PORE SIZE DISTRIBUTION AND FLOW CHARACTERISTICS IN A FORESTED HEADWATER CATCHMENT

Kasdi Subagyono and Tadashi Tanaka

ABSTRACT It is obvious in recent publications that pores and pores size distribution play an important role in flow generation, yet the study of dynamic behavior of the effects of pores and pores size distribution on flow characteristics is somewhat rare. As micro pores, mezzo pores and macro pores are various in the soil, the distribution as well as characteristics of those pores are the major factor of flow characteristics in the soils. Pores size distribution was determined considering the volumetric water content at each matric head defined from soil water characteristics curves. Mathematically, pores size distribution is calculated using formula of r = 0.15/h, where r is radius of the pore and h is matric head. The flux of water was determined by installing tensiometer and piezometer in a transect across the hillslope and riparian zone. The results showed that the different of those between hillslope and riparian provides insight that the effects of pores and pores size distribution varies with hydrological zone. In riparian zone, flows are highly affected by micropores (R^2 = 0.49), mezopores (R^2 = 0.26) and total porosity (R^2 = 0.28), while in hillslope side only micropore is dominant. The relationship between pores size distribution and water flow suggested that in hillslope side the flow was dominated by slow flow as micro pores has affected, while in riparian zone the rapid flow was more obvious as mezopores and total porosity have affected.

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ABSTRAK *Publikasi-publikasi terbaru menunjukkan bahwa pori dan distribusi ukuran pori memainkan peranan penting dalam pembentukan aliran. Namun kajian sifat-sifat dinamika dari pengaruh pori dan distribusi ukurannya dalam karakteristik aliran masih jarang. Karena keragaman micropores, mezzopores dan macropores dalam tanah, distribusi dan juga karakteristik pori menjadi faktor utama dalam sifat-sifat aliran dalam tanah. Distribusi ukuran pori ditentukan dengan memasukkan faktor kandungan air volumetrik pada setiap matric head yang ditentukan dari kurva karakteristik air tanah. Distribusi ukuran pori dihitung dengan menggunakan persamaan r = 0.15/h, dimana r adalah jari-jari pori dan h adalah matric head. Aliran (flux) air ditentukan dengan memasang tensiometer dan piezometer pada satu transek melintasi zona lereng dan riparian. Hasil perhitungan menunjukkan bahwa perbedaan antara zona lereng dan zona riparian memberi hasil bahwa efek dari pori dan distribusi ukuran pori bervariasi dalam zona hidrologi. Dalam zona riparian, aliran sangat terpengauh oleh micropores (R^2 = 0.49), mezopores (R^2 = 0.26) dan porositas total (R^2 = 0.28). Sementara, pada sisi lereng hanya micropore yang dominan. Hubungan antara distribusi ukuran pori dan aliran air menunjukkan bahwa pada sisi lereng aliran didominasi oleh aliran lambat karena micropore yang terpengaruhi. Dan di zona riparian, aliran cepat lebih tampak karena mezopore dan porositas total yang terpegaruhi.*

Kata kunci: *pori, distribusi ukuran pori, aliran, riparian, lereng bukit*

INTRODUCTION

Forested soils are rich in organic matter and it is common that the soils are also permeable. Pores and pore size distribution are the major factors determining the permeability and flow characteristics of the soils. Under such soils, subsurface and surface hydrological conditions differ with those under impermeable soils. Thus, the processes governing the flow generation are affected much by the pores and pores size distribution.

The importance of soil pores on the flow generation has been reported by many authors; however most of them have not explained yet the role of pores size distribution. Burt (1989) summarized the storm runoff mechanism relevant to the variable source areas concept. More recent studies have provided the important conclusion that macropores play a major role, by passing the soil matrix and providing rapid discharge of the water table (for example Scanlon *et al*., 2000), dominating the infiltration water through soil profile (Buttle and McDonald, 2000), and contributes much in the solute transport process (Tsuboyama *et al.*, 1994; Iqbal, 1999). Furthermore, these roles are determined by the morphological characteristics of macropores (Noguchi *et al*., 1997). This study is dealt with pore size distribution and its importance to flow generation in a forested headwater catchment.

