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Effect of rock fragments on macropores and water effluent in a forest soil in the stony mountains of the Loess Plateau, China

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Rock fragments exert important effects on soil water movement and macropores.However,they are not well-studied in forest hydrological processes. The results show that the steday effluent is markedly affected by the radius and density of macropores, especially the density of macropores with radii>1.4mm make up only 6.86% of the total,they contribute 67.4% to the variance of steady effluent rates. The area proportion of macropores can better explain the change in steady effluent rates than radii and density of macropores;the steady effluent rate is closely positively related to th area proportion of soil macropores. The increase of the volumetric content of rock fragments in the soil causes increase in the mean radius of the macropores, especially in the density of macropores with radius>1.4mm,but has little effect on the density of macropores with radius<1.4mm.These results show that the effects of rock fragments on the water effluent rate are exerted by affecting the radius and density of macropores to some extent.

Key words: Macropore, steady effluent, rock fragment, stony mountains, Loess Plateau.

INTRODUCTION

Soils with high rock fragment content are widespread throughout the world, accounting for about 30% of the land area in Western Europe, for example. In the Mediterranean zone, such soils occupy more than 60% of the land area (Poesen and Lavee 1994; Cousin et al., 2003). In China, rocky soils are also widespread in mountainous areas. In the mountain meadows around Beijing, for example, the content of rock fragments is higher than 22% on the surface of the coarse brown soil (Fu, 2005). In the Gongga Mountains of Sichuan province, rock fragment content is higher than 18.22% at soil depth of 0 to 30 cm (Cheng et al., 2004). In the second example, the rock fragments are defined as particles ≥3 mm. Rock fragments play an important role in the physical properties of soils including bulk density, hydraulic properties (Torri et al., 1994; Valentin, 1994; Ingelmo et al., 1994; Pérez, 1998), hydrological processes such as infiltration (Brakensiek and Rawls, 1994) and soil evaporation (Li et al., 2006), in runoff and soil erosion (Descroix et al., 2001; Cerdà, 2001), and in soil degradation (Valentin, 1994; Poesen and Lavee 1994).

The macropores originating from soil animals, decayed roots, and swelling or shrinking of the soil provide a pathway by which water can rapidly reach deep soil layers. This pathway has been named the macropore channel (Germann, 1988). Macropores in forest soils

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have important eco-hydrological effects. In the past few decades, several investigations have elucidated the characteristics and factors that control preferential flow (Flury et al., 1994; Wang et al., 1998; Dekker et al., 1999). Macropores, as one of the channels of preferential flow that play an important role in water flow and solute and nutrient transport, have also been studied extensively (Kluitenberg and Horton, 1990; Cote et al., 2000; Larsson and Jarvis, 1999). Beasely (1976) discovered that interflow in the soil occurs after rainfall continues for about 20 min sloped forest land; in this study, the soil profile was not saturated. Mosley (1982) considered that 40% of the rainfall quickly reaches the deeper soil layers by macropore channels. The study of Harr (1977) indicated that the interflow in the soil provides 97% of the storm flow runoff in some catchments with steep slopes. De Vries and Chow, (1978) discovered that the preferential flow induced by macropores can enter soil faster and flow deeper than water flow induced by the matrix potential in the same hydraulic conductivity; they concluded that the macropores are one of the most important factors enabling interflow to occur quickly. Wilson et al. (1990) also showed that macropores are mainly responsible for the interflow in soil on sloping land; particularly, macropores with diameters exceeding 1 mm play an important role in the conduction of soil water, even though there are few of these macropores on sloping land. The combination of different macro- and meso-sized pores can produce different hydraulic conductivity (Luxmoore et al., 1990). There are several kinds of macropores of different origins (Bouma, 1991), and as a result, they have different effects on water movement in different zones and soil types. Macropores have not been fully studied; for example, researchers still do not agree on the definition of a macropore (Beven and Germann, 1982; Flury et al., 1994). A macropore is usually considered as a pore with a radius ranging from 0.03 to 3 mm (Beven and Germann, 1982; Liu et al., 2001). Moreover, rock fragments are an important characteristic of forest soils in mountainous areas, but few studies have been conducted on the effect of rock fragments on macropores and the combined effect of rock fragments and macropores on water flow. Therefore, the effect of rock fragments on soil macropores and water movement needs greater study to thoroughly understand the processes of soil water, and the effects of forest hydrology and eco-hydrological processes of watersheds.

The study site investigated herein lies in the Xiangshuihe watershed, a stony mountainous area in the western part of the Loess Plateau, China. The area is a representative of the whole watershed with respect to climate, vegetation and soil, which is embedded with plentiful rock fragments. A study of the effect of rock fragments and macropores on water flow in this area will provide insight into the hydrologic cycle and soil water movement allowing improved characterization of parameters in a physically-based hydrological model and thus, watershed management.

MATERIALS AND METHODS

Study area and plots

The area is a representative zone of the Loess Plateau at the headwaters of the Jing River, which is a branch of the Yellow River. It is situated in the Xiangshuihe watershed (106°09′-106°30′ E, 35°15′-35°41′ N) in the Liupan Mountains in the southern part of the Ningxia Hui Autonomous Region of China (Figure 1). The altitude ranges from 2060 to 2931 m. The area has a warm temperate continental climate with a transition from semi-humid and semi-arid climatic zones characterized by hot and humid summers, dry and cool winters, and moderate temperatures in the spring and autumn. Annual average precipitation is 591.6 mm, falling mainly in summer and autumn. An annual mean temperature is 5.8°C, while mean monthly temperature is 17.4°C for the hottest month (July) and –7.0°C for the coldest month (January).

The soils are mainly gray-brown with large amounts of rock fragments at elevation <2700 m, and subalpine meadow soil at elevations >2700 m. The parent materials are accumulations of remnants, weathered sand mudstone, shale, and limestone. Large amounts of rock fragments in the area soils have radii ranging between 2 to 30 mm, but concentrated primarily in the range of 2 to 10 mm. Typically, rock fragments with radii < 10 mm are irregular polyhedron or round-grain in shape. Rock fragments with radii >10 mm are commonly thick-strip, round-flat or polyhedron in shape. While rock fragments with random distribution are mostly embedded in the soil. There are fewer rock fragments in the subalpine meadow than in the brown soil.

