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THE EFFECT OF VARIABILITY IN SOIL HYDRAULIC PROPERTIES ON WATER FLOW IN A FORESTED HILL SLOPE

Pengaruh Variabilitas Sifat-sifat Hidrolika Tanah Terhadap Aliran Air di Lereng Berhutan

HENDRAYANTO[1], **KOSUGI KEN'ICHIROU**[2] & **MIZUYAMA TAKAHISA**[2]

ABSTRAK

Pengaruh variabilitas sifat-sifat hidrolika tanah terhadap aliran air pada lereng berhutan dianalisis dengan menggunakan persamaan dua dimensi Richard secara numerik. Model fungsi-fungsi konduktivitas hidrolika dan retensi air digunakan model lognormal (Kosugi, 1996). Variabilitas sifat-sifat hidrolika tanah dievaluasi dengan menggunakan teori penyekalaan (scaling theory) (Hendrayanto, et al., 2000). Hasil penelitian menunjukkan bahwa penggunaan nilai rata-rata sifat hidrolika tanah cenderung memberikan nilai dugaan aliran air yang lebih rendah (under estimate). Pola penyebaraan faktor penyekala (scaling factor) mempengaruhi debit maksimum dan kurva resesi hidrograf. Makin besar faktor penyekala ke arah hilir lereng, debit maksimum makin lebih besar dan kurva resesi hidrograf makin curam, dan sebaliknya.

INTRODUCTION

The flow of water in the upper soil layer is a phenomenon encountered in various applications. Their modeling has been a subject of intense research. In a forested hillslope, the water flow phenomenon is very important for water resource management and predicting slope failure caused by heavy rainfall.

Forested hillslope is usually covered with forest soil, which has peculiar pore radius distribution and hydraulic properties. It has been frequently pointed out that the existence of large size pore increases the permeability of forest soil. This reduces the surface flow and increases the water infiltrates into soil profiles (Kirkby, 1978; Tsukamoto, 1992). The water flow studies in forested hill slope have been intensively done (Kubota *et al*.,1987; Ohta *et al*., 1983; Suzuki, 1984; Tsuboyama and Sammory, 1989; Sammory and Tsuboyama, 1990 etc.). Kosugi (1997) evaluated the effect of pore radius distribution on water flow. These studies applied a homogeneous soil, that is, the variability in soil hydraulic properties was not taken into consideration. However, forest soil shows high

[1] Scientist & lecturer of on Laboratory of Forest InfluenceFaculty of Forestry, Bogor Agricultural University Kampus IPB Darmaga, Bogor
[2] Graduate School of Agriculture, Kyoto University, Japan

variability in soil physical properties related to water flow phenomenon (Hendrayanto *et al*., 1999 and 2000).

The effect of variability in soil hydraulic properties on water budget of agricultural land has been studied extensively (Sharma and Luxmoore, 1979; Sharma *et al*. 1980; Hopmans and Sticker, 1989; Kim and Stricker, 1996; Kim *et al*., 1997). These studies showed that the water budget of the soil with the mean parameters was significantly different with the water budget of the soil with variable parameters.

Many approaches have been proposed to cope with the field variability for water flow simulation. One of them is to scale soil hydraulic properties according to the concept of similar media (Warrick *et al*, 1977, Sharma *et al*., 1980, Hopmans and Stricker, 1989). The attractiveness of the scaling theory lies in its potential to express spatial variability in terms of a single physically-based parameters. Using scaled hydraulic properties, the stochastic characteristics of spatial variability of hydraulic properties is described by the stochastic characteristics of scaling factors. Natural soils usually do not satisfy the strict similar-media requirement, and therefore the theory may have to be applied in an approximate form. Reichard *et al*. (1972) showed that laboratory-measured horizontal infiltration into soils having wide textural range could be scaled successfully. Hendrayanto *et al*., (2000) showed that water retention and hydraulic conductivity of forest soil could be scaled successfully by using the simultaneous method, in which the tortuosity parameter, *l*, was optimized (method 3b).

In this study, the effect of spatial variability in hydraulic properties on two dimensional water flow in a forested hillslope is evaluated.