A number of studies have shown that subsurface flow, which forms a major component of stream flow, is essentially through pipes (Jones, 1997; Tsukamoto and Ohta, 1988; Putty and Prasad, 2000). Most of the pipes are made by hydraulic pressure during the storm and activities of small animals and insects and decaying roots. Most of these pipes are maintained by the frequent passage of water as in colluvial soils or by the passage of insects and small animals. If the pipes are not maintained, they gradually disappear and become invisible, but are still very permeable. It is assumed that the invisible pipes contribute greatly to the high saturated hydraulic conductivities of the surface soil (Tsukamoto and Ohta, 1988). The important of pore size distribution to flow characteristic has also been reported by Luo *et al.* (2008). They found that preferential flow pathways in an intact structured soil consist of a complex network of earthworm burrows, root channels, interaggregate macropore**s**, and mesopore**s** or even micropores in the soil matrix**.** From their study in Tachikawa and Toyoura, Hamamoto et al. (2008) reported that a greater volume of large pores (>0.01 cm) and a more continuous pore network led to the greater density-driven flow.

Porosity is highly affected by compaction (Alauoi and Helbling, 2006), while variability of effective porosity highly affects the variability of the pore-size distribution (Hayashi, *et al*., 2009). The pore network may also vary with soil depth, in part due to the soil horizonation and different macropore**s** involved (Luo *et al.*, 2008). Cycles of wetting and drying (WD) naturally in soils affects the pore structure through altered hydraulic stresses (Peng *et al.*, 2007). Peth *et al.* (2008) reported that morphological feature of pore space determined the storage and transport of gas and water.

The objectives of the present study are to analyze relationship between pore size distribution and flow characteristic in a forested headwater catchment, and to elucidate the role of pore size distribution on the dynamic of water flow during storm event under different sites of hillslope and riparian zone.

MATERIALS AND METHODS

The study was conducted from August 2000 to August 2001 in Kawakami Experimental Basin, Nagano Prefecture and Central Japan. The Experimental basin belongs to the Agriculture and Forestry department of Tsukuba University.

Site Description

Kawakami Experimental Basin (KEB) is a first order basin of 5.2 ha from the total area of 14 ha. he altitude of the catchment ranges from 1500 m to 1680 m above sea level with slightly steep slopes (about 20%) over the riparian zone and very steep slopes (>60%) over the hillslope area.

This area underlied by late Neogene of the Meshimoriyama volcanic rocks, which consists of lavas and pyroclass of olivine-hornblende-pyroxene andesites (Kawachi, 1977). The upper soil mantle primarily consists of inceptisols with very narrow area of the riparian zone covered by 20 cm to 30 cm of peat. The A-horizon is rich in organic matter with rapid hydraulic conductivity (Ks = 21.6 - 93.6 cm/h), while the B-horizon which has more clay has a very slow hydraulic conductivity (Ks = 0.007 - 0.9 cm/h). Mean annual precipitation is about 1500 – 1600 mm, producing 853 mm of runoff (Matsutani, 1993). A natural deciduous forest of oak (*Quercus mongolica* Fisch), larch plantation (*Larix leptolepis* Gordon), and the bamboo grass (*Sasa nipponica*) are very common in this area.