In addition, the vegetation cover is 70 to 80%. The forest consists mainly of natural vegetation (such as *Betula albo-sinensis, Pinus armandii, Quercus liaotungensis, Tilia paucicostata* and *Populus davidiana*), plantation vegetation (such as *Larix principis-ruprechtii* and *Pinus tabulaeformis*) below 2,700 m, and dwarf shrubs and subalpine meadow above 2,700 m. Several types of shrubs are predominant on the mountain slopes facing the sun. Eight plots were established, including four natural arbor forest, two plantation, one shrub, and one subalpine meadow plot (Table 1).

Field sampling

Soil samples for determination of physical characteristics of the soils were collected using rings with a volume of 200 cm^3 (7 cm in diameter and 5.2 cm in height) at depths of 0 - 10, 10 - 20, 20 - 40, 40 - 60, 60 - 80, 80 - 100 and 100 - 120 cm. All plots representing different vegetation types (Table 1) were investigated by collecting three samples.

Sample treatment

First, the soil column in the ring was placed in a pan and immersed in water for 12 h to reach saturation. Then, the saturation moisture content and total porosity were determined by weighing. Subsequently, soil samples were placed on coarse sand for 12 h to drain water in the non-capillary pores only so that macroporosity could be measured. Capillary porosity was assumed to be the difference between total and non-capillary porosity. The drained soil column was further used to determine features of the macropores (radius and density) by breakthrough experiments.

Due to the different definitions of macropores, macropores were defined here as the pores between field water capacity and

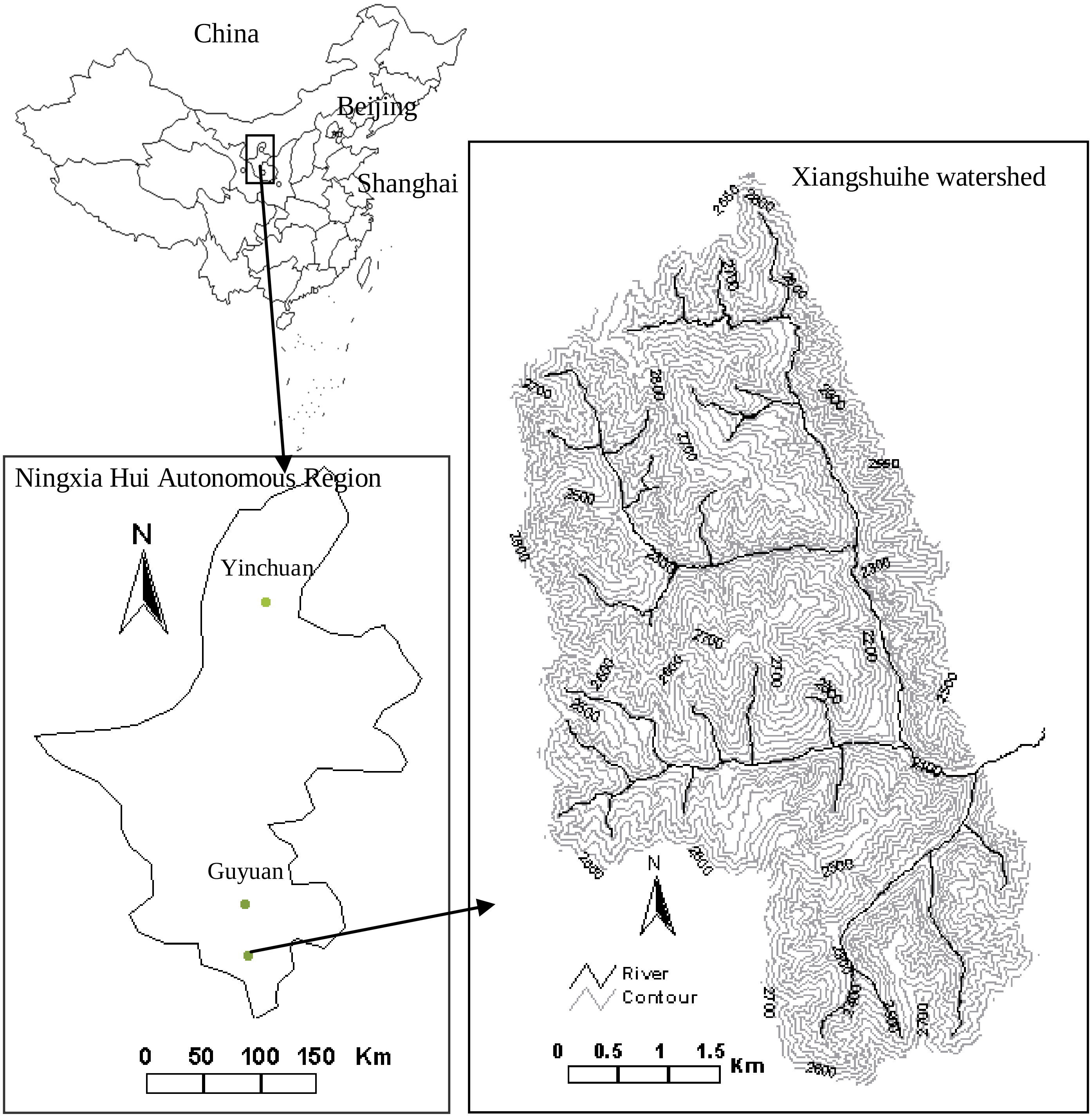

Figure 1. Location of the study area.

saturated moisture content (Shi et al., 2005). Breakthrough curves were determined as follows: the upper edge of the ring containing an undisturbed soil column with water content at field capacity was connected with another ring of the same size for holding water. Vaseline was applied between the two rings to create a waterproof seal and keep the water flowing through the soil column. A sheet of thin filter paper was placed at the soil surface to prevent soil disturbance from infusing water. During the breakthrough experiment, a constant water depth of 2 cm was maintained by using the Marriotte bottle technique. The seepage water from the bottom of the soil column was collected at intervals of 5 s from the beginning of water infusion until the water flux reached a stable level. The radius and density of the macropores in the soil column were calculated by the Poiseuille equation. The principles and computation method used were according to the study of Radulovich et al. (1989) and Shi et al. (2005).

