Journal of Hydrology 366 (2009) 62–75

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A three-dimensional model of the effect of stemflow on soil water dynamics around a tree on a hillslope

Wei-Li Liang *, Ken'ichirou Kosugi, Takahisa Mizuyama

Lab. of Erosion Control, Department of Forest Science, Graduate School of Agriculture, Kyoto University, Kitashirakawa, Oiwake-Cho, Sakyo-Ku, Kyoto, Japan

ARTICLE INFO

Article history:
Received 10 June 2008
Received in revised form 10 December 2008
Accepted 15 December 2008

This manuscript was handled by P. Baveye, Editor-in-Chief, with the assistance of Stephanie Roulier, Associate Editor

Keywords:
Bypass flow
Pore water pressure
Soil–bedrock interface
Soil water content
Stemflow
Three-dimensional model

SUMMARY

In forested stands, precipitation is intercepted by the canopy and partitioned into throughfall and stemflow as diffuse input and point input, respectively. Therefore, the water reaching the forest floor is not spatially uniform. Although there are many numerical models that simulate precipitation redistribution processes, the rainwater concentrated by stemflow is usually disregarded. In this study, we performed detailed observations of soil water dynamics during a storm event and developed a three-dimensional model of the effect of stemflow on soil water dynamics around a tree on a forested hillslope. In the stemflow infiltration process, water flowed rapidly through a deep layer, causing irregular changes in the vertical soil water content. This process is very different from the vertical rainfall infiltration process, in which the wetting front expands slowly from the upper layer to the deeper layer. Thus, simulations using the conventional net precipitation input assumption are likely to contain large errors as a result. The model proposed in this study, which considered the point input characteristic of stemflow and parameterized stemflow as a source flux spring in the soil layers, showed adequate spatial and temporal variations in soil water dynamics and closely agreed with observations. Applying the variable source term in the Richards equation to stemflow is a new approach and makes it possible to represent the root-induced bypass flow infiltration process around a tree growing on a hillslope.

Introduction

In forested stands, trees can increase the heterogeneity of the rainwater input process. When precipitation is intercepted by the canopy, it is partitioned into throughfall and stemflow components as diffuse and point inputs, respectively. Trees can also increase the heterogeneity of the rainwater infiltration process. Beven and Germann (1982) indicated that macropores in soil may be associated with either living or decayed tree roots and that the structure of macropore systems derived from roots may be very effective at channeling water through the soil. Root-induced channels are preferential flow pathways, and stemflow tends to follow these channels into the soil (Martinez-Meza and Whitford, 1996; Voigt, 1960). Thus, stemflow has a double contribution to uneven water input and preferential rainwater infiltration that enlarges the heterogeneity of soil water dynamics in forested stands (Johnson and Lehmann, 2006).

Previous studies of soil water dynamics in forested stands have paid little attention to the effects of stemflow, due to the low ratio of stemflow to precipitation observed. However, the point input characteristic of stemflow may have major implications for soil water dynamics, even for tree species with a low ratio of stemflow to precipitation. Aboal et al. (1999) quantified the stemflow of 30 sample trees belonging to six different species in a laurel forest and found that precipitation could be concentrated up to 12.8 times in the infiltration areas of the trees by stemflow, even though the annual stemflow only represented 6.85% of the gross precipitation. Liang et al. (2007) observed that stemflow rapidly moved into soil layers along the pathways around roots. This suggested that stemflow not only serves as a point source of rainwater on the forest floor, but also has a high potential to infiltrate multiple soil layers as bypass flow. Additionally, they observed that uneven and locally concentrated stemflow caused the generation of an asymmetric saturated zone around a tree on a hillslope. Knowledge of saturated zones at the soil–bedrock interface is important in predicting the location and timing of shallow landslide occurrences (Montgomery et al., 2002; Wang and Sassa, 2003). Saturated zones can also contribute to runoff generation and deeper bedrock flow recharge (Montgomery and Dietrich, 2002). Thus stemflow may have a large effect on shallow landslide occurrences, runoff generation, and bedrock flow recharge on a hillslope.

It appears clear from these studies that stemflow should be an important element of hillslope hydrological models. Although there are many numerical models that consider the division of precipitation into interception and throughfall components (e.g., Belk et al., 2007; Bouten et al., 1992; Keim et al., 2006), the rainwater concentrated by stemflow has generally been disregarded. In a

---

* Corresponding author. Tel.: +81 75 753 6091; fax: +81 75 753 6088.
E-mail address: iritu@kais.kyoto-u.ac.jp (W.-L. Liang).

0022-1694/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2008.12.009

one-dimensional model developed by Belk et al. (2007) to evaluate the variation in soil water content in a tropical forest, the rainfall entering the forest system was partitioned into throughfall and canopy interception. Bouten et al. (1992) simulated soil water dynamics in a forested lowland catchment with the Soil Water in Forested Ecosystems (SWIF) model, in which throughfall and stemflow were treated as net precipitation and added evenly to the forest floor. They attributed the discrepancy between observations and their simulation to bypass flow. Keim et al. (2006) simulated subsurface flow generation on a hillslope during storm conditions with a two-dimensional finite element model (HYDRUS-2D). In their study, rainwater added to the forest floor was throughfall only. They stated that factors not included in their model, such as the spatial inhomogeneity of water input due to stemflow, the rapid recharge of groundwater due to bypass flow, and the preferential flow paths in a structured forest soil, may have been important.

