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Analysis of water movement in paddy rice fields (I) experimental studies

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Abstract

For the purpose of increasing the amount of ground water recharge, we investigated the hydraulic characteristics of water infiltration in a flooded paddy rice field in Ten-Chung, Chung-Hwa county, Taiwan. Experimental results based on mini-tensiometers and double ring infiltrometer measurements indicated that the least permeable layer occurred at the interface of the puddled topsoil and non-puddled subsoil. The average thickness of this layer was about 7.5 cm and saturated hydraulic conductivity ranged from 0.034 to 0.083 cm/day. Vertical infiltration flow was saturated within the plow sole layer and became unsaturated in the subsoil below the plow sole layer. The hydraulic conductivity of the subsoil, 20–30 times greater than that of the plow sole layer, revealed that the subsoil was more permeable than the plow sole layer. In situ measurements also demonstrated that breakage of the plow sole layer increased infiltration rate by a factor of 3.7. Increasing ponded water depth from 6 to 16 cm increased infiltration 1.5 fold. It is suggested that using the fallow paddy rice fields without puddling is a feasible way to enhance groundwater recharge, but for cultivated paddy rice fields, breaking the plow sole needs further study in terms of its recoverability and because of the potential contamination of the shallow aquifer by agrochemicals. The experimental data can be applied in numerical simulation models to quantify detailed water movement mechanisms and accurately estimate the amount of ground water recharge in paddy rice fields. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Infiltration; Paddy rice field; Plow sole; Hydraulic conductivity

1. Introduction

Flooded paddy rice fields perform many functions such as ecological and environmental conservation, as well as rice production since the field is periodically flooded with water. A flooded paddy rice field can be considered as an artificial wetland and as a major source of groundwater recharge.

Takagi (1960) pioneered studies on the mechanism of irrigation water movement. He pointed out that the infiltration of soil water from paddy fields could be estimated assuming unsaturated steady-state flow. Zaslavsky (1964) verified that if the permeability of the lower layer is larger than that of the upper layer, the negative pressure head may remain constant at the interface of the two layers and extend downward to a certain distance in a two-layer system. Sanchez (1973) developed a soil water balance model to compute the percolation rate of a paddy field. Wopereis et al. (1992, 1994) and Bouman et al. (1994) adopted the SAWAH (simulation algorithm for water flow in aquatic habitats, developed by ten Berge et al.

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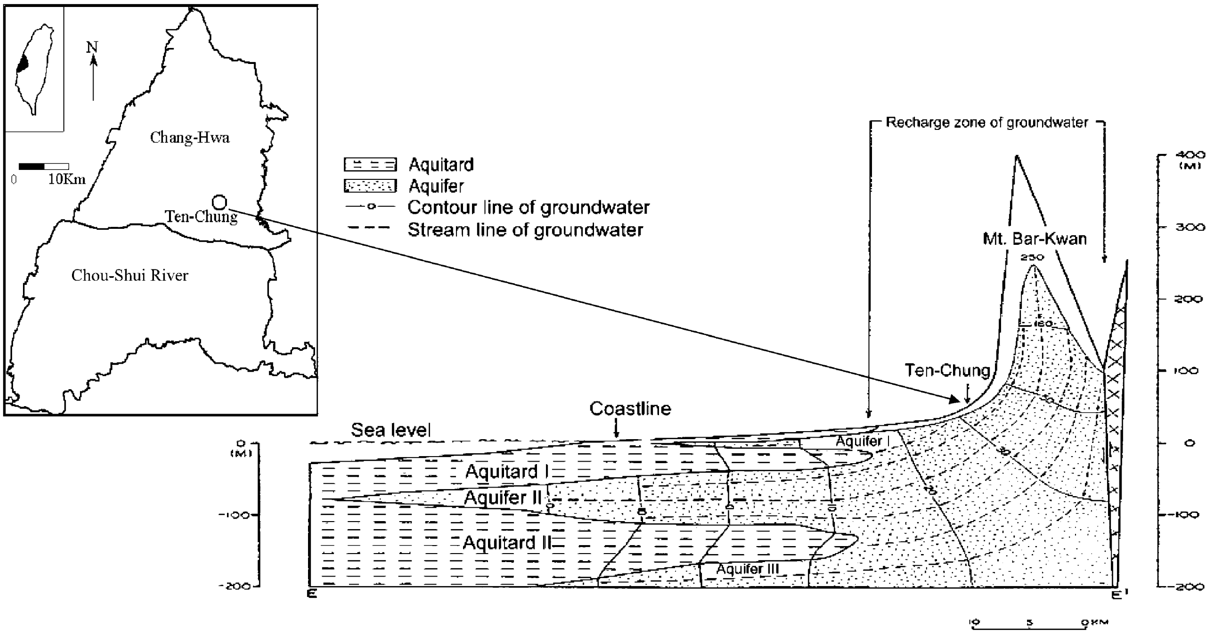