Methods

Pores and pores size distribution were characterized prior to identify the conductance properties and flow water characteristics through the soil at different part of headwater catchment including hillslope side and riparian zone. Pores size distribution was determined considering the volumetric water content at each matric head defined from soil water characteristics curves. Water fluxes along hillslope and riparian zone were measured using a transect nested by tensiometers and piezometers.

a. Determination of three-phase distribution

To identify the volumetric proportion of solid, liquid and gaseous phases, three phase distribution was analyzed for every horizon within the soil profile in the southern and northern hillslope as well as in the riparian zone. Undisturbed soil sample taken from each horizon of the soil profile was fixed in the three phase meter to determine the solid proportion. The liquid and the gaseous proportions were, then, calculated involving the data of bulk density and the volumetric water content.

b. Determination of pores and pore size distribution

The diameter of the pores was calculated, which is based on the phenomenon of capillarity. A capillary tube dipped in a body of free water will form a meniscus as the result of the contact angle of water with the wall of the tube. The curvature of this meniscus will be greater curvature causes a pressure difference to develop across the liquid-gas interface as illustrated in the following equation:

$$\triangle P = (2\gamma\cos\alpha)/r \qquad (1)$$

Where $\triangle P$ is the pressure difference between the capillary water (under the meniscus) and the atmosphere, γ is the surface tension between the liquid and the air, α is the contact angle and r is the radius of the capillary. The hydrostatic tension (negative pressure) in a capillary tube is proportional to the height (h) above the free water surface. The height of rise of water in a uniform capillary is given by the following equation:

$$h = (2\gamma\cos\alpha)/(r(\rho_l-\rho_g)g) \qquad (2)$$

or,

$$h = (2\gamma\cos\alpha)/r\rho_w g) \qquad (3)$$

This relation has been used widely in the work on soil water. If the contact angle between solid and liquid is zero, then cos α = 1 and

$$h = 2\gamma/(r\rho_w g) \qquad (4)$$

Assuming for water at 20^{o}C γ = 72.75 dynes. cm^{-1}, ρ_w = 0.9989 g.cm^{-1} and g = 981 cm.s^{-1} Thus,

$$r = 0.15/h \qquad (5)$$

The diameter of pore in µm was plotted again the pores space in volume percentage. The pore sizes were classified based upon the size and the function of the pores as presented in Table 1.

Table 1. Size and function of pores, which are considered in the evaluation of subsurface water flow

Pores	Diameters (µm)	Functions
Macropores	> 100	Drainage by gravity flow and aeration. Rapid water flow trough soil and aeration at field capacity takes place through the network of macropores. The pores in which roots proliferate are also classified into the macro pores.
Mesopores	30 – 100	Conduction of water by rapid capillary flow.
Micropores	< 30	Water retention and slow capillary flow. Micropores are significantly important in the section on available water capacity.

Source: Verplancke (1995)

c. Hydrometric measurements

To define flow characteristics of the basin, transect nested with piezometers and tensiometers in different depths was set up at the northern valley in the place where the riparian zone was prominently developed. A partly perforated piezometer was used, which is a PVC tube with an inner diameter of 0.04 m and the outer diameter of 0.048 m and bottom perforation length of 0.10 m. The rest of about 0.20 to 0.30 m remains above the surface to avoid overland flow water (if any) to enter the piezometer. Manometric tensiometer used for experiment was a mercury container connected with water column of various depths. The water column was a PVC tube with inner diameter of 0.015 m and outer diameter of 0.017 m complemented with porous cup at the bottom.

Hydrometric data was recorded in monthly base data and event base data of small, medium and large storm. During large storm event on August 21-22, 2001, soil water and groundwater potentials were recorded every two hours covering the whole process of the storm event. During small storm event on March 28-29, 2001, soil water and groundwater potentials were recorded every two hours.

d. Statistical analysis

Relationship between pores size distribution and flow water was analyzed using regression.

RESULTS AND DISCUSSION

Three-phase Distribution

In general, the soils across the riparian and the hillslope have large amount of porosity than the solid phase (Figure 1). At the northern hillslope, volumetric water content was high in the top of 0.8 m (about 60%), decreased at a depth of 1.2 m to the value of 45% then tends to increase with depth. Although the total porosity was high, only 5% was composed with air (air-filled porosity). The volumetric water content of the soil of the southern hillslope increased with depth with some exceptions for 0.5 m and 1 m depth.

