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Desalinization of a Salt-affected Field Using a Rice Husk Underdrainage System

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Abstract: Excess salt and water must be drained from fields to avoid salt accumulation in dry regions. An underdrainage system effectively maintains adequate soil salinity and moisture. However, the installation of modern underdrainage systems is too expensive for developing countries. Therefore a more affordable underdrainage system is required. A rice husk underdrainage system (RHUS) is one alternative. In this study, model experiments clarified the process and the limit of desalinization in RHUS. A leaching experiment using a soil tank was performed in a laboratory, and the results were analyzed by a numerical model. The HYDRUS 2D/3D code was used for the numerical experiments. The results clarified the following: 1) when leaching water is supplied to the surface soil, the salt and water in the plow layer immediately move to the rice husk zone and are discharged out of the soil system; 2) the water and salt movements in the no-tilled zone (NTZ) were very small, and it is very difficult for RHUS to desalt the NTZ and avoid the re-accumulation of salt; 3) making a deep plow zone enhanced the desalinization ability of RHUS; 4) the connection between plow and rice husk zones is very important to increase the desalinization performance of RHUS.

Key Words: Arid region, Leaching, Numerical analysis, Salinity, Solute transport

1. Introduction

Salt accumulation is a great problem for agriculture in arid and semi-arid regions. Before planting, farmers often irrigate their fields with a large amount of water to reduce the soil salinity. This temporary moves the excess salts to the lower soil layers, but after the crop is harvested, the salt easily returns to the surface layers in impermeable soils (Yamamoto, 2009).

For sustainable agriculture, excess salts must be removed from fields. Although an open-channel drain is an ordinary facility for the salt and water management of a field, it is not effective in removing salts from fields (Kitamura *et al*., 2006). Therefore, an underdrainage system is necessary for effective desalinization of salt-affected fields.

High permeable filter materials and drain pipes are used in modern underdrainage systems. A construction guide of such a system has been written by the Japanese institute of irrigation and drainage (1993) and its performance is very good. However, the cost is unreasonable for farmers. Especially, it is financially difficult for developing countries to introduce the system into all salt-affected farmlands. Therefore, the development of a more affordable underdrainage system is needed for these countries. The rice husk underdrainage system (RHUS) is one alternative. Inosako and Ohara (2004) applied it to a salt-affected paddy field in Tanzania and evaluated its performance. The amount of drainage with RHUS was less than a modern underdrainage system with a corrugated pipe. However, the salinity concentration of the drained water from RHUS was three times that of the modern system, and the salt load removed by these systems was about the same. Therefore, they concluded that RHUS effectively removed the accumulated salts from salt-affected paddy fields. However, the process and the desalinization limit in RHUS were unknown and the construction method was not established. In this study, we did leaching and numerical experiments using a soil tank to clarify the process and limit of this system.

2. Materials and Method

2 .1. Leaching experiments in a laboratory

2.1.1. Soil tank

Leaching experiments were performed in a laboratory with a 50-cm long, 100-cm high and 15-cm wide soil tank (**Fig. 1**) that has a ceramic filter at the bottom to simulate soil condition. A 4-cm diameter outlet was made in its lower left corner.

2.1.2. Outline of experiments

Light clay soil was packed into the tank by a hydraulic filling method to a depth of 60 cm with a bulk density was 1.20 g/cm^3. An 8000 cm^3 solution of NaCl with a concentration of 0.03 mmol/cm^3 was poured into the soil, which was dried by lamps until salt accumulation was confirmed on its surface.