Table 1. Basic characteristics of vegetation and soils in the investigated plots.

Plot	Slope degree (°)	Slope aspect	Slope location	Altitude (m)	Vegetation	Soil depth (cm)	Volumetric content of rock fragment (%)	Bulk density mixed soil and rock fragment (g cm^{-3})
A	7	SE	lower	2155	*Pinus tabulaeformis*	100	23.37	1.20
B	35	NW	middle	2200	*Betula albo-sinensis*	120	27.89	1.11
C	35	SW	lower	2200	*Pinus armandii*	120	36.92	1.30
D	10	E	lower	2150	Shrub	100	25.04	1.03
E	35	E	lower	2220	*Betula platyphylla*	100	22.22	1.06
F	31	N	lower	2060	*Quercus liaotungensis* and *Tilia paucicostata*	100	15.33	1.15
G	45	SE	upper	2286	*Larix principis-ruprechtii*	100	3.73	1.22
H	25	S	upper	2900	Subalpine meadow	100	0.64	1.06

After the breakthrough experiment, the soil column was dried at 105°C to calculate bulk density. In this paper, rock fragment is defined as a particle with a diameter ≥2 mm (Miller and Gurthrie, 1984). Therefore, rock fragments with diameters ≥2 mm (size classes of the rock fragments: 2 - 4, 4 - 6, 6 - 8, 8 - 10, 10 - 12, 12 - 14, 14 - 16, 16 - 20, 20 - 30 and 30 - 40 mm) were sieved according to their sizes, and then washed to remove attached soil particles. Rock fragments were dipped in water to measure their volumetric content.

RESULTS AND DISCUSSION

Variation in volumetric content of rock fragments

The content of rock fragments in the soils of the Liupan Mountains was high and varied with soil depth and among plots. Mean volumetric content of rock fragments at each soil depth for the investigated plots was used to describe vertical distribution of rock fragments. The results indicate that the rock fragment content and its standard error increase with soil depth (Table 2). The depth-weighted mean volumetric content of rock fragments in the 0 - 120 cm layer was compared among plots. The highest volumetric rock fragment content was 36.92% for plot C (*P. armandii*); the lowest was 0.64% for the 0 - 100 cm layer of plot H (subalpine meadow), and the second lowest was 3.73% for plot G (*L. principis-ruprechtii*) (Table 1). The mean volumetric content of rock fragments at the 0 - 100 cm depth for all plots was 16.02%, with a standard error of 10.00%.

Table 3 lists the variance of the volumetric content of rock fragments of different sizes in different soil layers. The results indicate that most of the rock fragments were mainly concentrated in the size range of 2 - 8 mm, and the content of rock fragments in this size was in excess of 50% of the total. Volumetric content of smaller rock fragments (2 - 6 mm) varied less among the different soil layers (Table 3), and that of larger rock fragments (>6 mm) generally increased with increasing soil depth. Volumetric content of rock fragments in the 0 - 40 cm soil depth varied less (Table 3).

Characteristics of soil macropores

The radii of soil macropores ranged from 0.4 to 2.3 mm, with most in the range of 0.7 to 1.8 mm. The density-weighted mean radii of soil macropores ranged from 0.57 to 1.21 mm, with a mean of 0.89 mm. Macropore densities under different vegetation plots ranged from 57 to 1117 per square decimeter, with a mean of 408 and a coefficient of variance of 66.26%. The density of macropores with radii > 1.4 mm was low, making up only 6.86% of the total, and the density of macropores with radii < 1.4 mm was high. The area proportions of soil macropores ranged from 0.76 to 31.26%, with a mean of 10.82%, standard deviation of 7.73%, and coefficient of variation of 71.41% (Shi et al., 2007).

Comparison of breakthrough curves among plots

Breakthrough curves for different vegetation plots were calculated according to the outflow rate over time (Figure 2). Breakthrough curves differed among vegetation types. The steady effluent rate in the soil containing few or no rock fragments was low, at less than 0.3 ml s^{-1} at different soil depths for the subalpine meadow plot and the *L. principis-ruprechtii* plot. The steady effluent rate was higher in soil containing large numbers of rock fragments, e.g., for the *P. tabulaeformis*, *P. armandii*, *B. albo-sinensis*,

Table 2. Variance of the volumetric content of rock fragment at different soil depths.

Soil depth (cm)	0-10	10-20	20-40	40-60	60-80	80-100
Mean (%)	10.30	10.71	11.99	16.42	20.09	21.11
Std. Dev. (%)	8.32	7.08	8.83	11.89	11.12	14.81
Coefficient of Variance (%)	80.74	66.09	73.59	72.45	55.33	70.15

Table 3. Variance of the volumetric content of rock fragments in different sizes.

Soil depth	Volumetric content of rock fragment in different size (%)										
(cm)	2-4 cm	4-6 cm	6-8 cm	8-10 cm	10-12 cm	12-14cm	14-16 cm	16-20 cm	20-30 cm	30-40 cm	>40 cm
0-10	8.39	7.13	4.62	3.13	1.98	0.54	2.03	1.05	2.68	0.00	1.69
10-20	9.13	7.14	4.74	3.15	1.95	1.36	2.07	1.36	2.45	1.45	0.80
20-40	7.47	5.66	4.23	3.12	1.72	0.74	2.82	2.32	2.40	0.17	1.51
40-60	9.68	7.25	5.54	3.75	2.37	1.89	2.86	1.93	4.42	1.89	0.98
60-80	8.50	6.97	5.77	4.45	3.43	1.49	3.38	3.29	6.88	3.92	3.05
80-100	9.63	8.68	6.37	4.92	3.22	1.79	3.80	3.11	7.74	3.83	0.63

The data do not include plot H.

