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Measurements of groundwater recharge rate and unsaturated convective chemical fluxes by suction controlled lysimeter

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Abstract A newly-developed suction controlled lysimeter was applied to measure water and solute transport in unsaturated forest soil. The lysimeter consists of a porous plate connected to a vacuum system and two tensiometers. Soil matric pressure heads are measured just above the horizontally-installed porous plate, and at the same depth in the natural soil profile, at three-second intervals. The vacuum system is automatically controlled so that the readings of the two tensiometers match each other. The lysimeter succeeded in keeping soil moisture conditions in the water-sampling profile almost identical to that in the natural soil profile. Field observation showed that about 68% of rain-water was discharged at 30 cm depth; Cl^- concentrations in discharge-water showed a delayed peak compared to rainwater; NO_3^- was not detected in discharge-water because of extraction by roots; and about 5200 mg m^{-2} of SiO_2 was discharged at 30 cm depth as a result of soil weathering.

Key words convective chemical fluxes; groundwater recharge; lysimeter; sampling method; soil water flux; unsaturated infiltration; water quality

INTRODUCTION

It is difficult to quantify the unsaturated infiltration processes of rain- and irrigation-water in field soils accurately, although they are a major source of groundwater recharge, and solute transport in the unsaturated zone is important to groundwater quality. This is partly because existing unsaturated soil water sampling techniques are not necessarily appropriate given the mechanism of soil water flow. For instance, the tension-free-lysimeter can collect water only when the soil pore water pressure at the sampling depth becomes positive. Therefore, it makes soil moisture conditions in the sampling profile wetter than that in the natural soil profile. On the other hand, the widely-used tension-lysimeter collects water through porous cups by applying a constant vacuum pressure of about –200 to –400 cmH_2O. Since the water sampling rate depends on the applied vacuum pressure, the equipment cannot measure the actual infiltration rate. Moreover, the quality of water sampled by a tension-lysimeter reportedly depends on the applied vacuum pressure (Rhoades & Oster, 1986).

This study evaluates a new method of sampling soil water from the unsaturated zone that minimizes disturbance to soil moisture conditions in the sampling profile and can collect all of the infiltrated water.

METHOD

Suction controlled lysimeter

A lysimeter, which can automatically control a negative pressure for extracting water from unsaturated soil according to soil moisture conditions in the sampling profile, has been developed (Kosugi, 2000). Figure 1(a) is a schematic of the suction controlled lysimeter. The equipment consists of two tensiometers (DIK-3150, Daiki Rika Kogyo) and a porous plate (0675B0.5M2, Soilmoisture Equipment) connected to a suction system. The porous plate has an air entry value of 0.5 kPa ($\approx -510\ \mathrm{cmH_2O}$) and a saturated hydraulic conductivity of about $3 \times 10^{-5}\ \mathrm{cm\ s^{-1}}$. The porous plate is buried horizontally at the water-sampling depth in the sampling profile, and the soil matric pressure head just above the porous plate (ψ_a) is monitored by one of the tensiometers. The other tensiometer monitors the matric pressure head (ψ_b) at the same depth in the natural soil profile. In the sampling profile, infiltrated water is collected through the porous plate by applying suction so that ψ_a becomes equal to ψ_b. The suction system consists of a water container connected to a vacuum pump, a valve to release the negative pressure, and a pressure transducer to monitor the air pressure in the water container (p_c). The water-sampling rate is automatically measured by weighing the water container. A data logger (CR10x, Campbell Scientific) was used to record ψ_a, ψ_b and p_c as well as to control the vacuum pump switches and the release valve through relay systems.

