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An inverse modeling approach for the characterization of unsaturated water flow in an organic forest floor

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Abstract

Although the retention of rain-water by a forest floor consisting of vegetation litter has large hydrological and geomorphological effects in a forested catchment, its physical processes have not yet been clarified. For the purpose of examining the applicability of Richards equation to unsaturated water flow in forest floor, results of artificial rainfall experiments were analyzed by the inverse method. Forest floor samples were collected from a beech-stand, an oak-stand, a cedar-stand and a mixed-stand of coniferous and broad-leaved trees. The samples were piled up to make long columns of 20.6 cm in inner diameter and about 50 cm in height, with which step-wise drainage experiments and random-rainfall experiments were conducted. Parameters in water retention and hydraulic conductivity functions were optimized by comparing the observed versus computed discharge rates for the step-wise drainage experiments. The derived retention and conductivity functions succeeded to reproduce the observed drainage hydrographs during the random-rainfall experiments, indicating that Richards equation can describe the unsaturated water flow in all the forest floor studied. The derived retention functions suggested that the forest floors have a small water capacity except for the very wet range where the matric pressure head, ψ, is greater than -5 cm. The conductivity functions of all the forest floors exhibited a sharp drop in the range of $\psi > -5$ cm, and decreased gradually as ψ decreased further. The forest floors at the beech-stand and the oak-stand had larger water capacities and smaller conductivity values than the forest floors at the cedar-stand and the mixed-stand. Consequently, the discharge hydrographs of the forest floors at the beech-stand and the oak-stand were characterized by more gradual responses to rainfall than the forest floors at the cedar-stand and the mixed-stand. Overall, the proposed inverse technique was effective to characterize the unsaturated water flow in forest floor.

Keywords: Forest floor; Organic soil layers; Water retention; Hydraulic conductivity; Inverse method

1. Introduction

In a forested catchment, a forest floor consisting of vegetation litter and roots often develops on the surface of mineral soil. The thickness of the forest floor depends on climate, vegetation, topography, soils and human impacts (Walsh and Voigt, 1977), and can exceed 50 cm (Sharratt, 1997). It is widely recognized that the forest floor plays an important role in nutrient and mineral cycling, soil formation and weathering (Walsh and Voigt, 1977). The forest floor is also important in geomorphological and hydrological processes. By protecting mineral soils from the direct impact of falling raindrops, the forest floor prevents rain-splash erosion and maintains soil infiltration capacity (Onda and Yukawa, 1994).

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A thick forest floor cover reduces evaporation from the underlying mineral soil (Tamai et al., 1998). Moreover, insulating properties of the forest floor can affect soil-freezing processes (Sharratt, 1997).

Retention of rain-water by the forest floor also has large geomorphological, hydrological and environmental effects; the amount of water stored in the forest floor is the key factor to predict a potential forest fire (Blow, 1955; Chrosciewicz, 1989), the forest floor is an important source of water for plants (Sharratt, 1997), and evaporation from the forest floor plays a significant role in water and energy transfer (Schaap et al., 1997). By intercepting rainfall, the forest floor serves as a temporary reservoir and allows more time for infiltration into the mineral soil beneath (Blow, 1955). As a result, overland flow and consequent soil erosion are reduced, and the form of runoff hydrograph is altered (Walsh and Voigt, 1977). In spite of such relevancy, forest floor water content dynamics have received little attention in forest hydrological research compared with the forest canopy interception and water movement in mineral soils.

In recent years, several modeling studies on forest floor water content dynamics have been published. Tamai et al. (1998) simulated water balance of the forest floor by using a simple 'bucket' model; drainage from the forest floor was assumed to be zero as long as the forest floor water storage was less than its maximum, and the drainage rate was computed as the difference between precipitation and evaporation rates when the storage reached the maximum. Tiktak and Bouten (1992) assumed that the forest floor was composed of a surface litter layer and a sub-surface fermentation layer, and applied the simple bucket model to the surface litter layer. Based on the fact that the sub-surface fermentation layer had a high root density and a good contact with the underlying mineral soil, they applied Richards equation, which was developed to describe unsaturated water flow in mineral soils, for the modeling of water content dynamics in the fermentation layer. The application of Richards equation to the entire forest floor was performed by Schaap et al. (1997) who assumed the forest floor as an integral part of the underlying mineral soil with water retention and conductivity characteristics described by van Genuchten's (1980) functions. Although these studies succeeded in modeling forest floor water content dynamics as one of the hydrological processes in the studied watersheds, physical processes of water retention by the forest floor were not clarified.

On the other hand, forest floor water retention processes have been studied by some laboratory experiments using a rainfall simulator (Walsh and Voigt, 1977; Pitman, 1989; Murai et al., 1995; Putuhena and Cordery, 1996). Experimental results of these studies indicated that (1) the amount of forest floor water storage increases as the rainfall intensity increases, (2) the discharge rate is below the rainfall rate just after rainfall begins and the saturation of water storage is not achieved quickly, (3) when rainfall ceases, there is a rapid decline in discharge followed by a long tail of delayed discharge and (4) the drainage rate from the forest floor is positively related to the amount of water storage. All these findings suggest that Richards equation describes the water content dynamics of forest floor better than the simple bucket model.

For the application of Richards equation, the volumetric water content θ and the hydraulic conductivity K of forest floor should be given as the functions of the matric pressure head ψ. However, few studies (Boelter, 1969; Busby and Whitfield, 1978; Sharratt, 1997; Schaap et al., 1997) have evaluated the θ–ψ relationship (i.e. the water retention curve) of the forest floor and the K–ψ relationship has been rarely measured. This is most likely because the measurement of the matric pressure head of the forest floor is difficult. Measuring the matric pressure head using a micro-tensiometer, Ohta et al. (1992) found that the tensiometer response was much slower for forest floor than for mineral soils.

