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Abstract

The water use efficiency of a flooded puddled rice field was studied through analysis of the components of the water balance in the field and through simulation modelling. Seepage and percolation (SP) losses were the main determinants of water use efficiency in a field experiment conducted in the Philippines. Seepage through and underneath bunds can greatly increase total water loss. Seepage and percolation rates in well-puddled soil varied from 0.4 $cm \cdot d^{-1}$ without seepage to 3.62 $cm \cdot d^{-1}$ with seepage, and cumulative SP losses varied between 90 and 350 cm per crop cycle, respectively. The vertical profile of an irrigated puddled rice soil can schematically be described by a layer of ponded water, a muddy layer with little resistance to water flow, a plow sole with large resistance to water flow, and the non-puddled subsoil. Using this concept, the one-dimensional flow model SAWAH (Simulation Algorithm for Water flow in Aquic Habitats) accurately simulated ponded water depth and pressure head gradients within the soil profile for the test field without seepage, using measured soil-hydraulic input data.

Keywords: Rice; Water use efficiency; Simulation modelling

1. Introduction

More than 75% of global rice production is harvested in irrigated rice ecosystems which constitute 55% of total harvested rice area. About 25% of total rice acreage is under rainfed

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lowland cultivation, and produces 17% of global rice production (IRRI, 1993). In rainfed ecosystems, water is the major factor that determines rice production. In irrigated rice ecosystems, the availability of water for agriculture is threatened in many places by increasing urban and industrial demand. In view of projected increases in rice production demands from a growing world population (65% increase from 1992 to 2020; IRRI, 1993), efficient use of water in rice-ecosystems is of crucial importance. Water use efficiency of rice fields can be analyzed by studying the components of the water balance.

In Asia, contributing 90–95% of world production (Pathak and Gomez, 1991), rice in irrigated and rainfed lowland environments is mostly grown under flooded conditions. To achieve this, fields are bunded and soils are puddled by plowing at water-saturated conditions, followed by harrowing and levelling. Puddling leads to destruction of soil aggregates and macropore volume, and to a large increase in micropore space (Moormann and van Breemen, 1978). Consequently, the hydraulic conductivity and percolation rate are considerably reduced. Preferred rates for infiltration are 1–3 $mm \cdot d^{-1}$ in rainfed or inadequately irrigated lands (usually in the tropics) and 5–15 $mm \cdot d^{-1}$ in irrigated temperate lands where higher infiltration may be needed to leach organic toxins that can persist from year to year.

The water balance of a puddled rice field is determined by the following components (Fig. 1): irrigation supply, rainfall, evaporation, transpiration, seepage and percolation (SP). Rainfall in excess of bund height leaves the system as surface runoff. This surface runoff can be an input for a neighbouring field, but in a sequence of fields, neighbouring fields will pass-on the surface runoff until it is lost in a drain, creek or ditch. Transpiration