THEORY OF TWO DIMENSIONAL WATER FLOW

Figure 1 shows a schematic of a hillslope considered in this study. The two basic equations for water flow are Darcy-Buckingham law,

$$q_x = -K\left(\frac{\partial \psi}{\partial x} + \sin\omega\right)$$

$$q_z = -K\left(\frac{\partial \psi}{\partial z} + \cos\omega\right) \quad \text{.......... (1)}$$

and the continuity equation

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_x}{\partial x} - \frac{\partial q_z}{\partial z} \quad \text{.......... (2)}$$

where q_x and q_z are water flow in the x and z directions, respectively, t is time, and α is slope gradient. Elimination of q_x and q_z from eq.(1) and (2) leads to the well-known Richards' equation:

$$C(\psi)\frac{\partial\psi}{\partial t}=\left[\frac{\partial}{\partial x}\left\{K(\psi)\frac{\partial\psi}{\partial x}\right\}+\frac{\partial}{\partial x}K(\psi)\sin\omega\right]+\left[\frac{\partial}{\partial z}\left\{K(\psi)\frac{\partial\psi}{\partial z}\right\}+\frac{\partial}{\partial z}K(\psi)\cos\omega\right] \qquad (3)$$

where $C(\psi)=\dfrac{d\theta}{d\psi}$ is the water capacity function defined as the slope of the soil water retention curve. To solve eq. (3)
requires the models for soil water retention and hydraulic conductivity functions. In this study, the models for soil water retention and hydraulic conductivity functions were represented by LN models of Kosugi (1996). Based on LN model, the water retention function is expressed as :

$$S_e=(\theta-\theta_r)/(\theta_s-\theta_r)=Q\left[\ln(\psi/\psi_m)/\sigma\right] \qquad (4)$$

The water capacity function $C(\psi)$ is derived by differentiating eq. (4)

$$C(\psi)=\frac{\theta_s-\theta_r}{\sqrt{2\pi}\sigma(-\psi)}\exp\left[-\frac{\left\{\ln(\psi/\psi_m)\right\}^2}{2\sigma^2}\right] \qquad (5)$$

and hydraulic conductivity function is expressed as:

$$K(\psi)=K_s\left[Q\left(\frac{\ln(\psi/\psi_m)}{\sigma}\right)\right]^l\left[Q\left(\frac{\ln(\psi/\psi_m)}{\sigma}+\sigma\right)\right]^2 \qquad (6)$$

Equation (3) was combined with eq. (5) and eq. (6), and solved using Crank-Nicholson finite difference scheme. The domain having a size of 30 x 1 m (Fig. 1) was divided into 3000 elements. The size of each element was 30 x 10 cm. The slope gradient of the domain was 35° (Figure 1). The constant pressure head under the equilibrium condition with a 10 cm saturated zone was imposed to compute discharge at the outlet of the slope (a-b in Figure 1). At the bottom of soil profile and the upper boundary of the slope (b-c and c-d in Fig. 1), zero-flux condition was imposed. At the soil surface (a-d in Figure 1), natural rainfall was applied as the input for simulations. The initial condition was the hydraulic equilibrium with a limitation of the minimum pressure head of – 300 cm. The same rainfall condition was repeatedly used for two months and the latter half period was considered for analyses in order to eliminate the effects of initial conditions.

METHOD

To evaluate the effects of spatial variability in soil hydraulic properties on two dimensional water flow, the reference soil was de-scaled for each of the 3000 elements (Figure 1) by using randomly generated scaling factors. Twenty-five sets of scaling factors were generated randomly using Box and Müllar method assuming that the scaling factor obeys the lognormal distribution. The mean and the variance of $\ln\alpha$ were set to be equal to those obtained by Hendrayanto *et al*., (2000) the mean was 0 and the variance was 0.86.

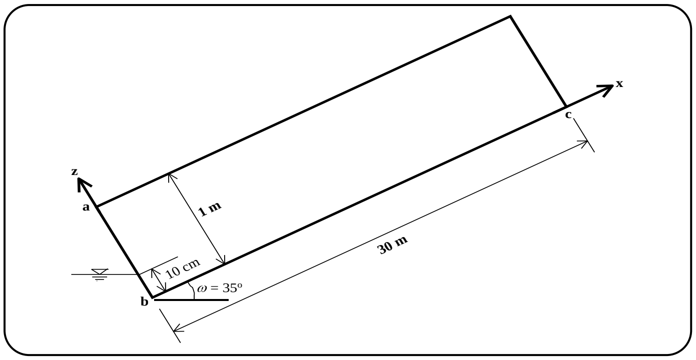


Figure 1. Schematic hillslope as a domain applied in the simulations

RESULTS

Figure 2 shows the hydrograph for reference soil and 25 hydrographs for heterogeneous soils using 25 sets of randomly generated α values. Figure 2c to 2e are enlarged hydrographs for the periods T1 to T3 in Figure 2b, respectively. In Figs. 2c and 2d, all hydrographs for heterogeneous soils (shown by dotted lines) had higher peak discharge rate than the hydrograph for the reference soil. In Figure 2e, the hydrographs for heterogeneous soils were scattered around the hydrograph for the reference soil, but mostly still lied above the hydrograph for the reference soil. That is, the reference soil parameters tend to underestimates storm water discharge, provided that the soil heterogeneity in nature is fully described by the randomly generated scaling factor distribution. By using a greater σ (black cyrcle hair line in Figure 2b), the hydrograph for the reference soil had larger peak discharge rate than the original hydrograph. On the contrary, a smaller σ value reduced the peak discharge rate (white cyrcle line in Figure 2b).