Objectives of this study are to examine whether Richards equation can apply to unsaturated water flow in forest floors, and, if that is the case, to derive the water retention and hydraulic conductivity functions of forest floors. Because of the difficulty in measuring matric pressure head, we propose to use the inverse method which has been intensively studied for the determination of soil hydraulic properties (van Genuchten et al., 1999); water content dynamics of the forest floor are analyzed by comparing numerical solutions of Richards equation with laboratory measured drainage hydrographs.

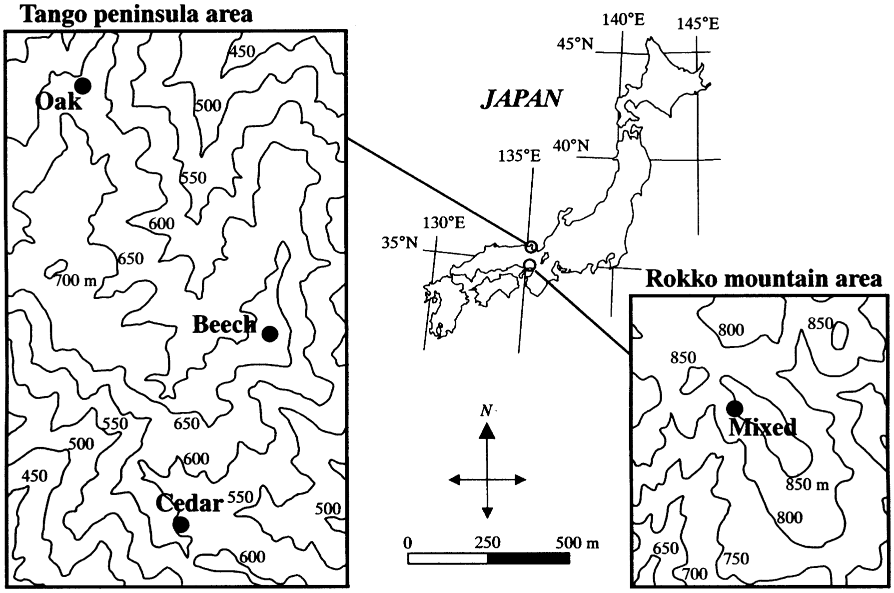

Fig. 1. Locations and topographies of the mixed, cedar, beech and oak forest floor sampling sites.

2. Materials and methods

2.1. Sampling sites

Forest floor samples were taken at a secondary forest in the Rokko mountain range (34°46′N, 135°16′E), Hyogo prefecture, Japan, and at a man-made forest (i.e. plantation) and two semi-natural forests in Tango peninsula (35°37′N, 135°10′E), Kyoto prefecture, Japan (Fig. 1). The Rokko mountain area has a mean annual temperature of 15°C, precipitation of 1600 mm, maximum snow depth of 10 cm and 10 snow cover days. The Tango peninsula area has a mean annual temperature of 15°C, precipitation of 2200 mm, maximum snow depth of 50 cm and 50 snow cover days. Canopy cover is complete in all the forests.

The secondary forest in the Rokko mountain range consists of *Quercus serrata* Thunb. (oak), *Pinus densiflora* Sieb. et Zucc. (pine), *Styrax japonica* Sieb. et Zucc., *Clethra barbinervis* Sieb. et Zucc., *Lyonia neziki* Nakai et Hara and *Pieris japonica* D. Don with a dense undergrowth of *Sasa nipponica* Makino (bamboo grasses). The forest floor is a mixture of leaf litters and roots of these plants and approximately 7 cm thick (the L, F and H layers are 2, 1 and 4 cm thick, respectively). The sample taken at this forest is referred to as the mixed forest floor because it consists of leaf litters of both coniferous (pine) and broad-leaved (oak and others) trees.

The man-made forest in Tango peninsula is a *Cryptomeria japonica* D. Don (cedar) plantation. All of the cedar trees are about 50 years old with an average height of 15 m. The undergrowth was a sparse shrub of *Sasa kurilensis* Makino et Shibata (bamboo grasses). The cedar forest floor is about 10 cm thick (the L, F and H layers are 7, 1.5 and 1.5 cm thick, respectively), and is mostly cedar leaf- and twig-litter.

The two semi-natural forests in Tango peninsula are called the beech forest and the oak forest in this study according to their dominant tree species. Dominant canopy tree at the beech forest is *Fagus crenata* Blume and the second dominant tree is *Quercus mongolica* Fisch. ex Turcz. var. *grosseserrata* Rehd. et Wils. The average tree height is 14 m, and undergrowth is dominated by *S. kurilensis*. The beech forest floor is 10 cm in thickness (the L, F and H layers are 3, 4 and 3 cm thick, respectively), and is mainly composed of beech litter and fine roots. Dominant canopy species at the oak forest are *Q. mongolica* and *Q. serrata*. These oak trees have an average height of 10 m. The undergrowth of *S. kurilensis* is not as dense as that at the beech forest. The oak forest floor is composed of a thin L layer 1 cm thick and F and H layers (both which are 1 cm thick) consisting of highly fermented organic material and fine roots.

At each forest, forest floor samples were collected using transparent acrylic core samplers of 20.6 cm in inner diameter. The sampler was inserted vertically into the forest floor without disturbing the structure. During the process of insertion, roots and organic material were carefully cut off from the forest floor around the sampler. The height of the sampler was the same as the forest floor thickness at each site except for the oak forest. Two cores of the oak forest floor were collected using a sampler of 6 cm in height.

Besides the forest floor samples, undisturbed mineral soils were collected at the secondary forest in the Rokko mountain range. The water retention curves for these mineral soils were measured by the hanging water column and pressure plate methods (Jury et al., 1991) using soil samples with a volume of 100 cm^3, and the saturated and unsaturated hydraulic conductivity data were observed by the steady-state flux control method (Klute and Dirksen, 1986) using a long sample column of 19.5 cm in inner diameter and 80 cm in length.