The results of these studies imply that large simulation errors may occur when stemflow is neglected. Tanaka et al. (1996) developed a primary model based on the infiltration area of stemflow-induced water to determine stemflow inputs to the soil surface. However, they did not simulate the detailed stemflow infiltration process in soil layers. Additionally, the model that they applied used a chloride mass-balance method to evaluate the effect of stemflow on groundwater recharge and could not represent the rapid infiltration that is characteristic of stemflow (Liang et al., 2007). Thus the influence of stemflow should be included in the discussion of forested hillslope hydrological processes, and numerical models of stemflow infiltration characteristics need to be improved.

The purpose of our study was to develop a three-dimensional model of the effect of stemflow on soil water dynamics around a tree on a hillslope. Field experiments and high spatial resolution observations of throughfall, stemflow, soil water content in the soil layer, and pore water pressure at the soil–bedrock interface were used to test the model. The soil water dynamics observed during a storm event were simulated using the model, and the results were compared with those simulated using the conventional assumption of net precipitation input.

Field observations and experiments

Setup of field observations and experiments

Precipitation redistribution dynamics

Observations were conducted on a hillslope at the Kamigamo Experimental Station of Kyoto University, located in southern Kyoto Prefecture, central Japan (35°04′N, 135°46′E). The study area has a warm temperate climate. Mean annual air temperature for 1971–2000 was 14.6 °C, with highest and lowest monthly averages of 27.8 °C (August) and 4.6 °C (January), respectively. Mean annual precipitation was 1582 mm. Rainfall was distributed throughout the year, with a peak in summer and just a few centimeters of snow in winter.

The hillslope, which had a mean gradient of 28°, contained brown forest soil classified as Cambisol (clay type), underlain by sandstone and slate. It was predominantly covered by tall stewartia trees (*Stewartia monadelpha*), which were planted in 1956 (Fig. 1a). Tall stewartia, which is widespread in natural forests in the western and southern regions of Japan, is a deciduous tree with smooth-exfoliating bark. It undergoes leaf fall in November and regrowth in April.

We selected a single tall stewartia (S2 in Fig. 1a; height, 13.83 m; diameter at breast height, 21.7 cm; projected canopy area, 12.84 m^2) around which to monitor precipitation redistribution dynamics. To collect the stemflow along the upslope (SF-up) and downslope (SF-down) sides of the trunk separately, we used two tubes cut longitudinally and wrapped spirally around each side of the trunk. The flow rates of SF-up and SF-down were measured using tipping-bucket gauges that tipped at 4 and 500 ml (DAVIS 7852M and IKEDA TQX-500, respectively). To measure throughfall distribution, we installed tipping-bucket rain gauges (DAVIS 7852M; 0.2 mm per tip; water collection area, 200 cm^2) at nine different points. The points were spaced 50, 100, and 200 cm upslope, downslope, and laterally from the tree stem S2 (Fig. 1a). Gross precipitation (open-area rainfall) was measured using a tipping-bucket rain gauge (IKEDA RH-5; 0.5 mm per tip) at an open site 112 m from the observation slope.

Soil water dynamics

To monitor the soil water dynamics around a tree, we selected another tall stewartia (S1 in Fig. 1a and b; height, 17.47 m; diameter at breast height, 22.3 cm; projected canopy area, 17.39 m^2) with a similar tree shape to tree S2, and delineated a longitudinal observation line from upslope to downslope of this tree. No understory vegetation or other trees existed along the observation line, so that only the effects of tree S1 on soil water dynamics would be identified. We installed capacitance meters (Sentek, EasyAG-5p) at the following ten points: 250 cm (P1), 200 cm (P2), 150 cm (P3), 100 cm (P4), and 50 cm (P5) upslope from the tree stem, and 25 cm (P6), 50 cm (P7), 100 cm (P8), 150 cm (P9), and 200 cm (P10) downslope from the tree stem (Fig. 1b). Each capacitance meter consisted of five sensors to measure soil water content at depths of 10, 20, 30, 40, and 50 cm. Hence, we used 50 sensors in total, each of which was assumed to measure the soil water content for each element of the mesh system shown in Fig. 1b. The same type of capacitance meter has been used in several other recent field studies (Mattos et al., 2003; Nachabe et al., 2005).

We installed tensiometers at the soil–bedrock interface at the same ten points used for pore water pressure measurements (Fig. 1b). The soil depth to bedrock at each point was determined by penetration tests using a knocking-type cone penetrometer with a 60° bit, a cone diameter of 20 mm, a weight of 2 kg, and a fall distance of 50 cm. From the results of the penetration test, we computed the penetration resistance value, N_h, as the number of blows required for a 10-cm penetration. Previous studies proposed that an N_h value of 100 could be an indicator of the boundary between soil and bedrock (Okimura and Tanaka, 1980; Yoshimatsu et al., 2002). The soil depths of all points were estimated to be between 104 and 190 cm (Fig. 1b). At the point 50 cm downslope from P10, we dug a trench of 110-cm width and 130-cm depth to measure runoff generation from the soil–bedrock interface (Fig. 1a).

Sprinkling experiments for the identification of stemflow and throughfall infiltration processes

Rainwater reaching the forest floor is separated into stemflow and throughfall as point input and diffuse input, respectively. To clarify the effects of these two kinds of rainwater inputs on infiltration processes, we performed two sprinkling experiments.

To identify the effect of stemflow, a stemflow-sprinkling experiment was conducted on 30 October 2007. Using a spray nozzle, a total of 250 L of water was sprinkled toward the downslope side of the tree stem S1 (Fig. 1a) during 82 min, corresponding to stemflow intensity of 10.5 mm/h per canopy projected area. Water sprinkled at a height of 1.3 m over an area of 20 cm^2 on the stem reached the stem base in approximately 2 s, and then infiltrated into soil layers without forming a surface flow. Simultaneous variations in soil water content from depths of 10–50 cm at P6 were recorded.