The higher air-filled porosity (compared with both the northern hillslope and the riparian zone) was clearly identified at the top of 0.6 m then decreased drastically with depth. The mean air-filled porosity was 10% of the total porosity. The soil of the riparian zone was almost saturated and only about 2.5% of the total porosity was filled with air. The volumetric water content drastically decreased up to a depth of 0.5 m then increased with depth. It is obvious that soil at southern hillslope has largest amount of air-filled porosity. About 20% of air-filled porosity was measured at a depth of 0.10 m then decreased with depth up to about zero at a depth of 0,80 m. The high amount of porosity is subject to distinguish flow characteristic in the soil of the study area with other watersheds especially when deforestation is obvious. It also suggests that in forested area, sub surface flow is more dominant than surface flow due to the fact that infiltration rate is obviously high. Porosity is agent of water flow and storage capacity in the soil. The more obvious the number and the size of pores to govern water flow the more dominant the role of sub surface flow. In contrast, if the number and the size of pores are suitable for water storage there will be amount of water stored in the soil.

Pores and Pores Size Distribution

Pores and pore size distribution at the three different sites of the northern hillslope, the riparian zone, and the southern hillslope are presented in Figure 2. Generally, total porosity decreased with depth at all soil profiles, except for the riparian zone profile. The soil profiles are dominated by micro pores (< 30 μm). Macro pores (> 100μm) decreased with depth up to 0.8 m then increased to a depth of 2 m, at the northern hillslope profile and up to 0.5 m then increased to a depth of 1.2 m at the riparian zone profile. These pores decreased with depth at the southern hillslope.

The pores size distribution in the soil profile either at southern hillslope, riparian zone and northern hillslope suggests that shallow sub surface zone in the soil profile is important to govern rapid sub surface flow. The macro pores is also dominant in soil bedrock interface which is also significant in affecting flow. It is in agreement with that found by Subagyono (2003) where rapid subsurface flow occurred in the soil-bed rock interface.

Pores Size Distribution vs Flow Water

Effect of porosity on flow magnitude was more obvious in riparian zone rather than that in hillslope side. In hillslope side, only micro pores have positive effect on flow magnitude, while in riparian zone the flow was not only affected by micro pores but also mezo pores and total porosity (Figure 3 and 4). The relationship between pores size distribution and flow of water suggested that in hillslope side the flow was dominated by slow flow as micro pores has affected, while in riparian zone the rapid flow was more obvious as mezo pores have affected. This evident was in accordance with hydrometric data that near surface riparian had the highest contribution to stream flow (45%) compared to that of hillslope soil water (35%) and deep riparian groundwater (20%) (Subagyono, 2003). In riparian zone, macropores have a negative effect on flow of water as depicted in Figure 4.

From hydrometric data, Subagyono (2003) also explained that at hillslope side, the water was rapidly infiltrated into the soil followed by the increase of the wetness in shallow sub-surface zone. This evidence proved as well that there was no "Hortonian" overland flow observed in the hillslope segment. This water was distributed in the soil profile and part of it moves down slope through the average depth of 1 m and it was identified to be the subsurface storm flow. This flow was similar with that defined by Freeze (1972) as a shallow perched saturated flow above the main groundwater level. Robinson and Sivapalan (1996) found that the flow in the stormflow zone is entirely down slope.

Figure 3 and 4 have also proven that the effect of pores and pores size distribution on flow is determined by the specific hydrological zone such as saturated zone (riparian) and unsaturated zone (hillslope side). The dynamic behavior of storm event is also a factor that could not be avoided as a determinant factor of stream flow generation, where the antecedent wetness plays an important role. Subagyono (2003) reported that the flow is dominantly vertical during pre-onset rain, then progressively developed into lateral flow due to the increase of rainfall amount and antecedent wetness following storm runoff. Different flow patterns were observed across the riparian and the hillslope segment during the onset rain. Those flow patterns included (a) vertical flow at the near ridge, (b) the progressively change of flow direction at the mid-slope, (c) variable flows at the border between the hillslope and the riparian, (d) lateral flow at near surface riparian zone in the near stream channel, and (e) considerably downward flow at the deep riparian zone combined with the lateral flow at the soil-bedrock interface.