2.2. Laboratory experiments

In a laboratory, a plastic wire-netting, composed of 0.3 mm diameter strands constituting a 1.5 mm square mesh, was attached to the bottom of each core sample to support forest floor. Then, the core samples collected at each site were piled up to make a long column of 49 cm in height for the mixed forest floor and 50 cm in height for the cedar, beech and oak forest floors (Fig. 2). The subsequent artificial rainfall experiments were conducted by using this long column of forest floor instead of each individual core sample, since the objective of this study is not to quantify the hydrological effect of forest floor at a particular experimental site, but to examine the applicability of Richards equation to forest floor and to estimate its hydraulic properties. If each individual core sample is used for the rainfall experiments, the amount of water intercepted by the forest floor sample is not very large resulting in a drainage hydrograph similar to the applied hyetograph. In that case, a small measurement error in drainage rate can have a serious

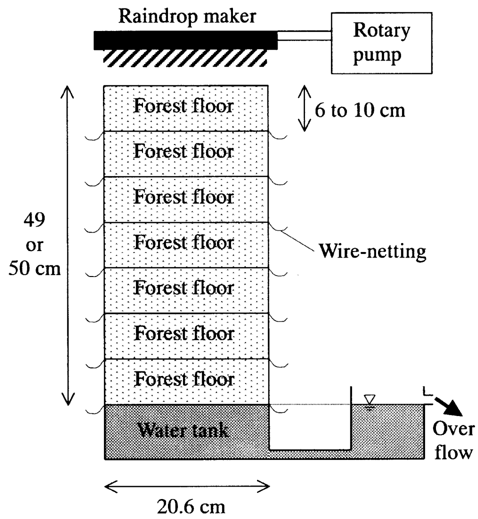

Fig. 2. Schematic of the artificial rainfall experiment.

effect on the characterization of unsaturated flow in the sample. Having a greater capacity to hold water, the long column of forest floor produces more gradual drainage responses, which makes the analyses easier.

The forest floor columns were irrigated by using the rainfall simulator described by Ohte et al. (1989); rainfall intensity was controlled by a rotary pump connected to a raindrop maker that produces water drops from tiny holes of 0.3 mm in diameter made in silicone tubes (Fig. 2). The sample column was placed on a water tank in which a constant water table was maintained. Quantitative observations of water filtered through the forest floor (i.e. discharge rate) were done by automatically recording the over flow rate at 0.5 min intervals using an electric balance connected to a hand-held computer.

A step-wise drainage experiment and a random-rainfall experiment were conducted for each forest floor column. In both experiments, a constant water flux throughout the sample column was initially established by applying water at a constant rate of 5.7–8.3 cm/h in order to accurately define the initial condition required for the numerical simulation of unsaturated water flow. Whereas an initial condition may be easily defined for a mineral soil by measuring a matric pressure head or water content profile in a sample column, such measurements are difficult for forest floor samples. By establishing a constant water flux, an initial matric pressure head profile can be computed from the rainfall intensity and the bottom boundary condition.

Rainfall intensities applied during the step-wise drainage experiment were approximately 4, 2, 1 and 0.4 cm/h. At each step, a constant rainfall was applied until a constant discharge rate was established. After the irrigation ceased, the measurement of the recession hydrograph continued for more than 8 h until the drainage rate became almost zero. Observed data under the step-wise drainage experiment were subsequently used for estimations of the forest floor hydraulic properties.

The random-rainfall experiment was conducted in order to provide data for the validation of the estimated hydraulic properties. At 10 min intervals, rainfall intensities were randomly changed in the range of 0–8.7 cm/h. The random-rainfall continued for about 3 h and the transient discharge rate was continuously monitored. The experiment was conducted twice for the mixed forest floor and once for the other forest floors.

Pitman (1989) repeated a wetting procedure of forest floor three times, and found that the water absorbing process observed in the third run was different from those in the first and second runs. This might be attributable to water repellency which is commonly acknowledged for field soils (Wallis and Horne, 1992). Many studies have reported that the soil water repellency causes preferential flow pathways (Raats, 1973; Bouma, 1990; Ritsema and Dekker, 1994) and the repellency is most strongly expressed as the soil dries (Bond, 1964; Wallis et al., 1990). This was true of the organic forest floors studied here. When the forest floors were dry, they exhibited the water repellency, and preferential flow pathways were observed during irrigations; the forest floors did not become completely wet when the wetting front passed, and a few film flows on the wall of the acrylic core samplers were occasionally observed. In order to try and eliminate the effects of the water repellency, all of the step-wise drainage experiments and the random-rainfall experiments were conducted after irrigating more than 34 cm of water. After the irrigations, the forest floors were homogeneously wet and the film flows on the sampler wall ceased.

2.3. Inverse modeling

2.3.1. Characterization of unsaturated water flow

The one-dimensional, vertical flow equation for unsaturated soil water (Richards equation) can be written as

$$C(\psi)\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right)\right] \tag{1}$$

where t is the time, z the vertical distance taken positive upward, $C(\psi) = \mathrm{d}\theta/\mathrm{d}\psi$ the water capacity function and $K(\psi)$ the hydraulic conductivity function. Eq. (1) can be solved if hydraulic properties of the soil (that is, the $C(\psi)$ and $K(\psi)$ functions) are given, and initial and boundary conditions are specified.