Next, a 10-cm long, 60-cm deep ditch was made on the

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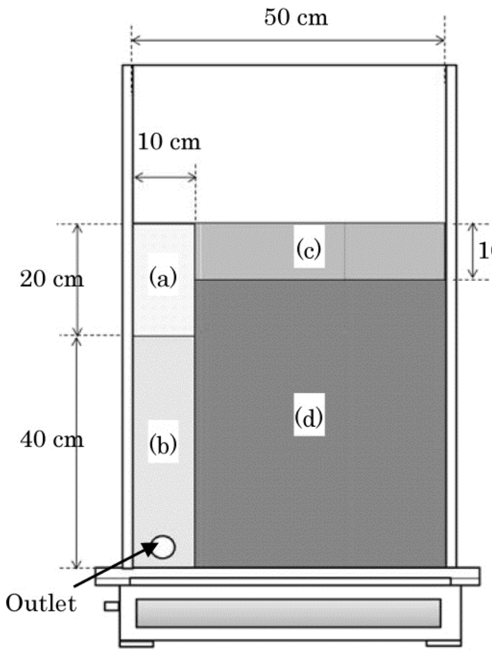

Fig. 1. Schematic diagram of the soil tank, (a) filled soil zone (FZ), (b) rice husk zone (RHZ), (c) plow zone (PZ), (d) no-tilled zone (NTZ).

tank's left. Rice husk was placed in the ditch up to 40 cm deep with a bulk density of 0.12 g/cm^3 and called the rice husk zone (RHZ). The remaining part of ditch was filled with surface soil and called the filled zone (FZ). Except for the FZ, a 10-cm deep area of the surface zone was plowed with a hand hoe; and called the "plow zone (PZ)". The bulk density of the plowed layer was 1.09 g/cm^3. The tilled zone (TZ) consisted of both of the FZ and PZ, whereas the no tilled soil zone (NTZ) was the remaining area.

Eight thousand cm^3 of tap water at a concentration of 0.00085 mmol/cm^3 was added to the soil tank for leaching and settled for 24 hours. Then, the outlet was opened and the amount of discharged water and concentration of solute were measured. The bottom of the filter gave a pressure head of -10 cm during the experiment.

2.2. Numerical analysis

2.2.1. Numerical model

HYDRUS 2D/3D software ver.1.11 (Šimůnek *et al*., 2006) was used for numerical analysis. In this model, water flow and solute transport were calculated using following equations;

$$\frac{\partial \theta}{\partial t} = \nabla\left[\mathbf{K}\left(\nabla h + 1\right)\right] \tag{1}$$

$$\frac{\partial}{\partial t}\left[\left(\rho_b K_d + \theta\right)C\right] = \nabla\left(\theta \mathbf{D} \nabla C - \mathbf{q}C\right) \tag{2}$$

where θ is the volumetric water content (cm^3/cm^3), h is the pressure head (cm), $\mathbf{K}$ is the hydraulic conductivity tensor (cm/s), t is time (s), ρ_b is the bulk density (g/cm^3), K_d is the distribution coefficient (cm^3/g), $\mathbf{D}$ is the hydrodynamic dispersion tensor (cm^2/s), and $\mathbf{q}$ is the Darcy-Backingham flux vector (cm/s).

The plow changes the surface layer's soil structure, and particularly increases the volume of macropores. Therefore, it changes the soil hydraulic properties. The Durner model (Durner, 1994) was adopted as a soil hydraulic model that can consider the effect of artificially made macropores:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$= w_1\left(1 + \left|\alpha_1 h\right|^{n_1}\right)^{-m_1} + w_2\left(1 + \left|\alpha_2 h\right|^{n_2}\right)^{-m_2} \tag{3}$$

where θ_r and θ_s are the residual and saturated volumetric water content, α_i, n_i, and m_i are the experimental constants, w_i is the weighting factor for the subcurves , and w_1+w_2=1.

2.2.2. Simulation of leaching experiment

We conducted a simulation of a leaching experiment using the soil tank to analyze the water and solute movements in RHUS. A simulation domain was the rectangular column of soil in the tank. The simulations were divided into four steps.

In the first step, salt accumulation occurred by evaporation. The soil tank was uniformly filled with light clay soil. The initial pressure head and concentration were given as -1.0 cm and 0.03 mmol/cm^3. We assumed that evaporation of 6 mm/d continued for two days. The boundary condition at the soil bottom (the lower boundary condition) was given at a constant pressure head of -10 cm.