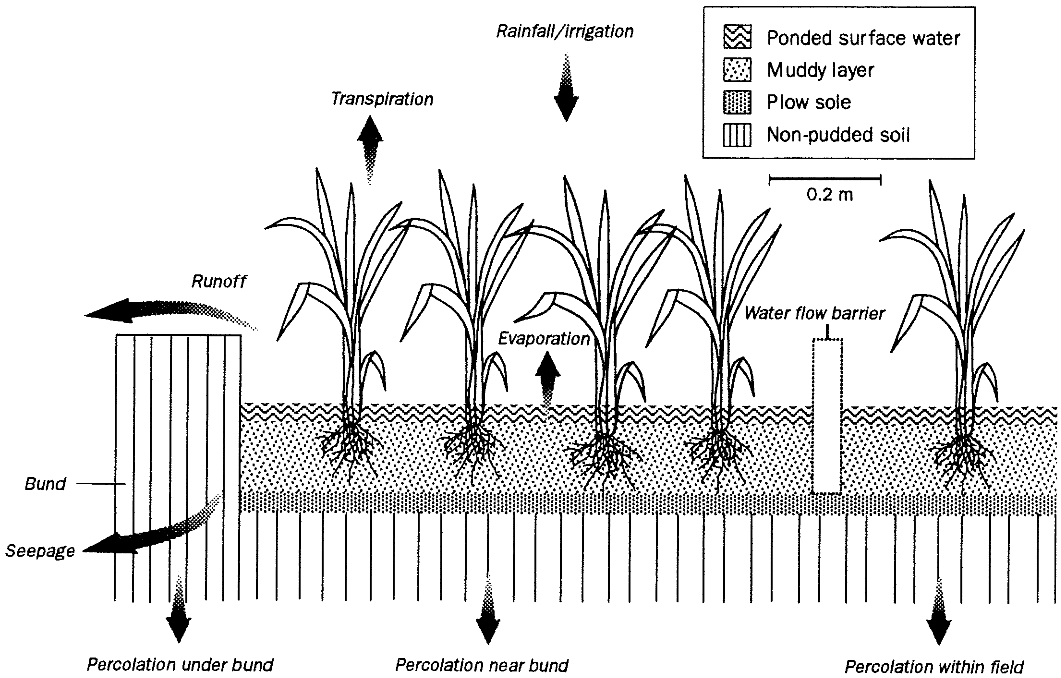

Fig. 1. Lay-out field experiment, components of its soil-water balance and functional soil layers used in SAWAH. The "muddy suspension" gradually increases in bulk density with depth, but is treated as a uniform layer in SAWAH.

by the rice crop withdraws water from the puddled layer (which is replenished with ponded water) and from the non-puddled subsoil, if rice roots are growing sufficiently deep.

Percolation is the vertical movement of water beyond the root zone to the water table, while seepage is the lateral movement of subsurface water (IRRI, 1965). In practice, the two are often inseparable (Wickham and Singh, 1978). The amount of seepage is determined by piezometer head differences between fields. The difference in piezometer head is large near drains, ditches or creeks and in terraced rice-fields with considerable difference in elevation. Seepage loss from rice terraces in the middle of a toposequence to lower lying fields may be offset by incoming seepage from higher fields. Top-end terraces will experience net seepage-loss; bottom-end terraces net seepage gain. Another possible water loss is leakage through the bunds: water moving laterally into the bunds and then down to the water table (Tuong et al., 1994). Here, under-bund flow losses are not dealt with separately but are considered part of the seepage component.

The amount of seepage is affected by the soil-physical characteristics of the field and bunds, the state of maintenance, the relative length of the bunds compared with the surface area of the field, and by the depth of the water table in the field and in the drain, ditch or creek (Wickham and Singh, 1978). The percolation rate of puddled rice fields is affected by a variety of soil factors (Wickham and Singh, 1978): structure, texture, bulk density, mineralogy, organic matter content and concentration of salts in soil solution. In general, a heavy texture, montmorillonitic clay mineralogy, high sodium content of irrigation water, and a high bulk density are favorable for effective puddling and low percolation rates. The percolation rate is further influenced by the water regime in and around the field. Increased depths of ponded water increase percolation due to the larger gradient in hydraulic head imposed. (Ferguson, 1970; Sanchez, 1973; Wickham and Singh, 1978). In a field survey in the Philippines, Kampen (1970) found, for the same reason, that percolation rates were larger in fields with a deep water table (>2 m depth) than in fields with a shallow water table (0.5–2 m).

Water use efficiency can be defined as the kilograms of dry matter produced per kilogram of water transpired by the plant or as the amount of water used (transpired) by the plant, relative to the total water input in the system. The latter definition is used here. Focus is on field losses only; conveyance losses in the distribution network of irrigation canals are not considered.

Though water loss and water use efficiency of puddled rice fields have been extensively studied, most studies so far have been empirical by nature. In this study, water use efficiency of puddled rice fields was related to soil hydraulic properties through simulation modelling. The one-dimensional soil water balance model SAWAH (Simulation Algorithm for Water flow in Aquic Habitats, ten Berge et al., 1992) was used to explore the dynamics of the water balance of puddled soil. SAWAH was validated using data from a field experiment conducted in the Philippines. The application of a one-dimensional flow model to simulate the water balance on a field scale is discussed. Overall conclusions are drawn on the water use efficiency of puddled rice fields based on analyses with SAWAH and the results of the field experiment.