Kosugi (1994a, 1996) derived the following model for soil water retention by assuming the soil pore radii to be lognormally distributed:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = Q\left[\frac{\ln(\psi/\psi_m)}{\sigma}\right] \tag{2}$$

where θ_s and θ_r are the saturated and residual water contents, respectively, ψ_m the matric pressure head corresponding to the median pore radius, σ a dimensionless parameter to characterize the width of the pore-size distribution and Q the complementary normal distribution function defined as

$$Q(x) = (2\pi)^{-0.5}\int_x^\infty \exp\left(\frac{-u^2}{2}\right)\mathrm{d}u \tag{3}$$

Differentiating Eq. (2) yields the following water capacity function:

$$C(\psi) = \frac{\theta_s - \theta_r}{(2\pi)^{0.5}\sigma(-\psi)}\exp\left\{-\frac{[\ln(\psi/\psi_m)]^2}{2\sigma^2}\right\} \tag{4}$$

Moreover, the unsaturated hydraulic conductivity function was derived by combining Eq. (2) with Mualem's (1976) model (Kosugi, 1996):

$$K(\psi) = K_s\left\{Q\left[\frac{\ln(\psi/\psi_m)}{\sigma}\right]\right\}^{0.5}\left\{Q\left[\frac{\ln(\psi/\psi_m)}{\sigma} + \sigma\right]\right\}^2 \tag{5}$$

where K_s is the saturated hydraulic conductivity. It has been shown that the retention and conductivity functions expressed by Eqs. (2) and (5) are similar to those proposed by van Genuchten (1980), and produce adequate descriptions of observed hydraulic properties of various soils (Kosugi, 1994a, 1996, 1997a,b; Kosugi and Hopmans, 1998). For the purpose of examining the applicability of Richards equation (i.e. Eq. (1)), we assumed that the hydraulic properties of forest floors are described by Eqs. (2)–(5).

2.3.2. Parameter estimation procedure

In the inverse method to determine soil hydraulic properties, it is generally recommended to use prior information about the model parameters, thereby minimizing non-uniqueness of the optimized parameters (Russo et al., 1991; Hopmans et al., 1994). This is especially important when the inverse method is applied to forest floor; accurate measurements of matric pressure head and water content, which are expected to be combined with out-flow data and improve the sensitivity of parameter estimation (van Dam et al., 1992; Eching and Hopmans, 1993), are difficult for the forest floor sample. In order to minimize the non-uniqueness of the parameter optimization, we reduced the number of the fitted parameters based on the prior information.

Using Eqs. (2)–(5), the hydraulic properties of forest floor are described by the five parameters, K_s, θ_s, θ_r, ψ_m and σ. Among these parameters, the saturated hydraulic conductivity K_s was fixed at a value measured by the constant-head method (Jury et al., 1991). The residual water content θ_r of forest floor is reportedly small (about 0.005 cm^3/cm^3) as estimated from air-dry water content (Sharratt, 1997). Hence, we used the same assumption as Schaap et al. (1997) that θ_r of forest floor is equal to zero. Moreover, Schaap et al. (1997) fitted van Genuchten's (1980) retention function to observe retention curves of forest floor and found that the parameter θ_s of the forest floor was estimated to be much lower than the total porosity. Therefore, we used a water content θ_1 measured at a near-zero matric pressure head ψ_1 as a matching point for Eq. (2) instead of fixing θ_s at the equivalent of total porosity. For water content θ_1, Eq. (2) becomes

$$\frac{\theta_1 - \theta_r}{\theta_s - \theta_r} = Q\left[\frac{\ln(\psi_1/\psi_m)}{\sigma}\right] \tag{6}$$

Inverting this equation with respect to $(\theta_s - \theta_r)$, substituting the result into Eqs. (2) and (4), and assuming θ_r is equal to zero, yields the following water retention and capacity functions:

$$\theta = \frac{\theta_1 Q[\ln(\psi/\psi_m)/\sigma]}{Q[\ln(\psi_1/\psi_m)/\sigma]} \tag{7}$$

$$C(\psi) = \frac{[\theta_1/(2\pi)^{0.5}\sigma(-\psi)]\exp\{-[\ln(\psi/\psi_m)]^2/2\sigma^2\}}{Q[\ln(\psi_1/\psi_m)/\sigma]} \tag{8}$$

The value of θ_1 was measured by the hanging water column method (Jury et al., 1991) applying a near-zero matric pressure head ($-5 \leq \psi_1 \leq -3$ cm).

As a consequence of the above-mentioned assumptions, the number of fitted parameters was reduced to two; ψ_m and σ were optimized by Marquardt's (1963) maximum neighborhood method to minimize residual sum of squares (RSS) comparing the observed ($q_{out,obs}$) versus computed ($q_{out,cal}$) discharge rates for the step-wise drainage experiment

$$RSS = \sum (q_{out,obs} - q_{out,cal})^2 \tag{9}$$

For the computation of $q_{out,cal}$, Eq. (1) was numerically solved using an implicit finite difference scheme with equally spaced nodes (element lengths were 1 cm) and a constant time step of 5 s. The constant water table condition (i.e. $\psi = 0$) was imposed at the bottom of the sample column (see Fig. 2), and the experimental rainfall condition was used as inputs for the water flux at the surface. The initial condition was the equilibrium condition under the initially applied constant rainfall. That is, an initial ψ-profile was computed by the numerical solution of Eq. (1) for the given values of ψ_m and σ during each iteration procedure of the parameter optimization. The iterative optimization procedure was continued until the relative change in every parameter became <0.01%.

