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Numerical Calculation of Soil Water Movement in a Water Harvesting System with Sand Ditches Using HYDRUS-2D

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Abstract: A water harvesting system with ditches filled with highly permeable materials that has potential to reduce soil water evaporation has been proposed. Laboratory experiments were carried out using a soil tank with dielectric sensors and various fillers for the ditch to evaluate the water storage ability of this system. The soil water movement in the system was simulated using HYDRUS-2D, and the results were compared with the measured results. The simulated water content distributions and cumulative water influxes were relatively in good agreement with the measured results in the infiltration process. The estimated evaporation rates did not agree well with the measured rates especially at the late stage in the evaporation process when the atmospheric boundary conditions were applied to the model. This may be due to excluding the calculation scheme of vapor flux in the model.

Key Words: Arid region, Ditch, Simulation, Soil water content, Water harvesting

1. Introduction

Rain water harvesting systems are traditional agricultural ways to collect and recharge runoff water into soils by such means as ditches and dams. They are essential for sustainable agriculture and afforestation without depending on irrigation systems in arid and semi-arid regions. In general, the most important point in evaluating the effect of water harvesting is determined how much water is collected and recharged into the soil. However, a large amount of water is lost from the soil and collected water surface due to high evaporation conditions in arid environments. As a measure for this problem, a new method of water harvesting that has potential to reduce soil water evaporation has been proposed by means of ditches filled with highly permeable materials (Saito *et al*., 2000; Abu-Zreig *et al*., 2000). In this method, a ditch is dug and then filled with highly permeable materials (e.g. sand) as a device to collect runoff water. It can be expected that runoff water infiltrates promptly into the ditch, and the infiltrated water then seeps to the adjacent soil through the side and bottom of the ditch due to the high matric potential gradient between the material in the ditch and adjacent soil. In addition, this method can reduce the amount of evaporation from the soil surface since the infiltrated water is stored deeper in the soil profile. Considering its distribution shape of the soil water, this method would be suitable for applying to trees. This filled ditch, called “sand ditch”, is simple and cost-effective, therefore it can be applied to large fields along contour lines.

The effectiveness of sand ditches has been confirmed through laboratory and field experiments. Abu-Zreig *et al.* (2000) reported that sand ditches increased water storage and infiltration depth in an olive field in Jordan. Saito *et al.* (2006) carried out laboratory experiments using various fillers for the ditches to evaluate their water storage ability and to examine suitable fillers. In addition to such experimental approaches, numerical modeling of the system is important to generalize the results. Simulation of the system may provide optimal designing of the ditch and filler based on the regional environmental conditions through numerical experiments. The objective of this study, therefore, was to model the water harvesting system with sand ditches. The soil water movement in the system was simulated using HYDRUS-2D (Šimůnek, *et al*., 2005), and the results were compared with the measured results from laboratory experiments.

2. Materials and Methods

2.1. Experimental soil and filler in the ditch

A homogeneous and dry experimental soil was made by mixing silica sand with 10% by weight of Kibushi clay. Five types of large porous and highly permeable materials were employed as the filler in the ditch namely: sand mixed with 5% clay, sand, gravel, chopped plastic pipes and rice chaff. The ditches filled with the above fillers are rafter to as clay-ditch (CD), sand-ditch (SD), gravel-ditch (GD), pipe-ditch (PD) and rice chaff- ditch (RD), respectively. Some physical properties of the experimental soil and fillers are listed in **Table 1**. In addition to five types of the ditch treatments, non-ditch (ND) treatment was also performed as a control.

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2.2. Experimental setup and procedure

Figure 1 shows the schematic diagram of the experimental apparatus. The experimental soil was carefully placed in an acrylic test soil tank (inside dimension: 89 × 48 × 15 cm). The inside walls of the soil tank were previously treated by experimental soil with bonding adhesive to prevent fingering and preferential flow of water along the wall. A ditch was dug out (41 × 9 × 15 cm) at the side of the tank as shown in Fig.1, and filled with highly permeable materials. Dielectric soil moisture sensors (ThetaProbe ML2x, Delta-T Devices Ltd, Cambridge, UK: ADR method) were set up at 26 points along the side of the soil tank. All of the equipments were placed on weighing machines to measure evaporation rate.