Betula platyphylla, *Quercus liaotungensis, T. paucicostata* and shrub plots, compared to the soil containing few rock fragments. The steady effluent rates varied remarkably at different soil depths and were highest at the 0 - 10 cm depth in the *B. albo-sinensis* plot (2.0 ml s^{-1}) and at the 60 - 80 cm depth in the *Q. liaotungensis* and *T. paucicostata* plot (1.93 ml s^{-1}). We also discovered that the maximum steady effluent rate in the vegetation plots appeared at different soil depths. This implies that the steady effluent rate is affected by many factors, including content of rock fragments and their distribution at different depths.

The mean steady effluent rate had a decreasing followed by an increasing trend with increasing soil depth for all the investigated plots. The mean steady effluent rate at 40 - 60 cm depth was the lowest of all the layers between 0 - 10 to 80 - 100 cm (Figure 3). This indicates that steady effluent rates are affected by many factors. The radii and area proportion of macropores decrease because the effects of plants on soils weaken between topsoil (0 - 10 cm) and 40 - 60 cm depth; correspondingly, the steady effluent rate may be induced to decrease. Subsequently, the steady effluent rate increased between 40 - 60 and 80 - 100 cm depth. This may be mainly due to the higher radii and area proportion of macropores as the content of rock fragments rises with increasing soil depth. These results indicate that the effluent is commonly affected by the role of plants in soil development and the distribution of rock fragments at different soil depths.

Relationship of rock fragments and characteristics of macropores

The volumetric rock fragment content had a significant effect on the radius and density of macropores. A regression analysis showed that the weighted mean radii of soil macropores were positively related to the volumetric rock fragment content ($R=0.79$, $p<0.05$) (Figure 4). The effects of rock fragments on the density of macropores with radii >1.4 mm were analyzed. The results indicated that macropore density was positively related to the volumetric rock fragment content ($R=0.55$, $p<0.01$) (Figure 5). However, macropore density was low in the ellipse area in Figure 5, even though the rock fragment content was high. This may have been caused by a fast increase in the volume of single macropores with increasing rock fragment content. Without the data in the ellipse, the relationship of the volumetric rock fragment content to the density of macropores with radii > 1.4 mm would be strengthened. Furthermore, we also found that the total density of macropores was affected somewhat by the volumetric rock fragment content and this shows that the rock fragment mainly affects the density of macropores with the bigger radii.

Relationship of effluent and characteristics of macropores

Radius

Water flux was positively correlated with the quartic power of macropore radii in the Poiseuille equation. The results also indicated that the steady effluent rate was related to the radii of macropores such that the steady effluent rate increased with the increase of the mean radii of macropores. The quartic power of the radii contributed about 30% to the variance of the steady effluent rate (Figure 6). This implies that the radius of a macropore is only one of the factors that affect the steady effluent rate,

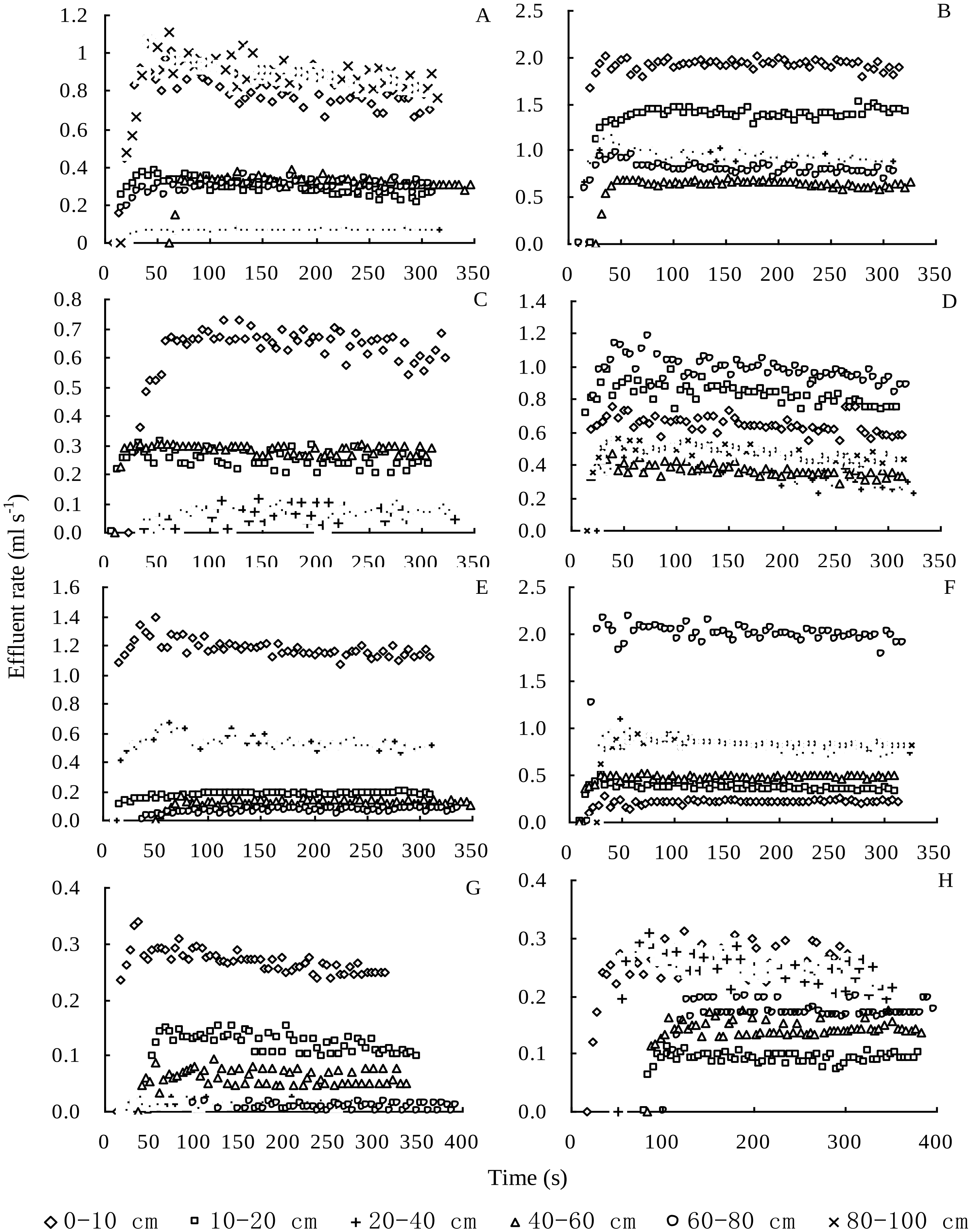

Figure 2. Soil water breakthrough curves for different plots and vegetation types.

and the quartic power of the radii has a remarkable effect on the steady effluent rate (r = 0.55, p<0.01); however, the coefficient of correlation was low.