The hydrographs for the heterogeneous soils are characterized by the scaling factor distribution in the domain. It was found that the peak discharge rate tends to be larger when larger α values were allocated to the down-stream part of the slope shown in Figure 1. To clarify this phenomena, the extreme conditions were set; one of the 25 sets of randomly generated α values were arranged to be larger in lower slope part (Case L), and the others; one of the 25 sets of randomly generated α values were arranged from the smallest to the largest (Case L) and the others were arranged from the largest to the smallest (Case S) in an increasing order downslope were arranged to be smaller in lower slope part (Case S). The results are presented in Figure 3. The figure shows that the hydrograph for the Case L had a larger peak discharge rate, whereas the hydrograph for Case S had a smaller peak discharge rate. As a result, the effect of the scaling factor arrangement is significant.

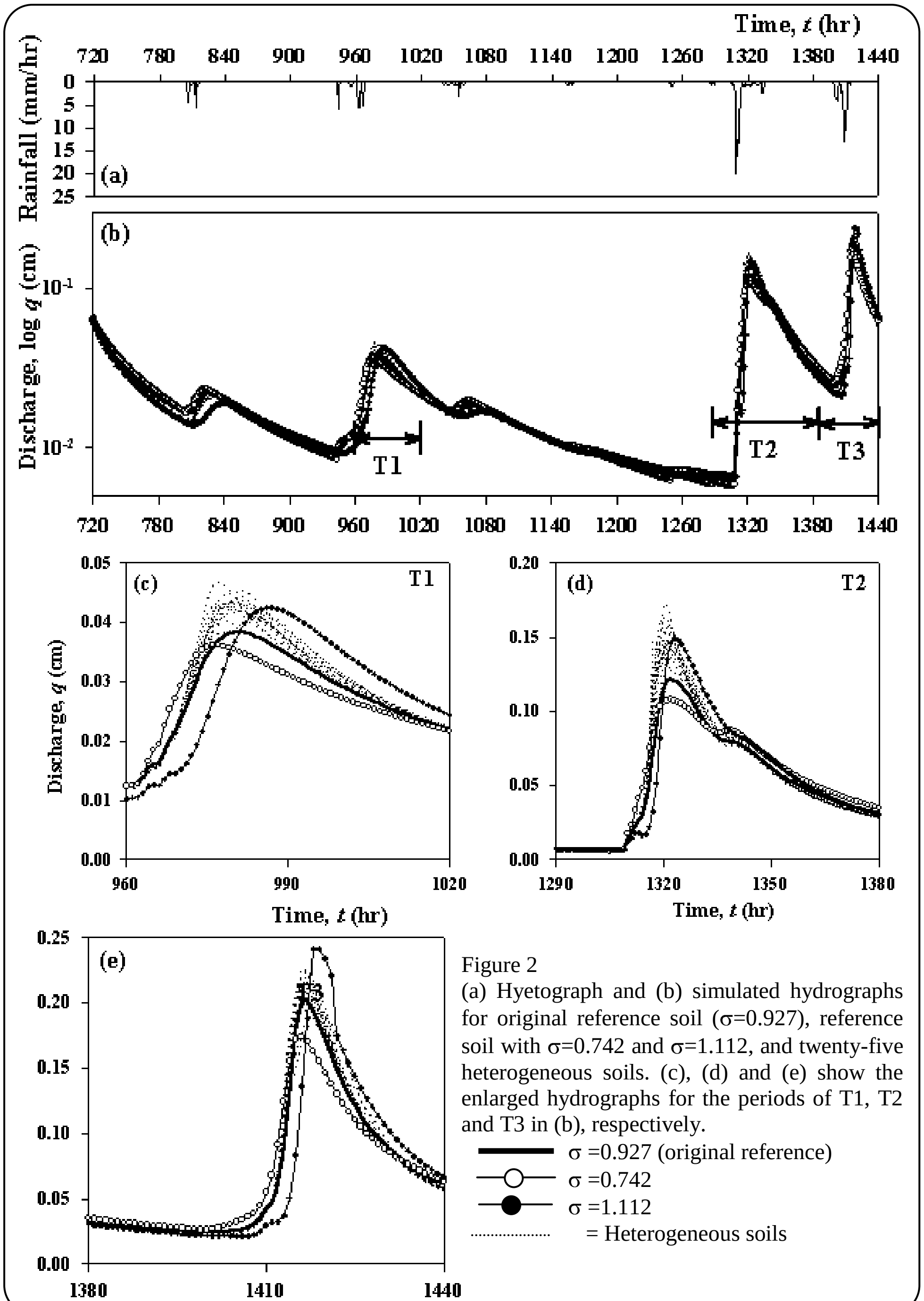


Figure 2

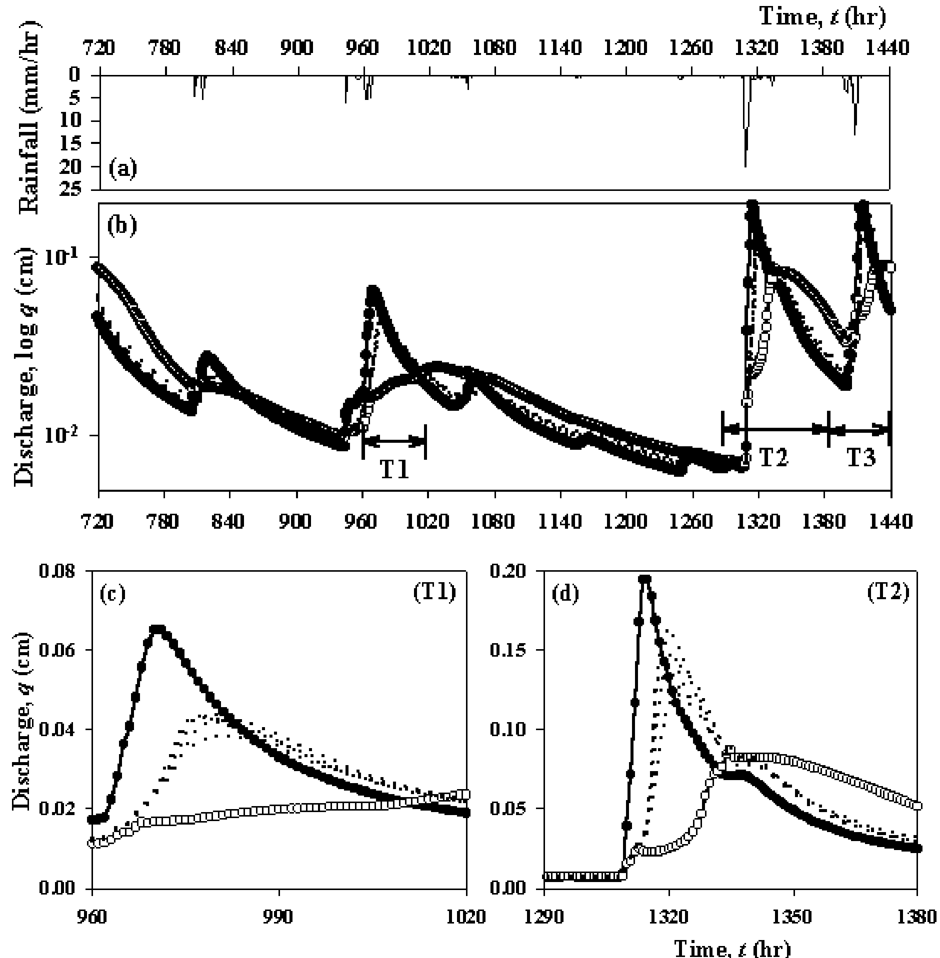