Fig. 1. Schematic diagram of the aquifer in the Chou-Shui-Alluvial fan in Taiwan. The Ten-Chung experimental paddy rice field is situated in the upper part of this region.

(1992, 1995)) model to evaluate water use efficiency of the flooded rice fields and to assess percolation and seepage losses. Several field experiments and numerical simulations have also been conducted to quantify water loss from paddy rice fields and to understand soil/water interactions (IRRI, 1965; Walker and Rushton, 1984; Miyazaki et al., 1993; Iwata et al., 1994; Tuong et al., 1994). The controlling parameters of infiltration in paddy fields have also been investigated. Increasing ponded water depth may create a greater vertical hydraulic gradient and enhance infiltration rate (Ferguson, 1970; Sanchez, 1973). Field experiments have found that percolation rates were larger in fields with a deep water table (>2 m depth) than that with a shallow water table (0.5–2 m) (Kampen, 1970). Maintaining shallow ponded water depth did not significantly affect percolation loss through uniformly puddled soil but greatly reduced losses in non-puddled spots and under-bund percolation (Tuong et al., 1994). The infiltration rate of puddled rice fields is affected by a variety of soil factors, including structure, texture, bulk density, mineralogy, organic matter content and concentration of salts in soil solution (Wickham and Singh, 1978). The presence of a plow sole, which has a very low hydraulic conductivity, is vital in controlling the infiltration rate in a flooded paddy field (Wopereis et al., 1992, 1994; Bouman et al., 1994). The plow sole was created by puddling, harrowing and leveling the soil under water-saturated conditions. Puddling destroys soil aggregates, reduces macropore, and increases micropore volume (Moormann and Van Breemen, 1978; Sharma and De Datta, 1985). Consequently, the hydraulic conductivity is considerably reduced and a low hydraulic conductivity layer is formed. This low hydraulic conductivity layer is called the plow sole or hard pan. Therefore, a typical soil profile of a puddled rice field consists of a saturated muddy layer with low density and high permeability, which gradually transforms into a relatively poor permeable layer (i.e. plow sole) at the interface of puddled and non-puddled soil. The non-puddled subsoil is unsaturated because the largest resistance occurs to water movement in the plow sole (Prihar et al., 1985; Adachi, 1990).

To increase water use efficiency in Taiwan, the

Table 1
The physical characteristics of the soil at Ten-Chung

Soil depth (cm)	Soil property		
	Water content (g/g) (%)	Soil bulk density (g/v)	Soil saturated water content (v/v) (%)
0–20	27.98	1.33	49.3
20–22.5	31.36	1.49	47.18[a]
22.5–25	25.04	1.50	47.18[a]
25–27.5	25.74	1.51	47.18[a]
27.5–30	26.83	1.53	47.18[a]
30–40	21.04	1.46	48.33
40–60	22.25	1.42	48.97
60–120	22.51	1.40	48.75

[a] The average soil saturated water content from 20 to 30 cm.