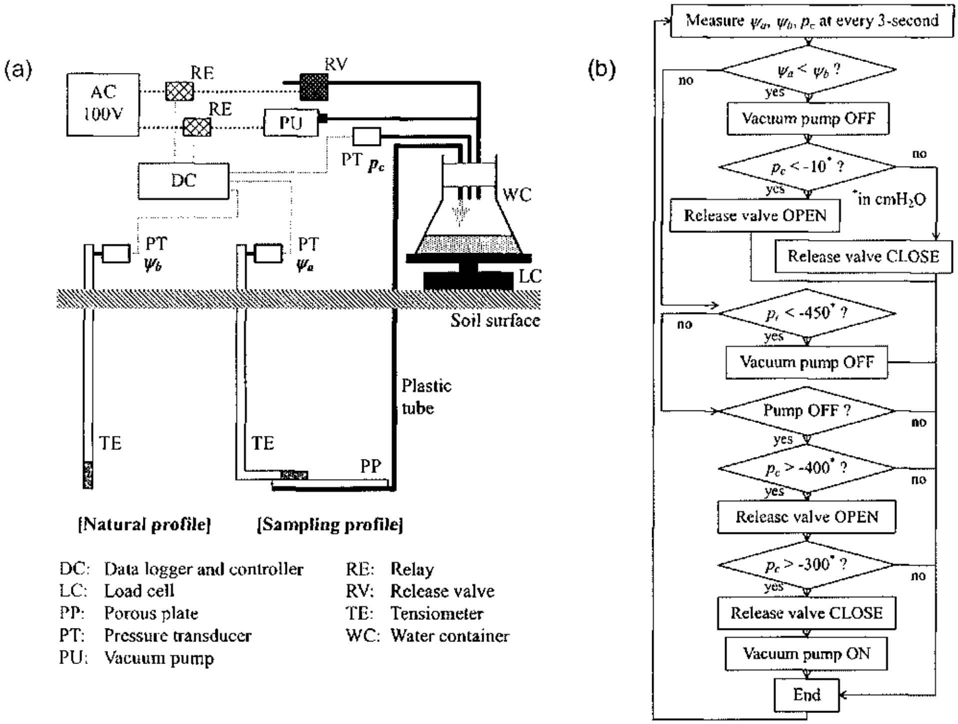


Fig. 1 (a) Schematic of proposed suction controlled lysimeter, and (b) flow chart for water suction control (modified from Kosugi (2000)).

Water suction control

Figure 1(b) is a flow chart for controlling the suction system for collecting soil water. Values of ψ_a, ψ_b, and p_c are continuously monitored at three-second intervals. When $\psi_a < \psi_b$ (that is, the sampling profile is dryer than the natural profile), the pump is turned off, and the valve is opened (only when $p_c < -10$ cmH$_2$O) in order to stop water extraction immediately by releasing the negative pressure in the water container.

When $\psi_a > \psi_b$, the sampling profile is wetter than the natural profile and soil water in the sampling profile should be extracted. Because the negative air-pressure applied to the porous plate should be greater than its air-entry value, the pump is turned off when the air-pressure in the water container, p_c, becomes less than –450 cmH$_2$O. As water is extracted, p_c gradually increases and the extraction rate gradually decreases. In order to maintain the high extraction rate, the pump is restarted when p_c becomes greater than –400 cmH$_2$O. To ensure smooth starting of the pump, the release valve is temporarily opened to increase p_c to greater than –300 cmH$_2$O, then the valve is closed and the pump is turned on. Use of this control method prevents soil water extraction when $\psi_a < -450$ cmH$_2$O. However, water and solute movement may be negligible under such dry conditions because of the low infiltration rate.

Several previous studies (van Grinsven *et al.*, 1988; Brye *et al.*, 1999; Ozaki, 1999) have proposed to control a suction pressure for collecting water from unsaturated soil by referring to tensiometer observations in sampling and natural soil profiles. These studies used longer intervals to monitor tensiometers (more than 3 min) and a gradual change of suction pressure in order to make the extraction rate the same as the infiltration rate. We suspect that the methods proposed in these studies cannot necessarily cope with the rapid changes of soil water content in a sampling profile which may occur under heavy storms and intensive irrigations. To avoid this difficulty, we use much shorter intervals to monitor the tensiometers (i.e. 3 s), and apply the large suction rate when $\psi_a > \psi_b$ and stop the extraction immediately by releasing the negative pressure when $\psi_a < \psi_b$. That is, the water extraction period is controlled in our method.

Field observation

The suction controlled lysimeter was installed at the water-sampling depth of 30 cm in a sparse forest consisting of both evergreen and deciduous broadleaved trees. In order not to disturb the soil structure, the porous plate was inserted through a horizontal tunnel from an adjacent soil pit. Upward force was applied to the plate by using screw jacks to make sufficient capillary connection between the plate and soil. The natural soil profile where ψ_b was measured was 0.6 m distant from the water-sampling profile. Neither the sampling nor the natural profile was covered by the forest canopy. In the sampling profile, tree and grass roots were homogeneously scattered and no remarkable preferential flow passes (e.g. macropore connections) were observed. Water sampling was conducted continuously from 16 May through to 28 August 2000. An open space for precipitation measurements was located 12 m distant from the water-sampling profile.

