Foundation of China (Grant No. 40641005 and 40171014), National Key Basic Research and Development Program of China (No. 2003CB415202-3) and International Foundation for Science, Stockholm, Sweden (No. D/3492-2).

References

- Aubertin G M (1971). Nature and extend of macropores in forest soils and their influence on subsurface water movement. U.S.D.A. Forest Service Research Paper, NE-192
- Gautom M, Watanabe R, Saegiss K H (2000). Runoff analysis in humid forest catchment with artificial neural network. *J Hydrol*, 235: 117–136
- Hao Z C, Feng J (2002). Current research status of water and solute in soil with macropores. *Irrigat Drain*, 21(1): 67–71 (in Chinese)
- Hikaru (1989). Characteristics of pipeflow in different soil layers in forest land. *J For*, 70(7): 318–323
- Hikaru K (1994). Relationship of pipeflow to soil water movement in forestry soil. *J Japan Soc Hydrol Water Resour*, 367: 63–115
- Hikaru K (1996). Study on the relationship of pipeflow to macropores. *Hydrolog Sci Japan*, 227: 81–114
- Johes J A A (1971). Soil piping and stream channel initiation. *Water Resour Res*, 7: 602–610
- Johes J A A (1978). Soil pipe networks: Distribution and discharge. *Cambria*, 6: 1–12
- Landon M K, Delin G N, Komor S C, Regan C P (1999). Comparison of the stable-isotopic composition of soil water collected from suction lysimeters, wick samplers, and cores in a sandy unsaturated zone. *J Hydrol*, 224: 45–54
- Qin Y D, Hu K L (1998). Effects of macropores on saturated infiltration rate in agricultural land. *Proc Water Sci*, 9(2): 107–111 (in Chinese)
- Shi Y H, Wang D, Pan L (2003). Relationship of rainfall and runoff in typical watershed in the Three Gorges. *J Soil Water Conserv*, 17(3): 118–120 (in Chinese)

- Wang M Y, Wang L X (1995). Research on the characteristics of rainfall in the Three Gorges area. *J Soil Water Conserv*, 9(2): 9–18 (in Chinese)
- Zhang H J, Cheng Y, Shi Y H (2001). Pipeflow characteristics in the slope of granite area, the Three Gorges, Yangtze River. *J Soil Water Conserv*, 15(1): 5–8 (in Chinese)
- Zhang H J, Cheng Y, Shi Y H (2003). Effects of the characteristics of soil pores on the pipeflow. *Resourc Environ Yantze River Watershed*, 12(1): 55–60 (in Chinese)
- Zhang H J, Shi Y H, Cheng Y (2002). Movement properties of pipe flow along granite slope of Three Gorges area of Yangtze River in China. *For Stud China*, 4(1): 35–43 (in Chinese)
- Zhang H J, Wang L X (1999). Soil loss characteristics in the slope in the Three Gorges and its dynamic modeling. Beijing: Chinese Forestry Press (in Chinese)
- Zhang H J, Wang Y J (2000). The pipe flow experiment in the granite slope of the Three Gorges area, Yangtze River. *J Beijing For Univ*, 22(5): 53–57 (in Chinese)