continuous irrigation method, which maintains a ponded water depth of 5–6 cm in rice plants except during weeding, fertilizing and harvesting, has been gradually replaced by a new irrigation scheme known as ‘rotational irrigation’. In this scheme, irrigation water is supplied in appropriate quantities, at the ideal time and in the proper order to ensure that all rice paddies receive their minimum water requirements. That is, during five to eight day periods, a total of 6–8 cm water is supplied to the rice paddies only for the first day. In order to facilitate this method of irrigation, the entire area is divided into several rotations. A typical Taiwanese rotational irrigation area generally consists of four irrigation units with a total area of 48 ha. However, following Taiwan’s fast economic development and changes in the eating habits of its citizens, rice has ceased to be the staple in recent years. Rice paddies are experiencing abandonment or alternative usage. The total area of diversified rice paddies in Taiwan increased from 43,700 ha in 1984 to 260,000 ha in 1997 (Tzia, 2000). A large amount of irrigation water can, therefore, be saved and used to supplement groundwater. Rice paddies that are situated in the upper stream of Chou-Shui River are primary candidates for using excess irrigation water or ample summer rainfall as groundwater recharge (Tzia, 1997; Liu, 1998). As recharged upstream groundwater moves downstream, the sharply declined groundwater levels that result from over pumping in coastal areas may gradually increase and hence reduce the sea water intrusion and land subsidence problems suffered in Taiwan.

Field and laboratory experiments were conducted to determine hydraulic infiltration characteristics in an experimental rice paddy field that is located in the upper stream of Chou-Shui-Alluvial fan. Evaluation methods, including increasing ponded water depth and breaking the hard pan to enhance groundwater recharge from paddy rice fields were also performed. Data were then employed to simulate water movement numerically in the second part of this study. The magnitude of lateral seepage and effective percolation for ground water recharge were also assessed.

Table 2
Saturated hydraulic conductivity (cm/day) of soils at different depths at Ten-Chung

Soil depth (cm)	Location			
	Eastern paddy	Western paddy	Central paddy	Average
0–20	1.65	1.21	2.02	1.63
30–60	0.98	0.84	1.22	1.01
60–90	1.67	1.87	1.71	1.75
90–120	1.05	1.66	1.85	1.52

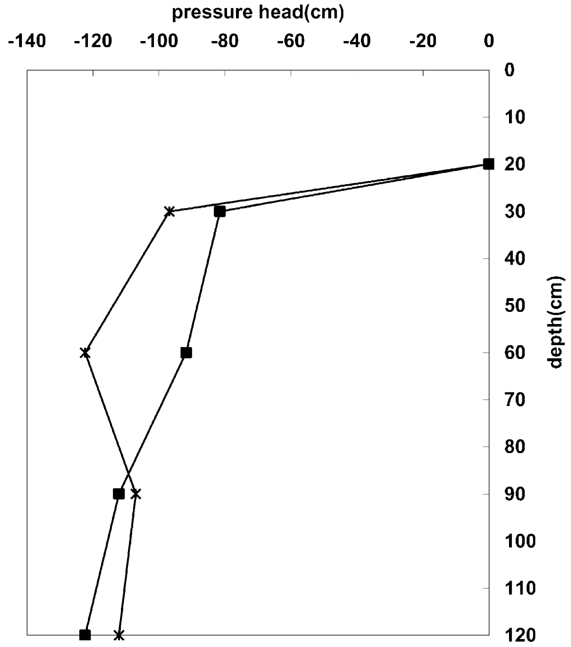

Fig. 2. Vertical pressure heads varying with depth at two measurement sites in the flooded paddy rice field after 25 days of flooding (the depth indicates the distance from the soil surface).

2. Materials and methods

2.1. Theory

For one-dimensional flow, the Darcy equation can be employed to express the flux density, $q_z(L/T)$, in saturated soil:

$$q_z = -K\frac{dH}{dz} \tag{1}$$

where K is the saturated hydraulic conductivity (L/T) and H is the hydraulic head (L). When the flux flows through a soil layer with thickness $\Delta z_L(L)$, Eq. (1) can be rewritten in a finite difference form:

$$q_z = -K_L\left(\frac{h_B - h_T - \Delta z_L}{\Delta z_L}\right) \tag{2}$$

where h_T and h_B are the pressure heads (L) at the top and bottom, respectively, and K_L is the hydraulic conductivity of the soil layer (L/T). The least permeable layer, i.e. the plow sole in the rice paddy restricts downward water flow. Furthermore, in situ measurement of steady-state infiltration rate and the Darcy equation of the finite difference form can determine the saturated hydraulic conductivity of the plow sole.