After the equipments were set up, assumed runoff water was uniformly showered over the soil surface using an irrigation device. Depth of the poured water was 40 mm per unit area. The poured water was ponded on the soil surface until infiltration was completed. The ponding time of each ditch treatment was measured as an index to evaluate the promotion of infiltration by the ditch. This ponding term is referred to as "infiltration process" in this paper. Following the completion of the infiltration, the soil tank was uncovered to allow evaporation. The soil water was evaporated under constant meteorological conditions during 7 days (168 h); this term is referred to as "evaporation process". Soil surface temperature was automatically regulated at 25ºC by temperature control devices, which were connected thermocouples and incandescent lamps. Room temperature was also kept at 25ºC. Wind velocity was kept constant by five blower devices.

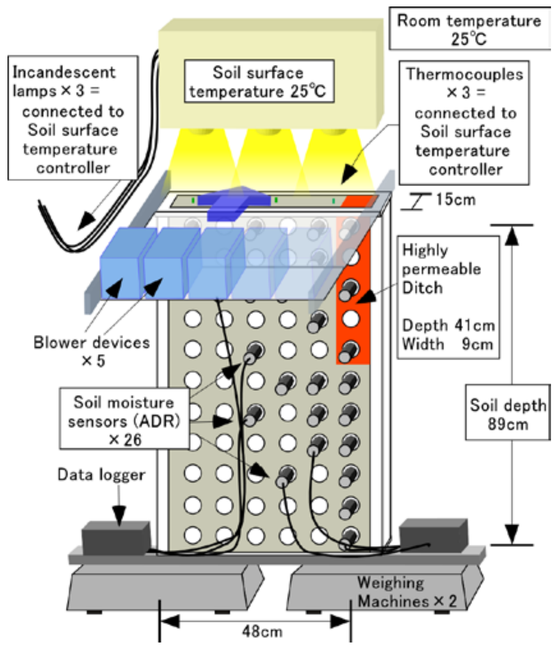

Fig. 1. Schematic diagram of the experimental apparatus.

2.3. Simulation of soil water movement

The HYDRUS-2D software package (Šimůnek *et al.*, 2005) was used to simulate the soil water movement in both infiltration and evaporation processes. The modified van Genuchten model (Vogel and Cislerova, 1988) was employed as the soil hydraulic model to adjust the air-entry value of the experimental soil since the soil was clayey. The soil hydraulic parameters given to the model were basically determined by referring the values in Table 1 and retention curves for each soil and filler. However, in order to stabilize the calculations, some parameter values such as the hydraulic conductivities of the fillers were adjusted within the range that had little influence on the water movement.

The simulations were separately performed for the infiltration and evaporation processes. In the calculation of the infiltration process, we applied the time variable pressure condition corresponding to the measured ponding depth as the upper boundary condition for each treatment. The final time of the calculation was also set at the measured ponding time. The simulation of the evaporation process was started after finishing the calculation of the infiltration process. The simulated water content distributions at the end of the infiltration process were imported as the initial water content conditions of the evaporation process. Two types of upper boundary conditions were applied for the evaporation process: (i) time variable flux condition corresponding to the measured evaporation rate and (ii) atmospheric boundary condition. In this paper, we show the simulated results for ND, CD, SD and GD in the infiltration process, and for ND and SD in the evaporation process.

3. Results and Discussion

3.1. Experimental results

The experimental results were described and discussed in detail by Saito *et al.* (2006). All of the with-ditch treatments promoted the infiltration of the poured water and reduced the cumulative evaporation compared to ND (non-ditch) treatment (**Figs. 2 and 3**). The tendency can be seen that the large pore fillers have high water storage ability.

3.2. Simulated results

Figures 4 and 5 show the distributions of volumetric water content at the ends of the infiltration and evaporation processes, respectively. The simulated distributions were in relatively good agreement with the measured distributions in the infiltration process. The simulated water content was a little higher than the measured water content in each ditch in the infiltration process; this was probably because the actual saturated water content in the test soil tank was lower than the

Table 1. Physical properties of the experimental soil and fillers.