The results of the first step were given as the initial conditions for the second step. The TZ and RHZ were newly set up in the simulation domain. The hydraulic and solute transport parameters of these materials are shown in **Table 1** and **Figure 2**. The variable and constant pressure heads were used as the upper and lower boundary conditions of the simulation domain, respectively. The variable pressure heads were -10 cm in the first 300 seconds, -1 cm from 300 s to 3600 s, and -0.1 cm from 3600 to 32,200 s. The condition was arbitrarily determined as the amount of supplied water became 8000 cm^3.

Table 1. Hydraulic and solute transport property of materials. It was assumed that the FZ parameters were the same as the tilled light clay soil. λ_L and λ_T were the longitudinal and transverse dispersivity.

Material	K_s (cm/s)	ρ_b (g/cm^3)	λ_L (cm)	λ_T (cm)	K_d (cm^3/g)
Rice husk	0.33	0.12	0.48	0.048	0
Light clay soil	2.7x10^{-5}	1.20	3.10	0.31	1.12
Tilled light clay soil	0.01	1.09	3.10	0.31	1.12

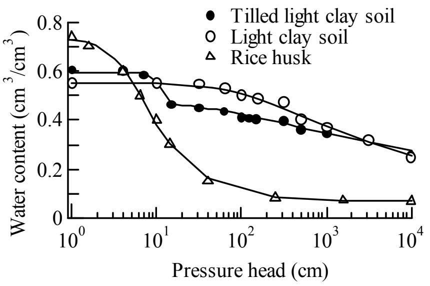

Fig. 2. Soil water retention curves of materials.

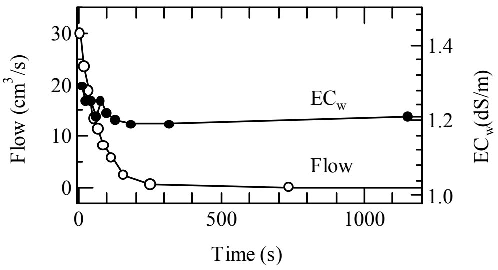

Fig. 3. Change of drainage rate from soil tank.

Table 2. Size of the FZ and PZ in the numerical experiment 2.

	PZ		FZ	
	depth	length	depth	length
Case 1	0	0	20	10
Case 2	4	50	0	0
Case 3	5	40	0	0

(cm)

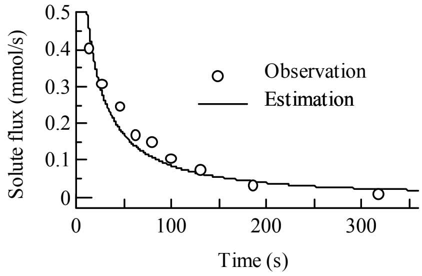

Fig. 4. Comparison of solute flux between observation and estimation.

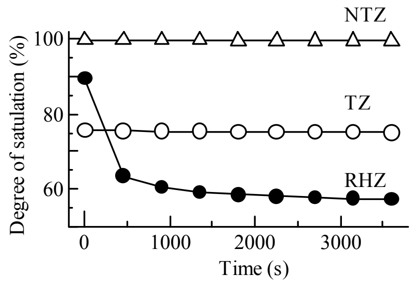

Fig. 5. Change of saturated ratio of each zone.

In the third step, the model simulated the condition where the soil tank was left standing on the floor for 24 hours using the results of the second step as the initial conditions. The upper and lower boundary conditions were no flux and constant pressure head of -10 cm.

In the fourth step, the seepage condition was given at the outlet point as a boundary condition. The results of third step were used as the initial condition. Moreover the boundary conditions were identical of them in the third step.

2.2.3. Numerical experiments

Numerical experiments were conducted to clarify the effective desalinization factors in RHUS. The focal points were the effect of the plow zone thickness and the tilled zone structure on desalinization. The PZ thickness was changed a 0, 5, 10, 15, and 20 cm in numerical experiment 1. Numerical experiment 2 was conducted under the conditions in **Table 2**. In cases 2 and 3, the PZs were not connected to the rice husk zone. Moreover, in case 3, the PZ was in contact with the right side of the calculation domain. Therefore, 20-cm deep and 10-cm long part on the RHZ was NTZ.