As non-puddled subsoil usually has a higher conductivity than puddled topsoil, negative pressure heads develop in the subsoil. In unsaturated soil, the negative matrix potential drives water movement. Therefore, the hydraulic conductivity of the latter becomes a function of the negative pressure head. As such Eq. (1) can be modified as:

$$q_z = -k(h)\frac{dH}{dz} = -k(h)\left(\frac{dh}{dz} + 1\right) \tag{3}$$

Under steady-state down flow, the negative pressure head that develops remains constant over a considerable depth and usually starts at the interface of both layers (Takagi, 1960; Zaslavsky, 1964; Wopereis et al., 1992).

2.2. Experiments

Field experiments were conducted at the Ten-Chung experimental rice paddy field that is situated in the upper part of the Chou-Shui-Alluvial fan, Taiwan (22°13′N, 138°42′E). This is an important ground water recharge area. Surface or rainwater can move directly into an unconfined gravel aquifer and recharge gradually into the three main confined aquifers that are situated in the middle and down stream regions (Fig. 1). The experimental field was quadrangular with a total area of 26 ha, most of which was well-puddled and flooded except for a small portion situated at the north and south borders, which were kept dry after first crop harvesting. The experimental site was adjacent to dry lands at the north and south sides and was separated by concrete bunds. The east and west sides were adjacent to the flooded area and were separated by farm roads that had concrete embankments. Groundwater tables from five observation wells that were located in the dry land/flooded area boundary were measured daily from July 18th, 1997 to January 31st, 1998. The rice paddy was initially irrigated with 15 cm of water which was followed by puddling in early July. Ponded water depth was maintained at 6–10 cm and remained for three months during the second crop period. Meanwhile, in dry areas, cracks developed around the butts,

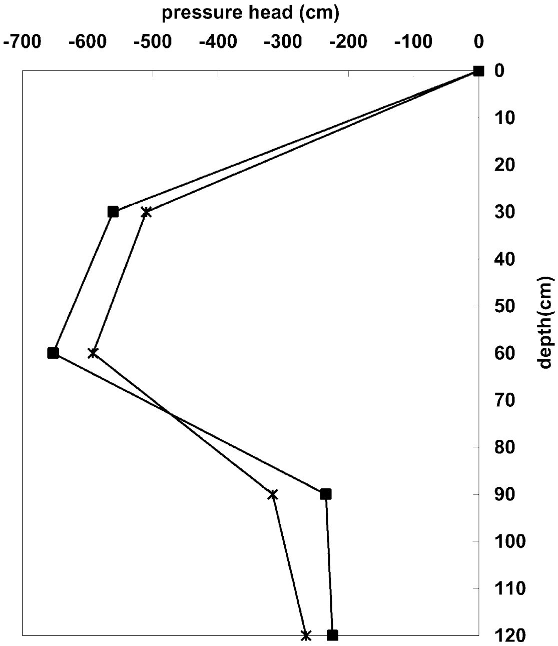

Fig. 3. Vertical pressure heads varying with depth at two measurement sites in the dry paddy rice fields (the depth indicates the distance from the soil surface).

the remaining of the paddy rice after harvesting. At the soil surface, cracks were 5 cm wide and propagated into the subsurface soil to 60–80 cm. In situ and laboratory measurements were conducted 20 days after the field experiments began.

2.2.1. In situ measurements

The soil profile could be grouped into three soil horizons from the soil surface according to its color variation: 0–30 cm was dark gray, 30–60 cm was light gray, and 60–150 cm was brown. The results provided a guideline to choose tension-meter locations and sampling depth for laboratory analyses. In situ measurements included soil water content, infiltration rate, and saturated hydraulic conductivity of the plow sole.

To determine the pressure heads distribution, five T3 tensiometers were first installed into the subsoil at 30 cm depth intervals until 120 cm depth at two flooded sites and at two dry sites. Seven T5 micro-tensiometers with data loggers were inserted into the plow sole at 2.5 cm depth intervals at four flooded sites to determine the thickness of the plow sole, using the method presented by Wopereis et al. (1992). Pressure data were recorded two days after the installation. The micro-tensiometers were also employed to measure pressure head distribution of the muddy layer at 2.5 cm interval from the surface to 20 cm depth at the same sites two days later.