Soil and filler in the ditch	Bulk density	Saturated hydraulic conductivity	Saturated volumetric water content
	Mg m^{-3}	cm s^{-1}	m^3 m^{-3}
Experimental soil	1.81	9.78×10^{-5}	0.288
Sand mixed with 5% clay (CD)	1.69	1.30×10^{-3}	0.326
Sand (SD)	1.67	1.05×10^{-1}	0.396
Gravel (GD)	1.30	6.35	0.495
Chopped plastic pipes (PD)	0.28	12.9	0.734
Rice chaff (RD)	0.12	1.29	0.840

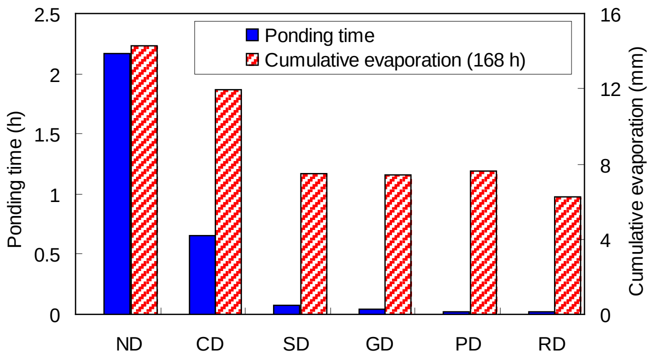

Fig. 2. Comparison of the ponding time in the infiltration process and cumulative evaporation at the end of evaporation process.

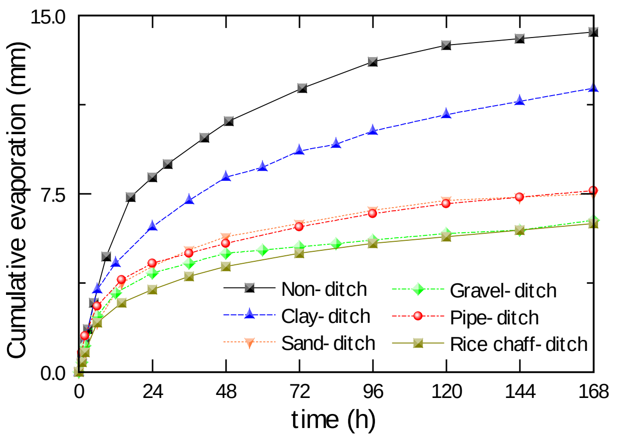

Fig. 3. Cumulative evaporation during the evaporation process.

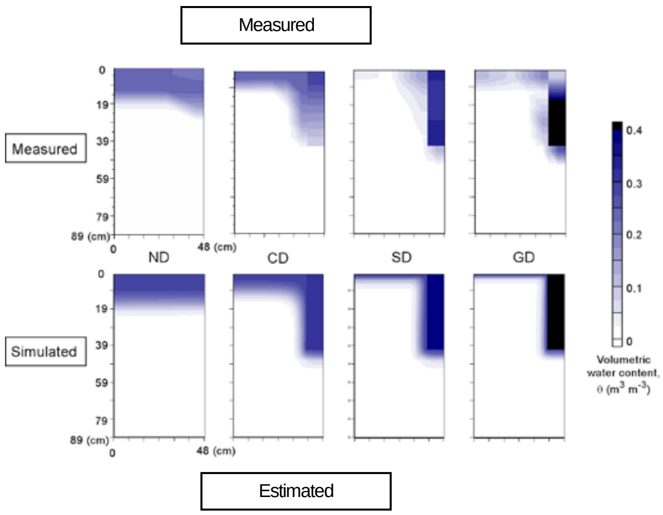

Fig. 4. Distributions of volumetric water content at the end of the infiltration process: ND = non-ditch, CD = clay-ditch, SD = sand-ditch and GD = gravel-ditch.