RESULTS AND DISCUSSION

Figure 2(a) shows that the suction controlled lysimeter succeeded in maintaining ψ_a similar to ψ_b; that is, soil moisture conditions in the sampling profile were about the same as in the natural profile and the water sampling rate was comparable with the infiltration rate in the natural profile throughout the observation period. During dry periods, ψ_b showed diurnal changes which may be attributable to evapotranspiration. Even in these periods, ψ_a was similar to ψ_b. In detail, ψ_a tended to exceed ψ_b during wetting processes following relatively dry conditions (e.g. day numbers 24–25 and 85–86 in Fig. 2(a)).

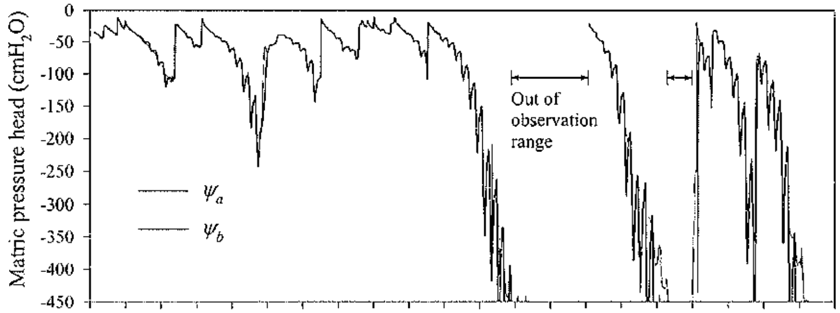
Total discharge (that is, the total amount of water collected by the lysimeter) and total precipitation during the observation period were 280.5 and 410.3 mm, respectively, and their ratio was 0.684. Figure 2(b) indicates that the ratio of discharge to precipitation was relatively large until day 38, and declined after that. This may be attributable to the increase in evapotranspiration in the summer season. The relationship between cumulative precipitation and discharge for each storm event is shown in Fig. 3 which includes data for five events observed in April 2000. The ratio of cumulative discharge to precipitation ranged from 0.24 to 0.99, and exhibited a slight trend to increase when the initial ψ_a value was greater than –50 cmH_2O. The correlation between the ratio and the initial ψ_a value may suggest that the antecedent water loss by evapotranspiration reduces the discharge. However, the correlation is not so distinct because the cumulative discharge depends on duration and intensity of rainfall as well.

Concentration and cumulative mass flux of some chemicals are shown in Figs 2(c–e). In Fig. 2(c), the Cl^- concentration of discharge-water shows a rapid decrease for the first 15 days, while the rainwater Cl^- concentration remains almost constant. It is reported that the Cl^- concentration of rainwater exhibits a seasonal change in the study area; precipitation caused by northwestern winter winds contains more Cl^- (Tokuchi *et al.*, 1991). Moreover, Tokuchi *et al.* (1991) showed that peaks in the Cl^- concentration of discharge-water from soil columns of 20 to 30 cm length lagged behind a peak in the Cl^- concentration of rainwater by 1 to 4 months. The lag was explained by the mobile–immobile water flow concept; Cl^- brought by small winter storms was supposed to be captured in the immobile region of soil pores (i.e. smaller soil pores) and to need a longer time to discharge (Ohte *et al.*, 1991). Therefore, it is probable that the rainwater had a peak in Cl^- concentration before the observation period, which caused a delayed peak in the Cl^- concentration of the discharge-water Fig. 2(c).

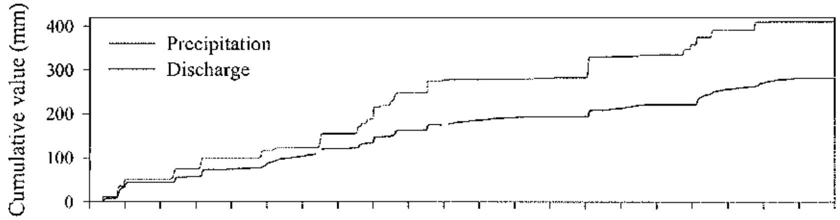
Figure 2(d) shows that NO_3^- was not detected in discharge-water whereas rainwater brought about 1100 mg m^{-2} of NO_3^- during the whole observation period. This is attributable to the extraction of NO_3^- by plant roots since trees usually suffer a nitrogen deficit in forests in Japan (Suzuki, 1992). On the other hand, the SiO_2 concentration of discharge-water was about 20 mg l^{-1} over the whole observation period in spite of zero concentrations in rainwater (Fig. 2(e)). This indicates that about 5200 mg m^{-2} of SiO_2 was discharged at 30 cm depth as a result of soil-weathering.