Double ring infiltrometers equipped with a marriotte buret were installed at ten sites in flooded fields and at four sites in dry fields. For each site, a metal ring with a diameter of 60 cm and a height of 50 cm was pushed into the soil to a depth of approximately 30 cm. A steel cylinder with a diameter of 30 cm and a height of 50 cm was placed in the center of this ring and pushed to the same depth as the outer ring. Increasing ponded water depth and breaking the plow sole can be carried out in practice by increasing the height of bunds, and by gasoline-powered tractor plowing to a depth of 27.5–30 cm or deeper (Tsao et al., 1987, 1989). In this study, the plow sole was broken by hand drill and the raising of ponded water depth was carried out within the double ring infiltrometers. The depth of flooded water was raised from 6 to 16 cm to evaluate the effect of increased ponded water depth on infiltration rates. Infiltration rates were measured with constant ponded water depth of 6 cm before and after breaking the plow sole.

Soil water content in the northern and the southern dry paddy fields were measured immediately after 200 mm rain using a portable EC-200 salinity multimeter. It was employed to measure percent soil moisture at different depths from 3 to 27 cm with an interval of 6 cm. The infiltration rate was also measured at four sites in dry land, following the procedures described above.

2.2.2. Laboratory analyses

Saturated hydraulic conductivities of subsoil and puddled soil at three measurement sites were determined by falling-head method (Klute and Dirksen, 1986). Subsoil samples were taken from 30 to 120 cm in depth, sample cylinders were 15 cm in height and 12.7 cm in diameter. The muddy layer samples were collected with a container and drained.

Samples for measurement of unsaturated characteristics of the subsoil were taken at two measurement sites from 30 to 120 cm in depth. The sorptivity method (Dirksen, 1975, 1979) was adopted to

Table 3
Hydraulic characteristics at ten measurement sites within the experimental flooded paddy rice field at Ten-Chung

Location number	Soil properties					
	Muddy layer thickness (cm)	Ponded water depth (cm)	Infiltration rate (cm/day)	Pressure head at muddy layer bottom (cm)	Saturated hydraulic conductivity Ks(cm/day)	Remark
1	18	6	0.291	18	0.034	
2	19	10	0.768	21	0.083	10 cm from bund
3	19	6	0.514	19	0.058	
4	18	8	0.342	18	0.040	
5	22	6	0.297	20	0.055	
6	16	8	0.322	16	0.039	
7	18	9	0.347	18	0.046	10 cm from bund
8	18	8	0.443	18	0.052	
9	21	7	0.326	20	0.036	
10	20	6	0.315	18	0.059	

determine the hydraulic conductivity as a function of soil water pressure in an unsaturated soil column. Sample cylinders were 15 cm in height and 12.7 cm in diameter. Water retention data were determined as a function of soil water pressure, using the hanging water column method (Richards, 1965) and the pressure cell method (Coleman and Marsh, 1961). Sample cylinders were 15 cm in height and 12.7 cm in diameter. The laser particle size analyzer, oven, and other ASTM (American Society for Testing Material, 1985) standard methods were adopted to determine particle size distribution, dry bulk density and water content, respectively.

3. Results and discussion

3.1. Physical characteristics of the soil

The laboratory analysis (Table 1) showed that the soil consisted of silt (90%), clay and sand (5–10%). Soils at depth of 20–30 cm were further analyzed at small intervals to locate the plow sole. The largest dry bulk density was at 20–30 cm while the smallest dry bulk density occurred at 0–10 cm. Six soil samples at depths of 20–30 cm were sliced at 2.5 cm intervals for detailed analysis. The dry bulk density remained unchanged whereas soil water content declined from 31% in the muddy layer to 25% in the plow sole suggesting that unsaturated flow may develop at these depths. Table 2 presents the hydraulic conductivities determined at varying depths. The soil was relatively homogeneous. In general, the 30–60 cm soil depth had low hydraulic conductivity and the 0–20 cm muddy layer had high hydraulic conductivity.