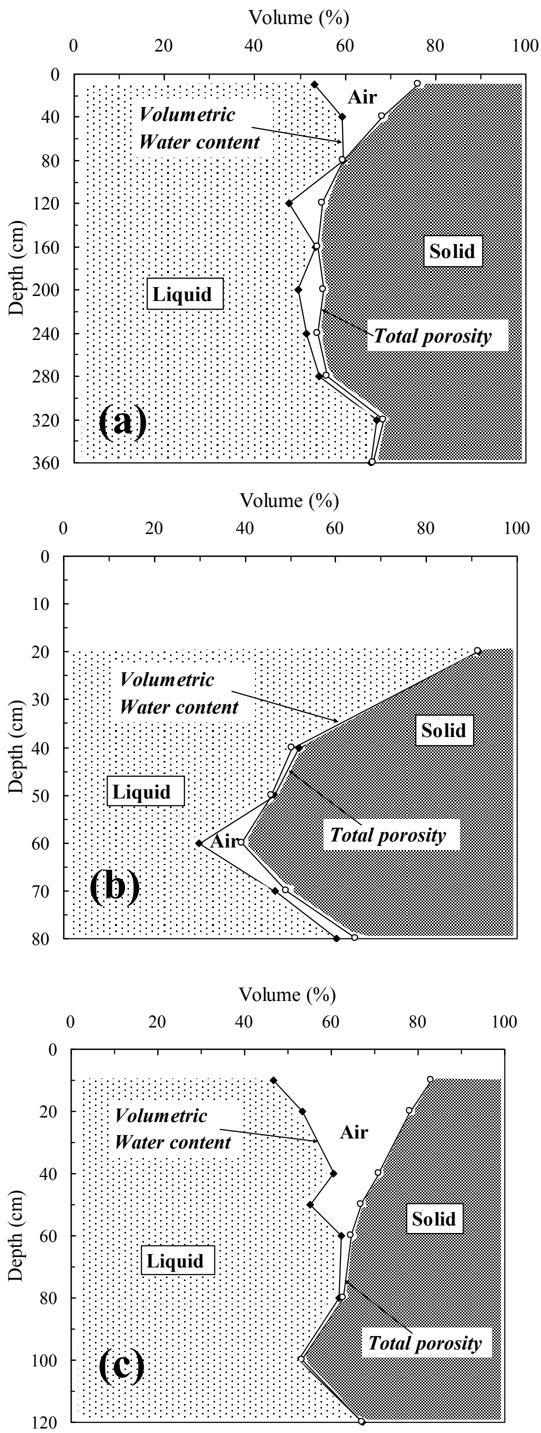

Figure 1. Profiles of three-phase distribution at (a) northern hillslope, (b) riparian zone and (c) southern hillslope