3. Results and discussion

3.1. Parameter estimation

Fig. 3 shows the relationship between the hydraulic gradient and water flux obtained by the constant-head method of measuring the saturated hydraulic conductivity K_s. The figure indicates that the measured plots are fitted well by straight lines except for the mixed forest floor for which just one measurement plot is available, suggesting that Darcy's law can be applied

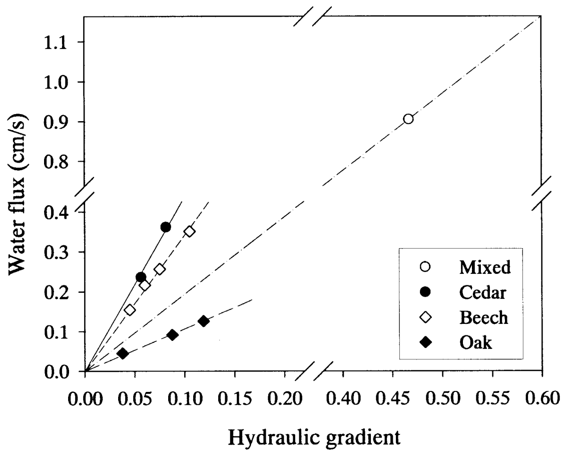

Fig. 3. Relationships between hydraulic gradient and water flux for determination of saturated hydraulic conductivity, K_s, of the forest floors.

to the saturated water flow in the forest floor samples. Values of K_s computed as the slope of the straight lines are summarized in Table 1 along with the measured ψ_1 and θ_1 values. All forest floor samples have large K_s values which are similar to those for gravel (Klute and Dirksen, 1986). Values of K_s for the cedar and beech forest floors are larger than those for the mixed and oak forest floors.

The parameter optimization runs were carried out using assumed initial parameter values of $\log(-\psi_m) = 1.2$ ($\psi_m \approx -15.8$ cm) and $\sigma = 1.8$. Fig. 4 shows that the computed hydrograph using the optimized parameters (Table 1) exhibits a good match with the observed hydrograph for all forest floor samples, suggesting that Richards equation can successfully describe the unsaturated water flow under the stepwise drainage experiment. The mixed forest floor has the largest optimized $\log(-\psi_m)$ and σ values, and the oak forest floor has the smallest (Table 1).

For the purpose of examining the solution uniqueness of the inverse method, Fig. 5a–d present contour lines of RSS on a coordinate system with $\log(-\psi_m)$ on the abscissa and σ on the ordinate. In these figures, $\log(-\psi_m)$ and σ domains were discretized into 63 and 75 discrete points, respectively, resulting in 4725 grid points to generate the response surfaces. The response surfaces imply the existences of local minima around $\log(-\psi_m) = 1$ and $\sigma = 1$ for the mixed, cedar and oak forest floor samples. The sensitivity of the parameter estimation is relatively low for the cedar forest floor comparing with the other samples. Nevertheless, all of the forest floor samples show well-defined global minima which correspond to the optimized parameter values summarized in Table 1. Hence, it can be concluded that the hydraulic parameters were determined with a certainty by the inverse method proposed in this study.

3.2. Hydraulic properties of forest floor

Fig. 6a and b shows the estimated retention and conductivity functions for the forest floor samples using Eqs. (7) and (5), respectively, with the parameter values summarized in Table 1. The figures include retention and conductivity data observed for the undisturbed mineral soil samples collected at the same site as the mixed forest floor sample.

The forest floor retention curves have consistently smaller θ values than the mineral soils (Fig. 6a). The θ–ψ curves of the mineral soils show large slope values in the range of $\psi > -30$ cm, that is the typical characteristics of soils which contain a lot of macropores (Kosugi, 1994b). In the very wet range of $\psi > -5$ cm, the mineral soils have small changes in θ except for the top soil (0–5 cm deep). In contrast to the mineral soils, the slopes of the forest floor retention curves are relatively steep when $\psi > -5$ cm and gentle when $\psi < -5$ cm. Since the water capacity C

Table 1
Observed K_s, ψ_1 and θ_1 values, and optimized ψ_m and σ values in Eqs. (5) and (7)

Forest floor	K_s (cm/s)	ψ_1 (cm)	θ_1	ψ_m (cm)	$\log(-\psi_m)$	σ
Mixed	1.9	−4.5	0.356	−526.8	2.72	3.28
Cedar	4.4	−5.0	0.309	−260.1	2.42	3.24
Beech	3.4	−5.0	0.354	−156.0	2.19	3.14
Oak	1.1	−3.0	0.282	−56.3	1.75	2.84