Density

Soil pores are divided into two structural domains,

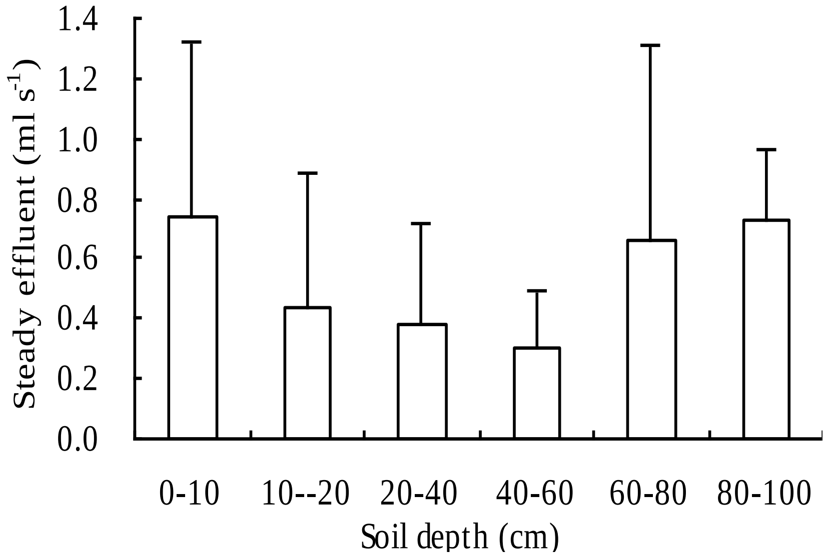

Figure 3. Variation of steady effluent at different soil depths; the bar is the standard errors.

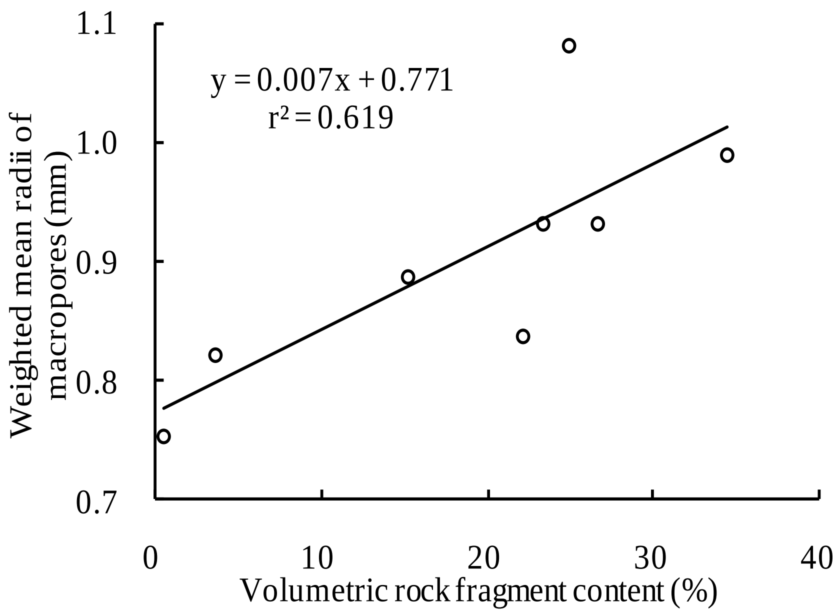

Figure 4. Influence of volumetric content of rock fragments on weighted mean radii of macropores in 8 plots.

namely, the macropore and the matrix domain. Three possible water flow regimes have been suggested: the matrix, macropore and transaction regimes. The Poiseuille equation for tube flow can be applied to represent the relationship between the hydraulic conductivity of the macroporosity and the total macroporosity. The Darcy's and Richards' equations are applicable to describe the flow in the matrix domain (Chen and Wagenet, 1992a, b; Roberto, 2002) and the mechanisms of water flow in the macropore and matrix domains are different. For macropores, the effect of different radius size is also distinct; hence, macropores are divided into two domains: domains with macropore radii more than 1.4 mm and those less than 1.4 mm. The results show that macropores with radii exceeding 1.4 mm contributed 67.42% to the variance of steady effluent rates though their mean density was only 28 per square decimeter, making up only 6.86% of the total density of macropores

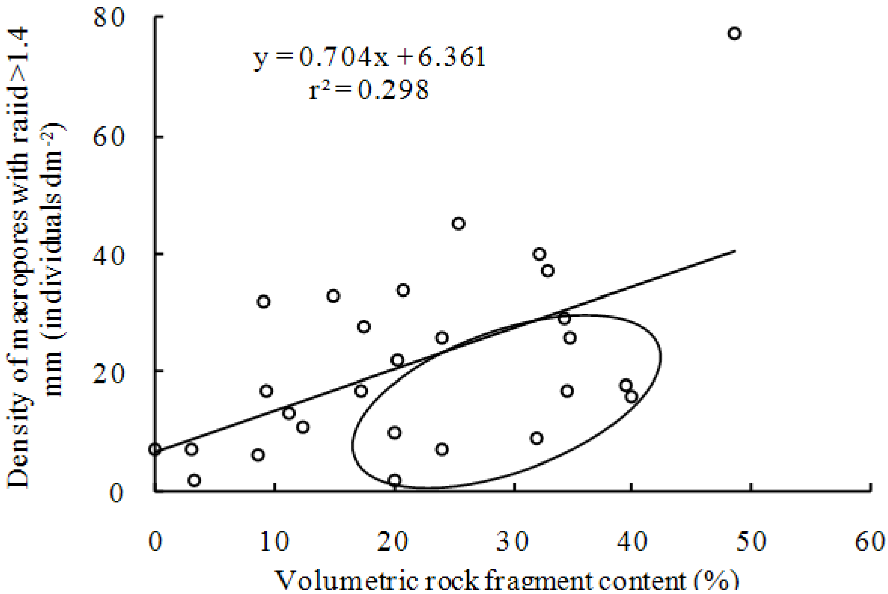

Figure 5. Influence of the volumetric content of rock fragments on the density of macropores with radius>1.4 mm.