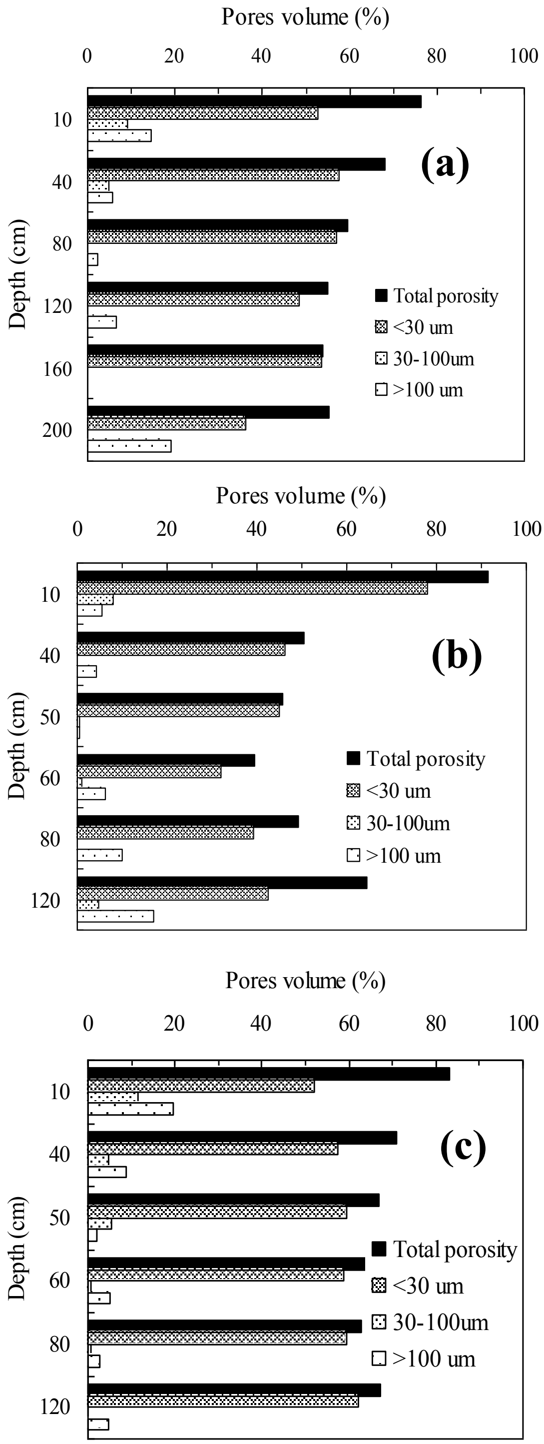

Figure 2. Pores and pore sizes distribution at different depths of (a) northern hillslope, (b) riparian zone, and (c) southern hillslope