3.2. Soil water pressure profiles

Negative pressure profiles for flooded paddy rice fields and dry land are shown in Figs. 2 and 3, respectively. Fig. 2 shows that an unsaturated flow developed below the muddy layer. The negative pressure gradient, which is small between 30 and 120 cm in depth, suggests that the vertical water movement in this region is dominated by gravitational flow. Fig. 3 shows that the entire profile is unsaturated in dry land after the harvest of the first rice crop. Soil water pressure head in dry land during two months of observation ranged from −3.3 to −6.9 m except in case of rainfall. The soil water pressure head returned to −3.3 m three days after a heavy rainfall of 200 mm. This value (−3.3 m) can be considered as field capacity. Comparing Figs. 2 and 3 confirms that the soil moisture content in dry land was much lower than that of flooded paddy rice fields.

3.3. Steady-state infiltration rate and thickness/hydraulic conductivity of the plow sole

Ten double ring infiltration tests were conducted to determine the steady-state infiltration rate. The depth of flooded water was approximately 6–10 cm. Each

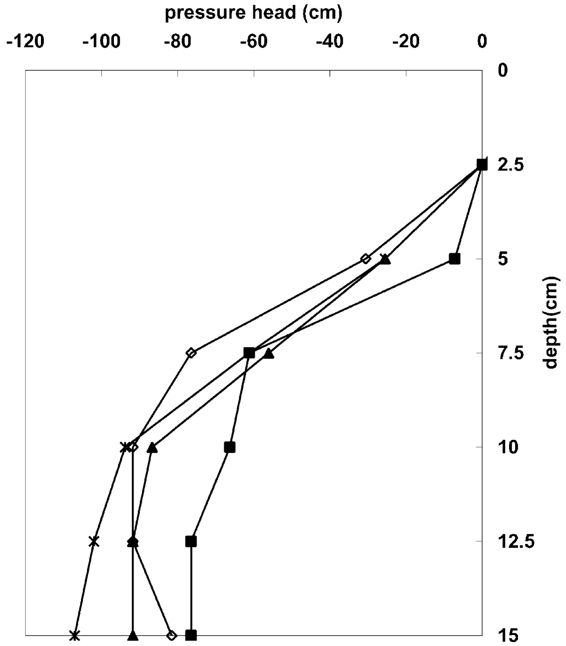

Fig. 4. Vertical pressure head variations in the plow sole at four measurement sites after 27 days of flooding (the depth indicates the distance from the bottom of the muddy layer, which is 20 cm below the paddy surface).

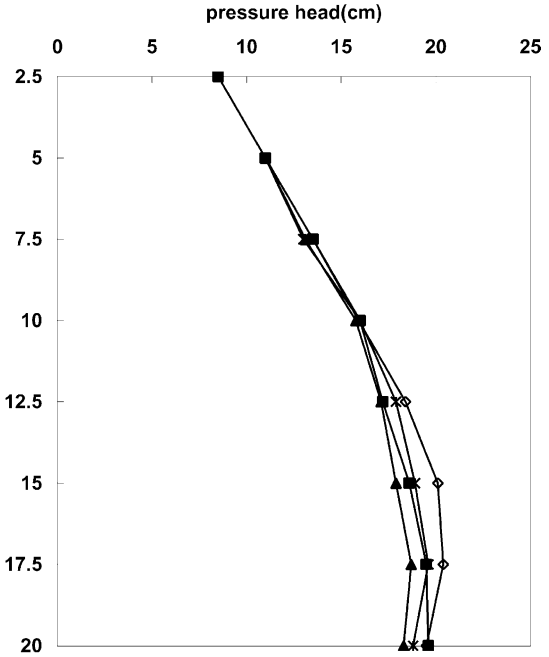

Fig. 5. Vertical pressure head variations in the muddy layer at four measurement sites in the flooded paddy rice field after 29 days of flooding (the depth indicates the distance from the soil surface).

test ran for 3 h while the T5 micro-tensiometer was positioned at the bottom of the muddy layer to monitor pressure head. Infiltration rate ranged from 2.91 to 7.63 mm/day and the muddy layer pressure head was between 16 and 21 cm (Table 3).