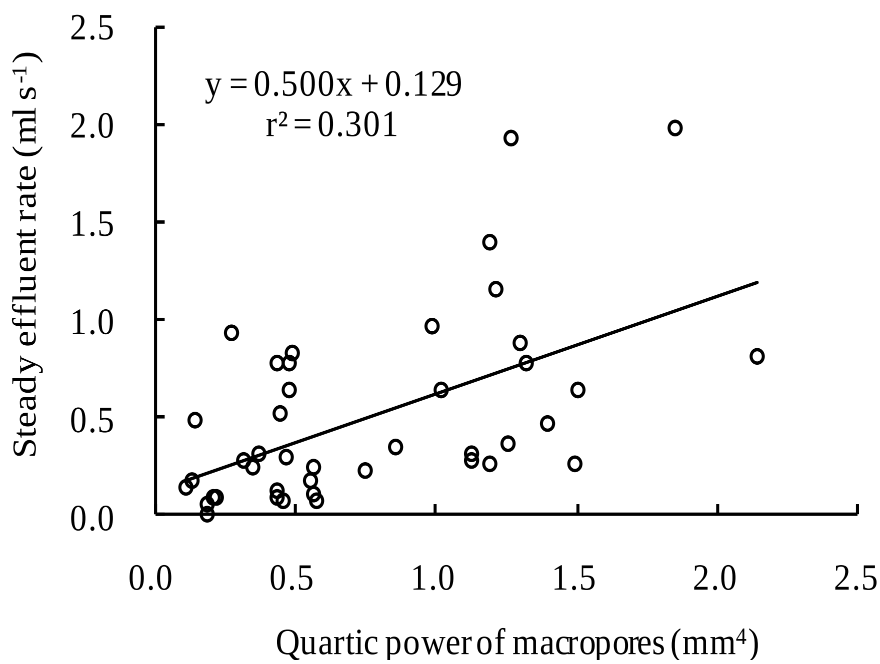

Figure 6. Effect of quartic power of mean macropore radii on the steady effluent rates.

(r=0.83, p<0.01) (Figure 7). On the other hand, macropores with radii less than 1.4 mm had less influence on the steady effluent rate even though the density of such macropores accounted for the larger proportion (r=0.36, p>0.05) (Figure 8). These results which are consistent with those reported by Shi et al. (2005) and Wilson et al. (1990), prove that macropores with larger radii (>1.4 mm) play a more important role in soil water movement than smaller macropores.

Area proportion of macropores

The area proportion of macropores systematically reflected the influence of the radius and density of macropores. Shi et al. (2005) discovered that the area proportion of macropores varied from 2.6 to 21.22% and

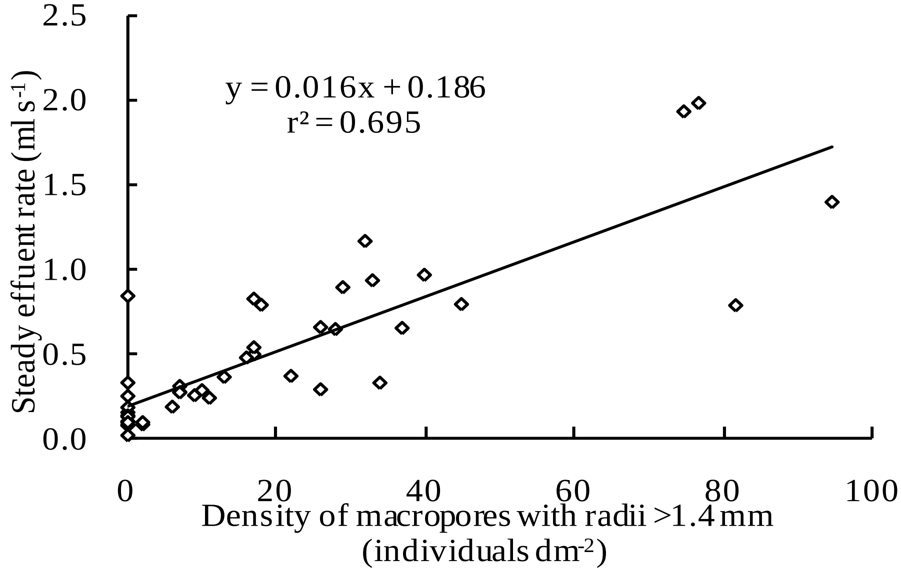

Figure 7. Effect of the densities of macropores with radii > 1.4 mm on the steady effluent rates.