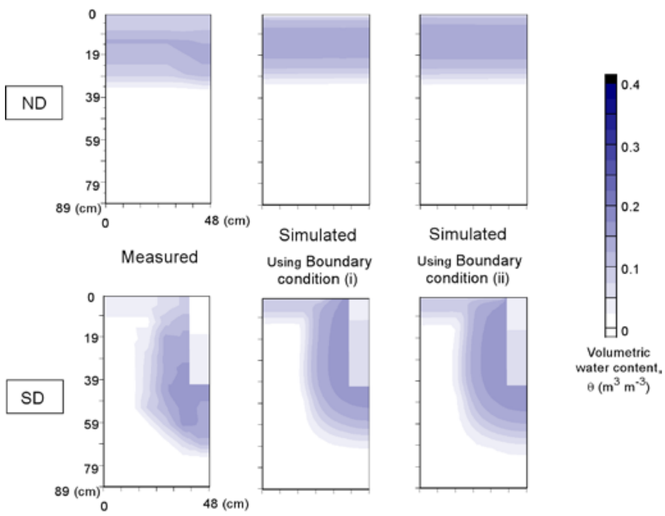

Fig. 5. Distributions of volumetric water content at the end of the evaporation process (168 h): ND = non-ditch and SD = sand-ditch. The boundary condition (i) is the time variable flux condition corresponding to the measured evaporation rate. The boundary condition (ii) is the atmospheric boundary condition.

saturated water content used in the calculation which was obtained from column saturation (Table 1). The calculated cumulative water influxes were also in relatively good agreement with the amount of the poured water.

In the evaporation process, the distribution trends of simulated water content were in moderate agreement with the measured distributions (Fig. 5). The soil water content at near-surface (0 - 10 cm) was overestimated in all of the simulated results. At the end of the evaporation process (168 h), the cumulative evaporation values calculated under the boundary conditions (i) were approximately equal to the measured values in both ND and SD, in contrast, the calculated values under the boundary conditions (ii) were 77 and 231% of the measured values in ND and SD, respectively.

The variations of the estimated evaporation rates with time under the boundary conditions (ii) are presented in **Figure 6**. The estimated rates were in relatively good agreement with the

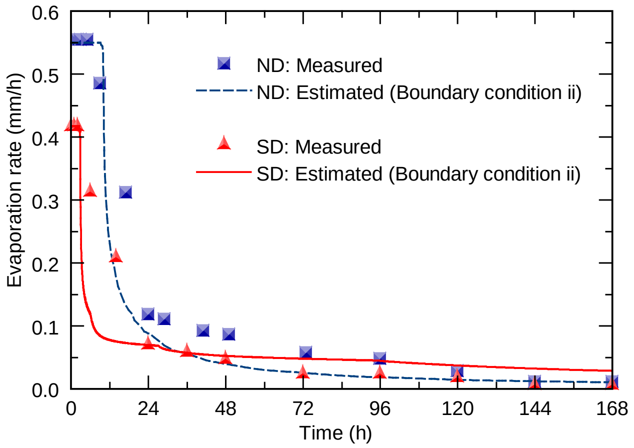

Fig. 6. Variations of the measured and estimated evaporation rates with time. The plots are the measured evaporation rate that corresponds to the time variable flux used for the boundary condition (i). The lines are the evaporation rate estimated by the model under boundary condition (ii).

measured rates at the initial steady state stage of evaporation in both ND ($h < 12$) and SD ($h < 4$). However, the evaporation rate of ND was underestimated at the second ($12 < h < 36$) and third stages ($h > 36$), and the rate of SD was underestimated at the second stage and was overestimated at the third stage. These estimation errors at the late stages may be caused by excluding the calculation scheme of vapor flux in the model. Further improvement of the model, introducing the calculation scheme of vapor flux, will contribute to the accurate estimation of water content distribution and evaporation rate. Obtaining optimal hydraulic parameter values especially at low water content range also seems to be effective for more accurate calculation at late stages of evaporation processes.

In addition, the parameter value of hCritA in HYDRUS-2D is important to estimate evaporation rate at low water content range. The hCritA means absolute value of the minimum allowed pressure head at the soil surface defined from equilibrium conditions between soil water and atmospheric vapor (Šimůnek *et al*., 2008); this parameter decides the lowest water content in the calculation. Theoretically, this parameter is decided by metrological conditions; however, the values were actually affected by the soil types. Seeking the optimal value of the hCritA for each soil type may be needed as a practical technique for better calculation.

4. Conclusion

The soil water movements in a water harvesting system with ditches filled with highly permeable materials was simulated using HYDRUS-2D. The simulated water content distributions and cumulative water influxes were relatively in good agreement with the measured results in the infiltration process. The estimated evaporation rates did not agree well with the measured rates especially at the late stage in the evaporation process when the atmospheric boundary conditions were applied to the model. Introducing the calculation scheme of vapor flux to the model and obtaining optimal hydraulic parameter values especially at low water content range will contribute to the accurate estimation of the evaporation rate.

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