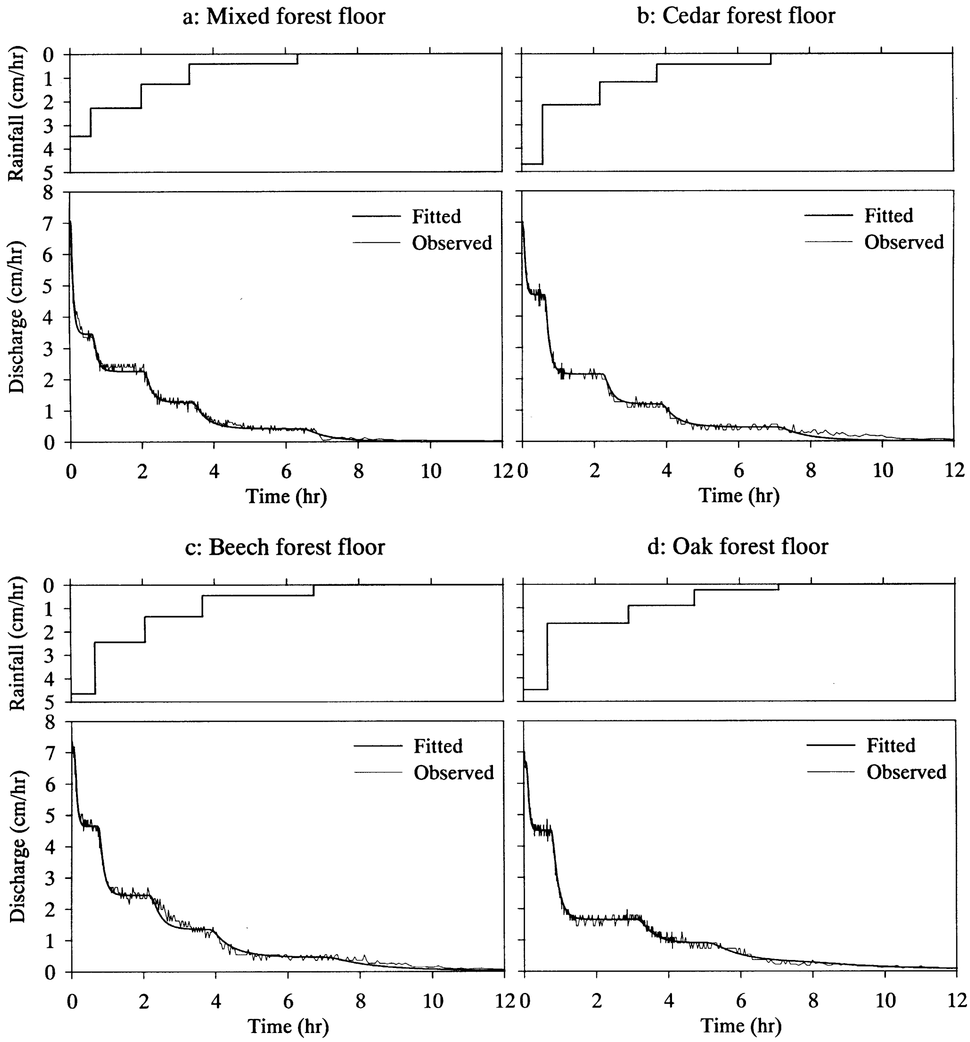

Fig. 4. Observed and fitted hydrographs for the step-wise drainage experiment.

is defined as the slope of the retention curve (that is, $C = d\theta/d\psi$), the forest floor samples have a smaller water capacity than the mineral soils except in the very wet range. The mixed and cedar forest floor samples have more gentle slopes of the retention curves than the beech and oak forest floor samples, reflecting the smaller water capacities.

The unsaturated hydraulic conductivity, K, values of the forest floor samples exhibit a sharp drop in the range of $\psi > -5$ cm, and decrease gradually as ψ decreases further (Fig. 6b). The mixed and cedar forest floor samples have larger K values than the beech and oak forest floor samples throughout the measurement range, and the oak forest floor has the least K among the four. The K–ψ curves of the forest floor samples are similar to those of the mineral soils at the depth of 15–40 cm except for the large saturated hydraulic conductivity for the forest floors (Table 1). The K–ψ curves of the surface mineral soils (0–10 cm deep) have relatively steep slopes and smaller K values than the forest floors in the range of $\psi < -20$ cm. The mineral soil at the depth

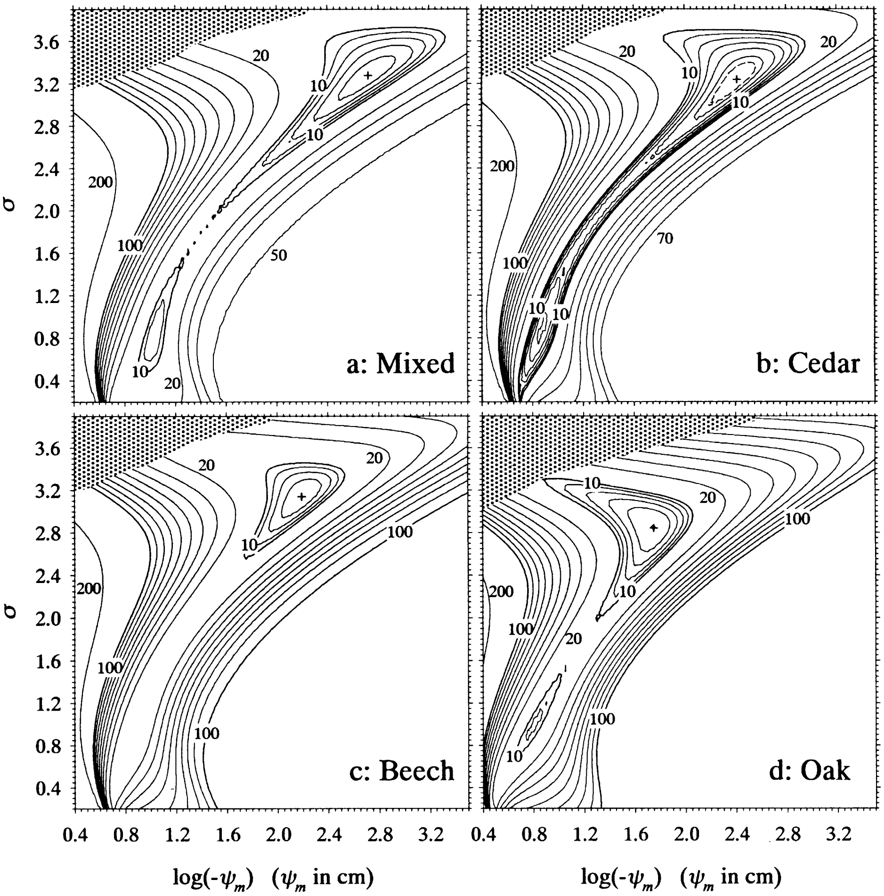

Fig. 5. Contour lines of RSS comparing the observed versus computed discharge rates for the step-wise drainage experiments. Values of RSS are in cm^2/h^2. Pluses indicate the optimized parameter values summarized in Table 1. With a small $\log(-\psi_m)$ and a large σ (that is, the shaded portion in each figure), Eq. (5) exhibits an immediate sharp change in hydraulic conductivity values which caused errors in the numerical solution of Eq. (1) for the step-wise drainage experiments.

of 40–50 cm has larger K values than the forest floors when $-35 < \psi < -20$ cm.

3.3. Validation of estimated hydraulic properties

Whereas various methods to measure soil hydraulic properties have been proposed and tested for many mineral soils (Dirksen, 1999), accurate measurement techniques for forest floor unsaturated hydraulic properties have not yet been developed. Therefore, we examined the validity of the estimated retention and conductivity functions of each forest floor by comparing the simulation results for the random-rainfall experiment with the observations rather than comparing the estimated θ–ψ and K–ψ curves with those measured by any other direct methods.