3. Results and Discussion

3.1 Features of desalinization in RHUS

Figure 3 shows the changes of the discharge rate and EC_w in drainage from the outlet. The maximum rate reached 30 cm/s at the beginning and exponentially decreased. It became 1/10 of the initial rate after 180 s. The electric conductivity of the effluent was stable around 1.2 dS/m. Although the EC_w of the leaching water was 0.00085 dS/m, the water dissolved the salts in the surface layer and moved to the rice husk zone in a day. Desalinization of the soil surface occurred.

Figure 4 compares the solute flux between the observation and estimation in the leaching experiment. The estimation was in good agreement with the observation. The numerical model reproduced the leaching experiment well.

Figure 5 shows the change of degree of saturation of each zone from the beginning of the drainage up to 3600 s. Since the degree of saturation of the NTZ was very high and stable, drainage in this zone did not proceed. The salt, which percolated into this zone, couldn't be drained by RHUS. The reduction of the degree of saturation of TZ was also small, because most of the water drained from this zone had already moved to the RHZ during the leaching (simulation of the second and third steps). Only the water stored in the RHZ was discharged from the outlet. The salts and water in the NTZ were not removed and only the TZ was desalted by RHUS.

3.2. Effective factors on desalinization in RHUS

3.2.1. Thickness of plow zone

Numerical experiments were performed to clarify the relationships between the solute flux and the PZ thickness. In all simulations, the initial conditions of the pressure head and the solute concentration were the same as the soil tank

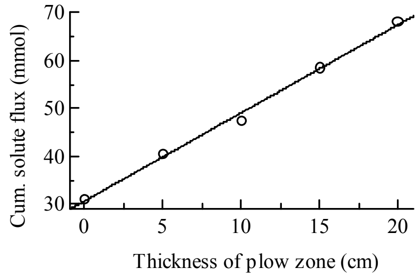

Fig. 6. Relationships between cumulative solute flux and PZ thickness.

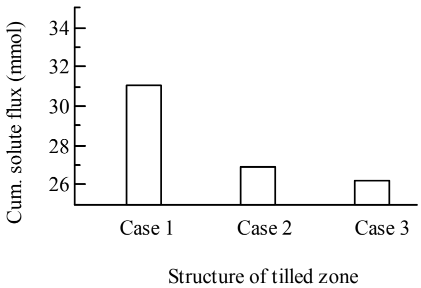

Fig. 7. Effect of structure of tilled zone on cumulative solute flux.

simulations. The amount of the leaching water of 8000 cm^3 was also the same.

As shown in **Figure 6**, the solute flux was proportional to the PZ thickness despite the same amount of leaching water. Therefore, a deep PZ increases the soil's permeability and the amount of salt transported to RHZ, suggesting that PZ plays a crucial role for increasing the desalinization efficiency in RHUS.

3.2.2. Effect of TZ structure on desalinization in rice husk underdrainage system

Figure 7 shows the effect of the TZ structure on the cumulative solute flux. Although the areas of all cases were the same, their cumulative solute fluxes were clearly different. In particular, the presence of FZ greatly influenced desalinization in RHUS, because the cumulative solute flux in case 1 was the largest among them. The results suggest that the connection between PZ and RHZ is crucial to effectively desalinize fields using RHUS.

4. Conclusions

A rice husk underdrainage system (RHUS) is a reasonable method for desalinization. In this study, the process and the limit of desalinization in RHUS were investigated through leaching experiments using a soil tank in laboratory and numerical experiments. This study clarified the following: 1) when leaching water was supplied to the surface soil, the salt and water in the plow zone immediately moved to the rice husk zone and were discharged out of the soil system; 2) the water and salt movements in the no-tilled zone were very small, and it was very difficult for RHUS to desalt the no-tilled zone and to avoid the risk of the re-accumulation of salt; 3) making a deep plow zone enhanced the ability of desalinization of RHUS; 4) the connection between plow and rice husk zones is crucial to increase RHUS desalinization.

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