This work demonstrates that unsaturated convective chemical fluxes as well as unsaturated water flux can be measured using the new water sampling method. This quantitative information on water and solute transport in unsaturated soils can be used for mass balance analyses and validation of simulation models.

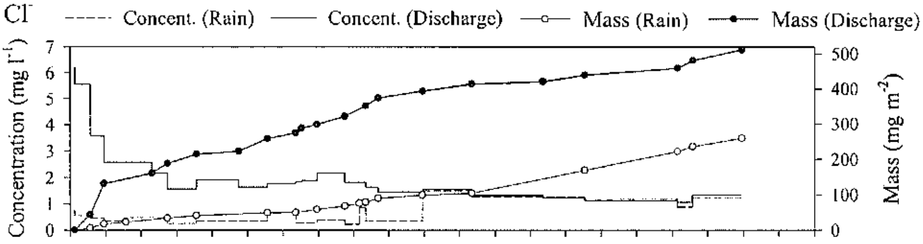
(a) Matric pressure head



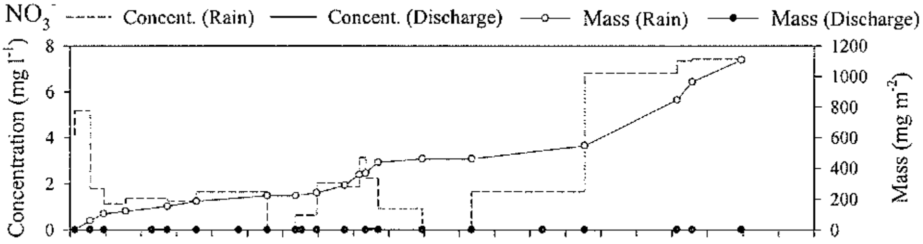
(b) Cumulative precipitation and discharge



(c) Cl$^-$



(d) NO$_3^-$



(e) SiO$_2$

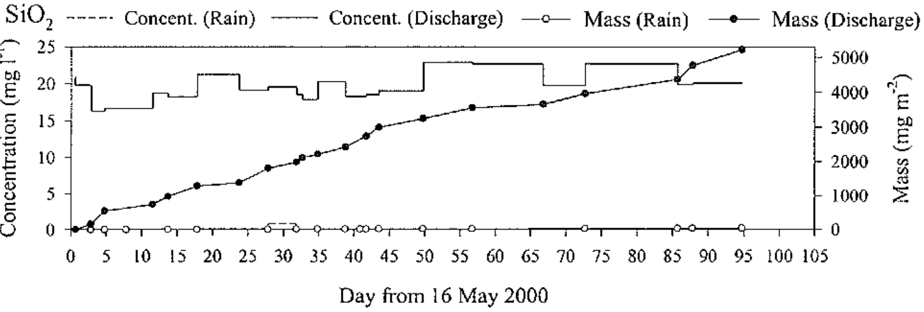


Fig. 2 (a) Matric pressure heads above the porous plate, ψ_a, and in the natural soil profile, ψ_b; (b) cumulative precipitation and discharge; and concentration and cumulative mass of (c) Cl$^-$, (d) NO$_3^-$, and (e) SiO$_2$ of rain- and discharge-water.

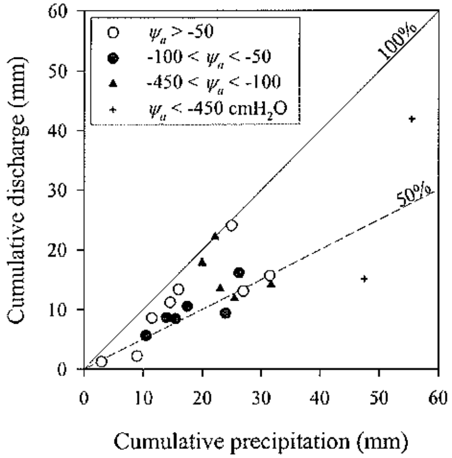


Fig. 3 Relationship between cumulative precipitation and discharge for each storm event. Plot symbol represents ψ_a value observed just before the storm event.

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