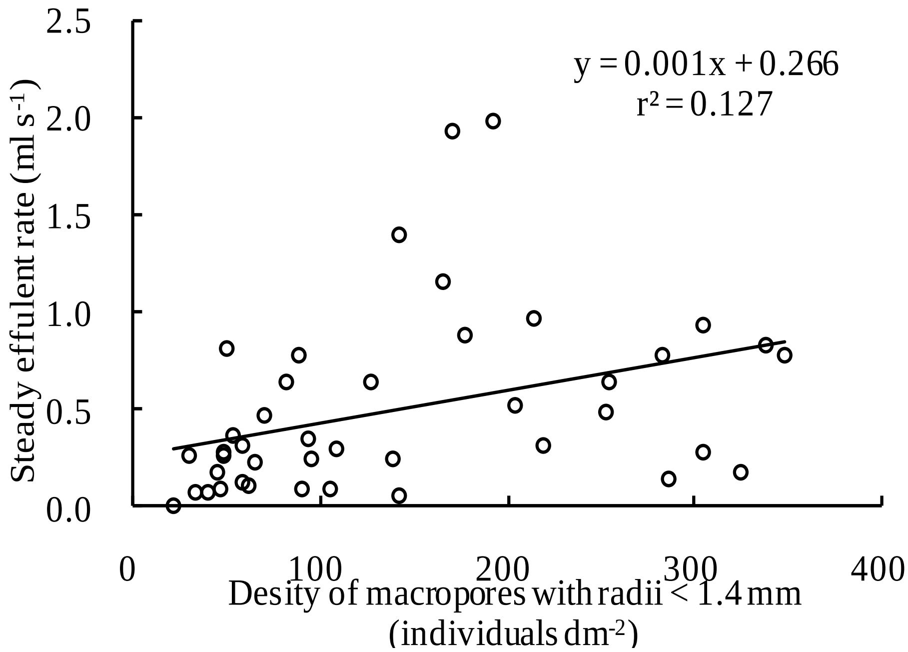

Figure 8. Effect of the densities of macropores with radii < 1.4 mm on the steady effluent rates.

may have a quadratic parabola or power relationship with the steady effluent rate in the reaches of the Minjiang River; namely, the steady effluent rate increased with the increase of the area proportion of macropores when the proportion was lower than 20% and declined when the proportion was higher than 20%. They also concluded that the continuity among the macropores may be the main factor that determined the drainage capacity of macropores when the area proportion of the macropores increased to about 20%.

Allaire-Leung et al. (2000) also found that the importance of macropore continuity increased with an increase in the adsorption coefficient and proved the continuity among the macropores had an important role in water movement and solute transport.

Our results, which were consistent with those reported

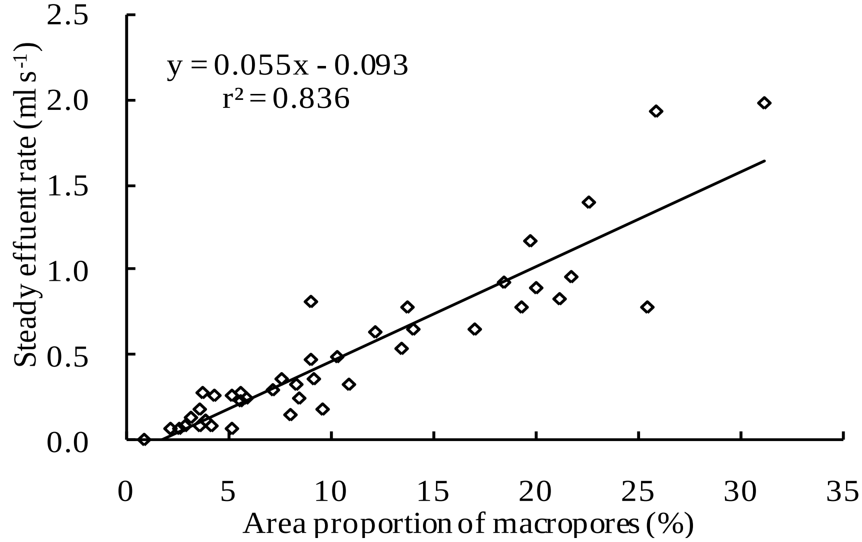

Figure 9. Effect of the area proportion of macropores on the steady effluent rates.

by Shi et al. (2005), indicated that the steady effluent rate had a distinct positive correlation with the increase of the area proportion of macropores (r=0.91, p<0.01) (Figure 9). We conclude that macropores with excellent continuity may be easily formed in the interphase between rock fragments and soil particles owing to the abundance of rock fragments embedded in the soil in situ; thus, water can flow more easily through macropores with less resistance. Further studies will be needed to investigate how rock fragments affect the amounts and continuity of soil macropores, and the physical mechanism by which pore continuity affects water flow.

Relationship of the effluent and the content of rock fragments

The effect of rock fragments on water effluent rate was analyzed for different soil layers (Figure 10). The results indicate that the steady effluent rates first increased then decreased with increasing content of rock fragment at 0 - 60 cm soil depth. However, in the 60 - 80 cm layer, the steady effluent rate slightly declined or did not change greatly with increasing content of rock fragments when the content of rock fragments was less than 15%; the effluent rate increased rapidly when the content of rock fragments was more than 15%. Meanwhile, we had insufficient data for the 80 - 100 cm soil depth to analyze this relationship. The interacting effects of rock fragments and macropores originating from plant roots and animals on soil water movement affect the change of the steady effluent at various soil depths. Roots are concentrated in the surface and topsoil layers, namely the main root layers (0 - 60 cm) where the volumetric content of rock fragments was low and changed less; the macropores originate mainly from the processes of plant roots penetrating the soil, so the steady effluent rates decrease with the increase of soil depths. In deeper layers of soil (>60 cm), the effects of plants on soil weaken gradually, and the effect of increasing content of rock fragments on the effluent rates is strengthened, so that the steady effluent rates are higher in deeper soil layers.

The effect of rock fragments on soil water movement is complex. Previous research (Cerdà, 2001) indicated that rock fragments in the soil surface can retard pond and surface runoff, increase steady-state infiltration rates and diminish runoff discharge, sediment concentrations and erosion rates; rock fragments enhance water percolation and reduce erosion by curbing erodibility and runoff. Descroix et al. (2001) identified two main surface features and hydraulically characterized them to reflect the hydrologic behavior of hillslopes. These features include crusted surfaces with embedded widespread gravel on gentle slopes induce runoff and erosion; stony surfaces, with free pebbles and blocks that protect the topsoil against raindrops and overland-flow kinetic energy lead to less runoff and soil loss. But Brakensiek and Rawls, (1994) considered that rock fragments in the soil can reduce infiltration, and rock fragments on soil surface may decrease or increase infiltration. The sizes of surface rocks have been shown to be directly related to infiltration; smaller rock fragments decrease and larger rock fragments increase infiltration. Fu (2005) summarized the effects of the presence of rock fragments on infiltration as complex; infiltration has positive or negative correlation with rock fragments' cover/content depending on various factors such as soil type, distribution of rock fragments in the soil, and pore characteristics near the rock fragments.