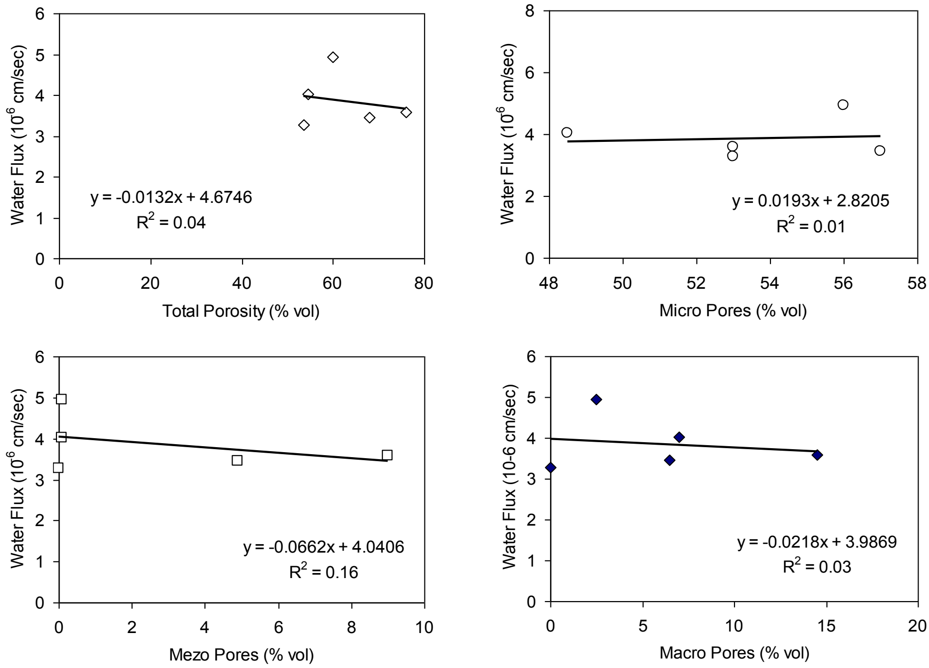

Figure 3. Relationship between pore size and water flux in hillslope side

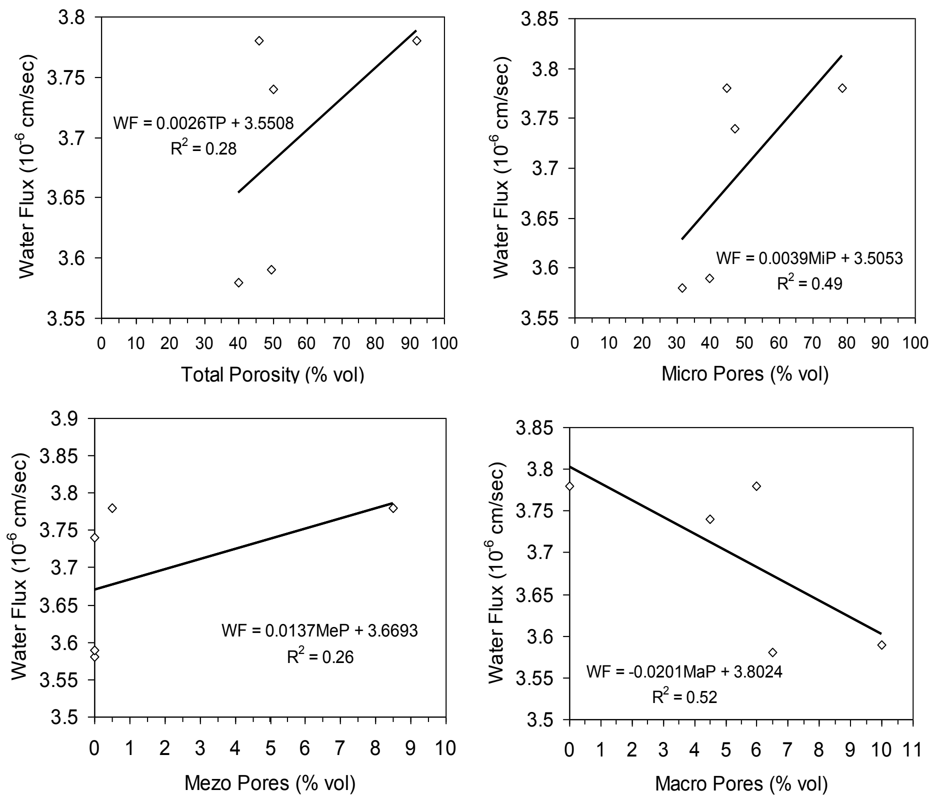

Figure 4. Relationship between pore size and water flux in the riparian zone

CONCLUSIONS

Pores and pores size distribution are determinant factors of water flow through soil. As micro pores, mezzo pores and macro pores are various in the soil, the distribution as well as characteristics of those pores are the major factor of flow characteristics in the soils. Evaluation on the relationship between pores and pores size distribution and water flow is crucial. In the present study, the different of those between hillslope and riparian provides insight that the effects of pores and pores size distribution vary with hydrological zone which is reflected in riparian and hillslope side. In riparian zone, flows are highly affected by micropores, mezopores and total porosity, while in hillslope side, only micropore is dominant. The macro pores is also dominant in soil bedrock interface which is also significant in affecting flow.

The relationship between pores size distribution and water flow suggested that in hillslope side the flow was dominated by slow flow as micropores has affected, while in riparian zone the rapid flow was more obvious as mezopores have affected. It suggests that antecedent wetness can not be neglected as a determinant factor of flow characteristics. In the saturated zone (riparian) where antecedent wetness is high, not only micro pores plays a role but also mezzo pores and total porosity give obviously effect to flow.

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