2. Materials and methods

2.1. The soil water balance model SAWAH

The one-dimensional soil water flow model SAWAH solves the general flow equation numerically under given boundary conditions. The model simulates saturated and unsaturated flow occurring simultaneously in different soil profile sections. It was developed for both upland and lowland rainfed rice environments. Rice soils are layered and hydrology is highly dynamic, often resulting in temporary single- or multiple perched water tables. SAWAH uses explicit and implicit solution schemes for unsaturated and saturated sections of the soil profile, respectively. The pressure head is defined zero at all saturated-unsaturated interfaces. This condition is used as an internal boundary condition to calculate flow through the distinguished profile sections. The position of these interfaces is evaluated after each time-step. SAWAH operates with a variable time-step that ranges between 0.0001 and 0.01 d. The model requires knowledge of the soil water retention curve, which relates the volumetric water content (θ) to soil water pressure head (h), and the hydraulic conductivity curve, which relates the hydraulic conductivity (k) to water content or pressure head. Soil hydraulic properties have to be specified for all identified soil layers in the profile up to a maximum of 10. External boundary conditions (irrigation, rainfall, evaporation, transpiration, water table depth) need to be specified daily. Because the water table is a boundary condition, capillary rise and percolating soil water do not affect its depth (complete lateral recharge and discharge). Runoff occurs when ponded water depth is higher than the specified bund height.

SAWAH can accurately simulate the soil water balance of rainfed, non-puddled rice fields (Wopereis et al., 1993a). Wopereis et al. (1992) have shown that a typical puddled topsoil consists of a ''muddy'' layer of low density in the top that gradually changes into a relatively poorly permeable layer at the interface of puddled and non-puddled soil (Fig. 1), i.e. the plow sole. The top of the puddled layer contains normally only about 20–30% soil particles by volume. Bulk density increases gradually with depth. The virtually hydrostatic pressure head profile found in these muddy topsoils, even under steady state percolation, indicate that either the resistance of this layer is negligible, or that the solid soil particles form no rigid soil matrix. The largest resistance is found in the plow sole at the bottom of the puddled layer, which was considered as the top layer of the soil profile in the simulations conducted with SAWAH. The pressure head at the top of this layer was taken as the sum of the depth of the muddy layer and the depth of the ponded water layer. Because of the low concentration of soil particles in the muddy layer, its higher mass-density with respect to water was neglected.

2.2. Field experiment

The experiment was conducted in the dry season of 1991 on a 30 × 15 m experimental field, not previously used for rice, at the International Rice Research Institute (IRRI), Los Baños, Philippines (14°30′N, 121°15′E). The field was not immediately surrounded by other flooded rice fields; the nearest was at about 5 m distance, leaving a strip of dryland along all sides. The soil was classified as a mixed, isohyperthermic Typic Tropudalf (Soil

Survey, 1975). At the start of land preparation, the field was submerged for 15 days, then plowed two times and harrowed four times with a water-buffalo. Throughout the experiment the field remained submerged. The soil horizon just below the puddled layer contained 49% clay, 37% silt and 14% sand (hydraulic functional horizon 2, in Wopereis et al., 1993b).

Rice (*Oryza sativa*, cv IR64) was transplanted on 2 February 1991, at a planting density of 20×20 cm. Measurements of the water balance components started 6 days after transplanting (6 DAT). On 18 February (16 DAT) a plastic sheet, supported by wooden planks, was installed at one meter from the bund, reaching down to the bottom of the puddled zone to reduce water losses near the bunds (water flow barrier in Fig. 1). This measure proved to be very effective as will be shown later. A hand weeding was carried out half-way the growing season, on 16 March (42 DAT). On 13 April (70 DAT) the field was divided into two subplots by placing a plastic sheet in the middle of the field. One plot remained submerged, while the other was left to dry-out.