(a) Hyetograph and (b) simulated hydrographs for original reference soil (σ=0.927), reference soil with σ=0.742 and σ=1.112, and twenty-five heterogeneous soils. (c), (d) and (e) show the enlarged hydrographs for the periods of T1, T2 and T3 in (b), respectively.

σ =0.927 (original reference)

σ =0.742

σ =1.112

= Heterogeneous soils



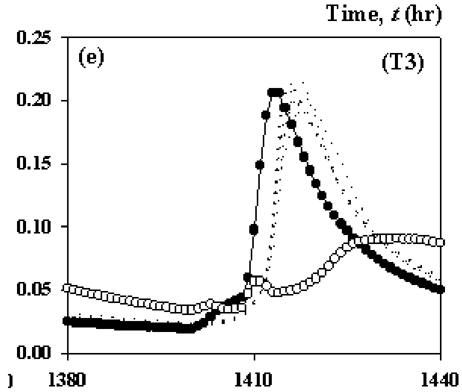


Figure 3
(a) Hyetograph and (b) simulated hydrographs for heterogeneous soil where α randomly arranged and arranged larger and smaller to downer slope part, Case L and Case S, respectively, (c), (d) and (e) show the enlarged hydrographs for the periods of T1, T2 and T3 in (b), respectively

Randomly arranged
Case L
Case S

CONCLUSIONS

Most of the twenty-five hydrograps for heterogeneous soils using randomly generated scaling factors had larger peak discharge rate than the hydrograph for the reference soil. This indicated that reference parameters tend to underestimate storm water discharge.

The effect of the scaling factor arrangement was significant; when the scaling factors were larger in the lower slope part, the peak discharge rate was higher, and vice versa.

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