The retention and conductivity functions for the forest floor samples estimated by the step-wise drainage experiment were subsequently used to predict discharge rates under the random-rainfall experiment. The initial, boundary and other conditions for the numerical solution of Eq. (1) were similar to those used for the analyses of the step-wise drainage experiment. The results showed that the agreement between the predicted and observed discharge rates was very good for all forest floor samples (Fig. 7). That is, the hydraulic properties of each forest floor determined by the step-wise drainage

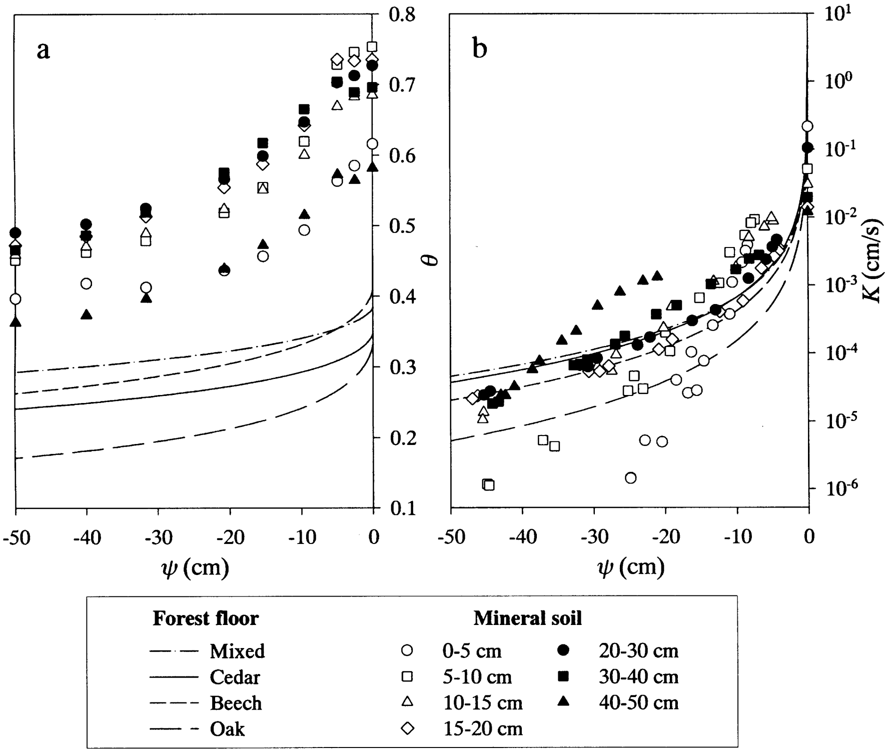

Fig. 6. Optimized (a) water retention and (b) hydraulic conductivity functions of the forest floor samples in comparison with those for mineral forest soils collected at different depths at the secondary forest in the Rokko mountain range.

experiment, were applicable to the random-rainfall condition consisting of both drying and wetting processes. As a conclusion, the rain-water discharge phenomena of the forest floor columns can be successfully modeled by Richards equation along with the hydraulic properties shown in Fig. 6.

As described in Section 2, all of the step-wise drainage experiments and the random-rainfall experiments were conducted after irrigating with more than 34 cm of water in an attempt to eliminate the effects of water repellency. Therefore, the hydraulic properties shown in Fig. 6 should be regarded as those obtained after the reduction of water repellency, and Fig. 7 shows the applicability of Richards equation to the organic forest floors when the effects of preferential flow caused by water repellency become small.

3.4. Comparison of flux responses

The estimation technique proposed in this study produced the unsaturated hydraulic properties of the four forest floors (Fig. 6). In order to compare water content dynamics of these forest floors, numerical simulations were conducted by assuming the same condition as the random-rainfall experiment for the oak forest floor; the column length was 50 cm and the hyetograph shown in Fig. 7d was applied to simulate flux responses at the bottom of the column. The hydrographs computed by using the hydraulic properties of the mixed and cedar forest floors are characterized by quick responses to rainfall and large peak discharge rates (Fig. 8). The beech and oak forest floors have smaller peaks and larger recession discharge rates. These differences in hydrographs are attributable to the hydraulic properties shown in Fig. 6; the mixed and cedar forest floors have the small water capacities, C ($= d\theta/d\psi$), and large unsaturated hydraulic conductivity, K, values which correspond to the sharp responses of the hydrographs, and the relatively large C and small K values of the