Fig. 4 shows the pressure profile measured by micro-tensiometers. Negative pressure increased rapidly between 0 and 7.5 cm depth and reached a steady-state beyond 7.5 cm depth. Takagi (1960) and Zaslavsky (1964) verified that if the permeability of the lower layer is larger than that of the upper layer, and vertical flow reaches a steady-state, the negative pressure head may remain constant at the interface of the two layers and extend downward to a certain distance in a two-layer soil. The pressure head measurements indicated that a two-layer system with contrasting hydraulic conductivities existed at about 7.5 cm below the muddy layer, i.e. the thickness of plow sole was about 7.5 cm.

The saturated hydraulic conductivity of the plow sole was then calculated using steady-state infiltration rate and pressure head gradient. The saturated conductivity ranged from 0.034 to 0.083 cm/day with an average value of 0.05 cm/day (Table 3), and compared well with results reported by Wopereis et al. (1992, 1994). The average hydraulic conductivity of non-puddled subsoil layers was 20–30 times larger than the hydraulic conductivities of the plow sole layers (see Table 2).

3.4. Pressure profile of the muddy layer

Fig. 5 shows that the pressure head was not equal to ponded water depth plus the depth of the muddy layer. The pressure heads at the bottom of the muddy layer, determined at four sites were approximately 18–20 cm, indicating that the muddy layer exhibited some resistance to downward movement of water at the bottom of the muddy layer since ponded water depth was 6 cm and the thickness of muddy layer was 20 cm.

3.5. Soil water content profile after rain

Fig. 6 shows that soil water content in the dry paddy field was unsaturated after rain below 9 cm depth for all sites (with significant variation). The variation can

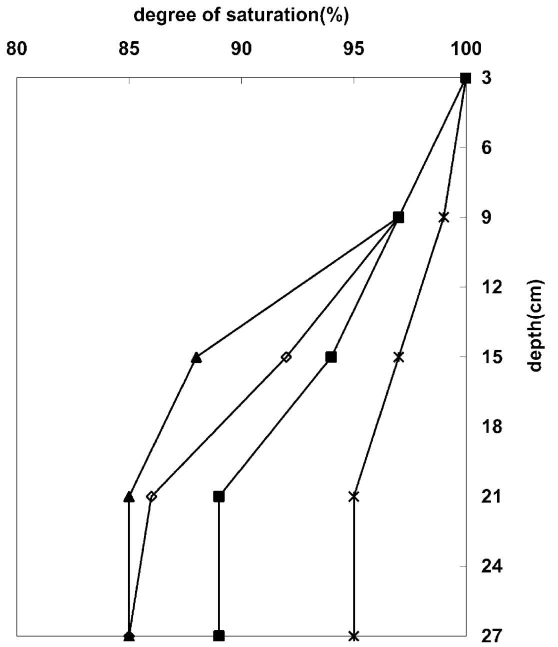

Fig. 6. Water saturation varying with depth after 200 mm of rainfall at four measurement sites in the dry paddy rice field (the depth indicates the distance from the soil surface).

be attributed to the difference in water holding capacity of the dry land among these sites. Water was ponding on the soil surface at only one site, which had the highest saturated soil water content. Double ring infiltration tests were also conducted at several sites. The average infiltration rate (1.6 cm/day after rain as illustrated in Table 4) was considerably smaller than that before rain (16 cm/day).

3.6. Enhancement of infiltration rate

Table 5 reveals that raising the ponded water depth from 6 to 16 cm increased infiltration rate by 1.5 times whereas breaking the plow sole increased infiltration rate by a factor 3.7. Therefore, breaking the plow sole is a more effective method to increase infiltration rate than raising ponded water depth.

Comparing the average infiltration rate 0.36 cm/day in flooded paddy rice fields (Table 3), versus 16 cm/day in the dry land (Table 4), there is a 45 times infiltration rate enhancement after rice harvest and if cracks are fully developed in the surface soil. The infiltration rate of the dry paddy rice fields reduced to 1.6 cm/day after two days' continuous precipitation, which was close to the infiltration rate after breaking of the plow sole in the flooded paddy rice field (1.3 cm/day, see Table 5). They were 4.5 and 3.7 times greater than that of the flooded paddy field (Table 3), respectively. This indicates that puddling of paddy rice fields before transplanting may significantly decrease infiltration rate.