Our study indicates that the steady effluent rates increase with the increase of the volumetric content of rock fragments when the rock fragment is less than 15%,

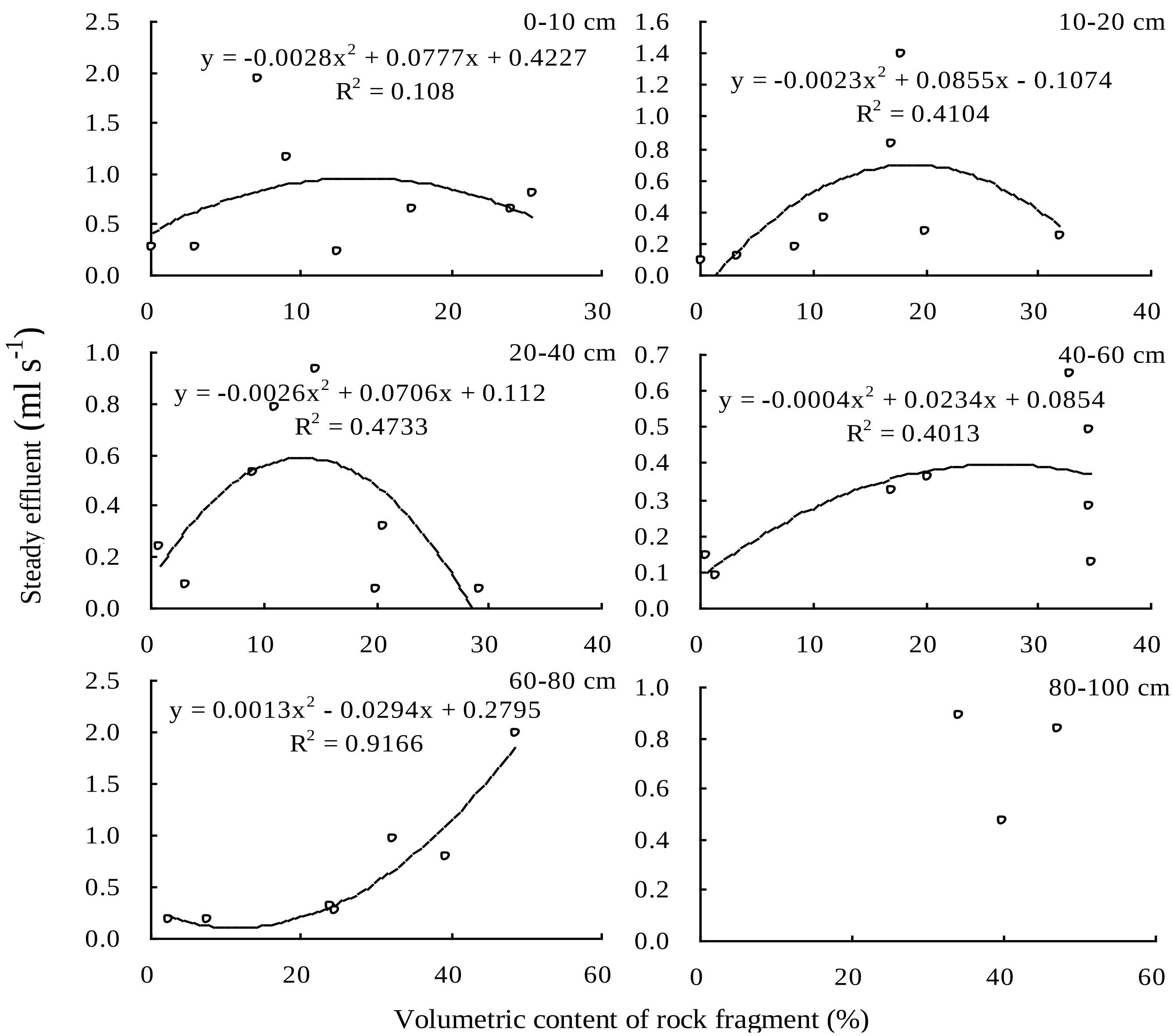

Figure 10. Effect of volumetric content of rock fragments on the water steady effluent volume.

example, a positive correlation, and the steady effluent rates decrease with the increase of volumetric content of rock fragments when the rock fragment is more than 15%, example, negative correlation at 0 - 60 cm soil depth. However, the relationship in the 60 - 80 cm layer was different than in the 0 - 60 cm layer, tends to decline or remain basically unchanged initially (rock fragment content <15%) and then increase rapidly (rock fragment content >15%).

This result is consistent with other results (Fu, 2005; Descroix et al., 2001; Cerdà, 2001). It is also partially consistent with a study of the effect of rock fragments embedded in the soil on infiltration (Brakensiek and Rawls, 1994), and this may be relative to the sizes and contents of rock fragments. How do rock fragments affect forest hydrological processes? At present we still do not know and need further study. However, we have confirmed that the volumetric content of rock fragments affects water movement by affecting the radii, density and area of macropores, and connectivity among the macropores to some extent.

To increase our understanding of the effect of rock fragments on hydrological processes, future research may be needed to address how to distinguish quantitatively the effects of shapes, arrangement, and distribution of rock fragments on hydrological process.

Conclusions

Macropores in soils have an important effect on interflow.

This research indicates that the steady effluent rates increase with the increase of the mean radii and densities of the macropores; the effect of the density of macropores with radii<1.4 mm on the steady effluent rate is relatively low and the effect of the density of macropores with radii>1.4 mm is significant, contributing 67.4% to the variance of the steady effluent rates even though they make up only 6.86% of the total. The area proportion of macropores is a parameter that reflects the combined effects of the radius and density of macropores. Compared with the single characteristic of macropores, such as radius or density, the area proportion of macropores can better explain the change in steady effluent rates, and the determination coefficient of the combined index reaches 0.8361.

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