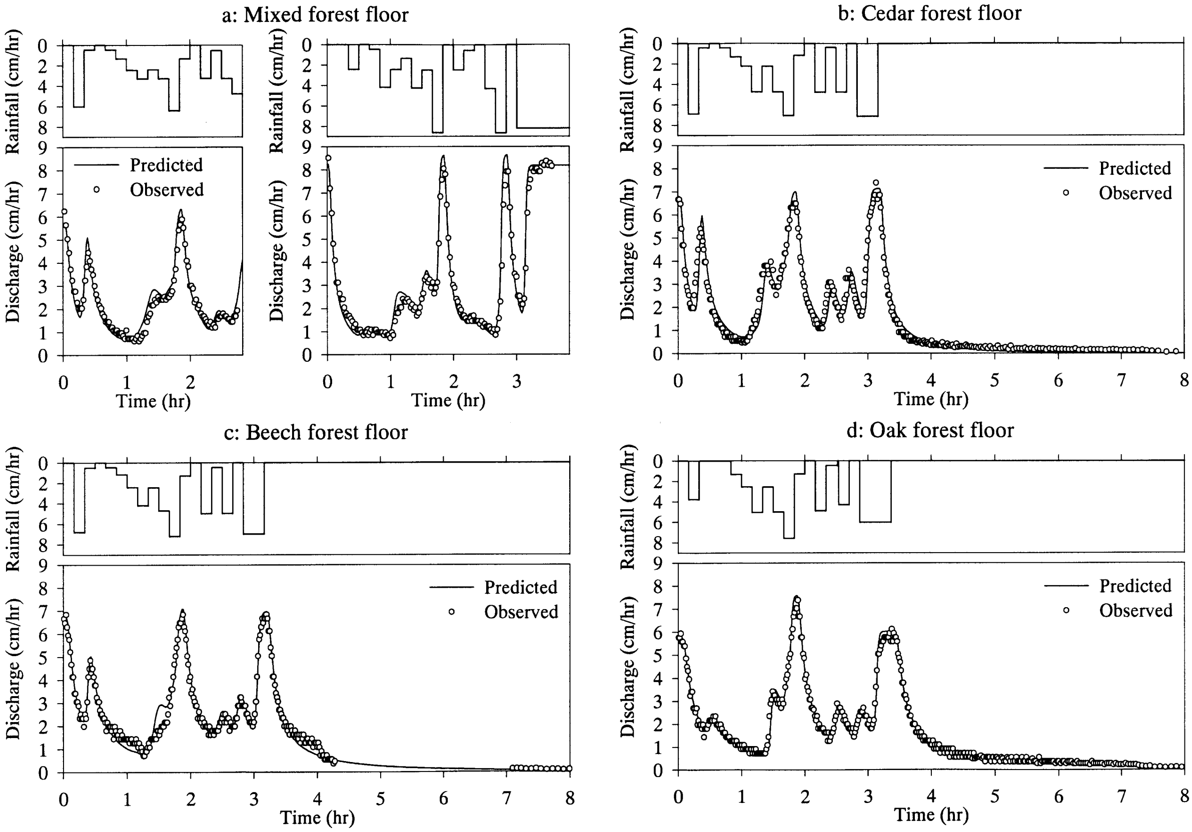

Fig. 7. Observed and predicted hydrographs for the random-rainfall experiment.

beech and oak forest floors result in the gradual hydrographs. Consequently, the capacity to hold rain-water is larger for the beech and oak forest floor columns than the mixed and cedar forest floor columns. This result is comparable to the result obtained by the laboratory experiment of Walsh and Voigt (1977) who found that the hydrograph for a beech-litter forest floor had a slower rise and a longer-lasting post-rainfall discharge than the hydrograph for a pine-litter forest floor.

Fig. 8 includes a hydrograph for a stratified mineral soil column with a length of 50 cm. It was assumed that each layer of the mineral soil column has the hydraulic properties of the mineral soils shown in Fig. 6, and the conditions for the numerical simulation were the same as those used for the forest floor columns. The mineral soil column produced the more gradual hydrograph than any of the forest floor column. That is, the rain-water holding capacity of every forest floor column is less than that of the mineral soil column.

4. Conclusions

For the purpose of examining the applicability of Richards equation to unsaturated water flow in forest floor, results of laboratory experiments using a rainfall simulator were analyzed by the inverse method. Parameters in retention and conductivity functions for four kinds of forest floor samples were optimized by comparing the observed versus computed discharge rates for the step-wise drainage experiments. The derived retention and conductivity functions succeeded to reproduce the observed drainage hydrographs during both the step-wise drainage experiments and

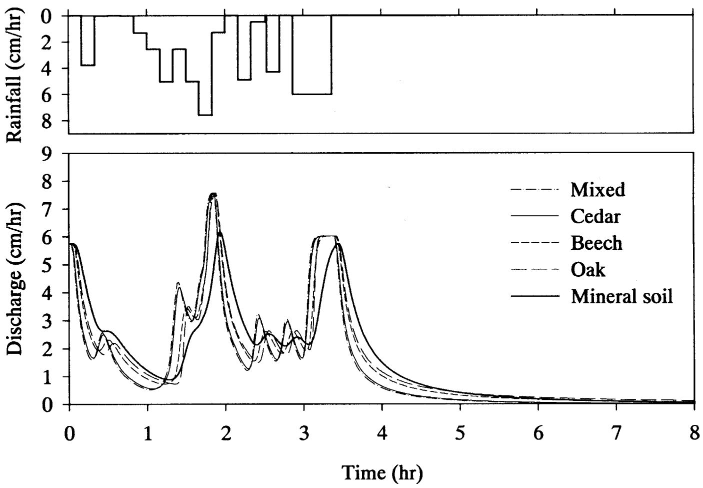

Fig. 8. Comparison of hydrographs simulated by assuming hydraulic properties of the mixed, cedar, beech and oak forest floors and those of the mineral forest soils. The used hydraulic properties are shown in Fig. 6. The assumed column length is 50 cm.

the random-rainfall experiments, indicating that Richards equation can describe the unsaturated water flow in all the forest floor samples studied.

The derived retention functions showed that the forest floors are small in water capacity except for the very wet range where the matric pressure head, ψ, is greater than -5 cm. The unsaturated hydraulic conductivity functions of all the forest floors exhibited a sharp drop in the range of $\psi > -5$ cm, and decreased gradually as ψ decreased further. The forest floors at the beech-stand and the oak-stand had larger water capacity and smaller unsaturated hydraulic conductivity values than the forest floors at the cedar-stand and the mixed-stand of coniferous (pine) and broad-leaved (oak and others) trees. Consequently, the discharge hydrographs from the beech and oak forest floors were characterized by more gradual responses to rainfall and smaller peak discharge rates than the cedar and mixed forest floors.

Although the inverse method has a disadvantage that determined hydraulic properties are affected by functional forms of assumed retention and conductivity models (e.g. Eqs. (5) and (7) of this study), alternative direct methods measuring unsaturated hydraulic properties of forest floor have not been developed yet. It can be concluded that the proposed inverse technique is effective to characterize the unsaturated water flow in forest floor and to evaluate its rain-water holding capacity.

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