3.7. Variation of groundwater table

Fig. 7 shows the variation of the groundwater table measured from five observation wells. The water table

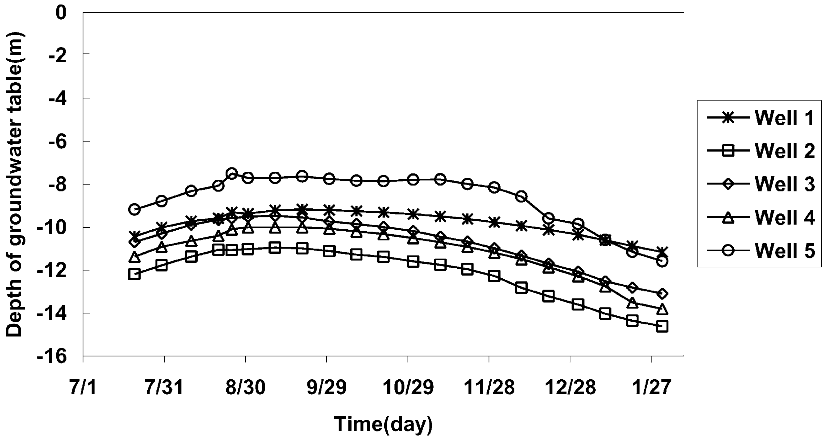

Fig. 7. Water table fluctuations from mid July, 1997 to late January, 1998, measured in five wells.

Table 4
Infiltration rates (cm/day) of the dry paddy rice field before and after 200 mm of rainfall

Weather condition	Location				
	Eastern paddy	Western paddy	Southern paddy	Northern paddy	Average
Before 200 mm precipitation	16.87	19.53	12.02	15.69	16.03
After 200 mm precipitation	1.98	1.54	1.62	1.22	1.59

raised from July and reached a peak in late August, and maintained a steady level for one month until early October. In this time, the paddy rice fields stopped to supply flooded water and the water table began to decline gradually. During the flooding period, the water table raised from about 0.9 to 1.2 m compared with the beginning of the experiment. Because the wet season started in May, therefore, the raising of water table may result partially from the paddy rice fields' infiltration. However, other local recharge sources or pumping activity may influence the variation of groundwater table. Part II of this paper evaluates groundwater recharge by infiltration from paddy rice fields into the groundwater table quantitatively using numerical simulation.

4. Conclusions

Water movement in rice paddies was studied to investigate ways to increase groundwater recharge in Taiwan. In situ and laboratory experiments were conducted to determine the hydraulic characteristics of rice paddies under flooded and dry conditions. The least permeable layer, i.e. the plow sole, was 7.5 cm thick with a hydraulic conductivity that ranged from 0.034 to 0.083 cm/day, with an average of 0.05 cm/day. The subsoil was 20–30 times more hydraulically conductive than the plow sole layer. Increasing ponded water depth from 6 to 16 cm and breaking the plow sole increased infiltration rate by 1.5 and 3.7 times, respectively. In addition, following harvest and full crack development in dry rice paddies enhanced infiltration rate by 45 times. However, infiltration rate decreased following continuous extended precipitation. This indicated that puddling rice paddies prior to transplanting results in a reduced infiltration rate. If the fallow fields were to be used as groundwater recharge pools during the second crop, doing without puddling would be both economical and would result in a higher infiltration rate. Maintaining dry topsoil and allowing cracks to develop fully could enhance the infiltration rate effectively during the summer.

It is suggested that using fallow paddies without puddling is a feasible approach to enhance groundwater recharge. However, within cultivated fields, plow sole breakage requires further study in terms of its recoverability and due to the potential contamination of the shallow aquifer by agrochemicals. In Part II of this paper, the experimental data presented here are used in numerical simulation models to study water movement mechanisms and to estimate the amount of ground water recharge in paddies accurately.

Table 5
The effect of hydraulic head and breakage of the plow sole on infiltration rate

Cases	Location			
	Eastern paddy infiltration rate (cm/day)	Western Paddy infiltration rate (cm/day)	Average infiltration rate (cm/day)	Remark
6 cm constant head	0.35	0.36	0.35	0.2 h to reach steady-state
16 cm constant head	0.51	0.53	0.52	1.2 h to reach steady-state
Breakage plow sole (6 cm constant head)	1.25	1.36	1.30	3.5 h to reach steady-state

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