2.3. Measurements

Ponded water depth was measured daily and before and after each irrigation using sloping gauges (Wickham and Singh, 1978). Water table depth was measured daily using piezometers that reached a depth of 1 m below the soil surface. Percolation rate was determined using double ring infiltrometers (FAO, 1979). Twelve sets in the area within the plastic sheets, and six sets between the sheets and the bunds were monitored daily.

Irrigation supply was controlled through a calibrated pump. Rainfall and evaporation (class A pan) were measured daily at a meteorological station within 200 m distance of the experimental field.

Crop evapotranspiration was measured from pots with plants placed in the field. To ensure minimal disturbance to the rice plants, pots were made of metal cylinders and were filled as follows: a metal cylinder (32 cm diameter; 45 cm height) was pushed in the puddled soil to a depth of approximately 40 cm. A smaller cylinder (20 cm diameter; 25 cm height) was placed in the center of this cylinder, and pushed downward to 5 cm below the upper rim. Soil material between inner and outer cylinder was removed. The inner cylinder, containing one hill or bare soil only, was taken out and the bottom was closed with a metal cover. These pots were reinstalled in plastic bags (to prevent possible leakage) in the outer cylinders in the field. Twenty pots (20 cm diameter, 25 cm height) were distributed regularly over the field in pairs of two: one pot with plant, one pot without plant. Each pot was weighed almost daily, between 7 and 8 a.m. in the morning. Losses due to evaporation (pots without plant) and evapotranspiration (pots with plant) were calculated as the difference in pot weight between successive days. Pots were kept well watered throughout the experiment. Weighing of the pots started on 8 March 1991 (34 DAT). After weighing, the pots were brought back immediately to their original positions in the field.

Hydraulic conductivities were measured of the plow sole and the underlying subsoil at 30 DAT. For the plow sole, in situ saturated hydraulic conductivities were measured at 12 sites distributed regularly over the field, using the method presented by Wopereis et al. (1992). With this method, hydraulic conductivities are derived from in-situ measurements of infiltration rate and pressure heads in a soil column, 20 cm in diameter and 25 cm in height, installed in the field. A perspex cover with a water inlet and air outlet is screwed on top of the sample cylinder and connected to a mariotte buret. Ten small pressure-transducer tensiometers (5 cm long, 6 mm outside diameter) are used to monitor the pressure head distribution in the soil column at 2-cm intervals from depths 4–22 cm from the puddled soil surface. At each measurement site, depth of the puddled layer was recorded as the depth of easily removed soft mud.

The saturated hydraulic conductivity of the subsoil horizon was measured for one site within the field, using the column method (Bouma, 1982). The unsaturated conductivity for soil water pressures h between 0 and -2 kPa was determined with the crust method (Booltink et al., 1991). Sample cylinders were 0.25 m high and 0.20 m diameter. The data were compared with measurements conducted for the same soil horizon within a 50 ha area surrounding the test field (Wopereis et al., 1993b). All conductivity data were parameterized using the equation:

$$k(h) = k_s \, |h|^p \tag{1}$$

where k_s is the saturated hydraulic conductivity ($cm \cdot d^{-1}$), h is the pressure head (cm), and p is a soil-specific dimensionless constant.

Samples for measurement of water retention of the subsoil were taken at the same measurement site as used for measurement of hydraulic conductivity. Water retention data were determined as a function of soil water pressure h, using the hanging water column method (Richards, 1965) for -15 kPa $<h<-0.5$ kPa (300 cm^3 samples), and the evaporation method for -80 kPa $<h<-15$ kPa (Bouma et al., 1983). For the evaporation method, pressure potentials were periodically measured in the soil samples, previously used for both column and crust method, while at the same time subsamples were taken to determine water contents. The data were compared with measurements conducted for the same soil horizon within a 50 ha area surrounding the test field (Wopereis et al., 1993b).

Measured water retention data were parameterized using the following equation presented by van Genuchten (1980):

$$\theta = \theta_r + (\theta_s - \theta_r)/(1 + |\alpha h|^n)^m (\text{with } m = 1 - 1/n) \tag{2}$$

where θ_r and θ_s are the residual and saturated water contents respectively (cm^3 water/cm^3 soil), and α (cm^{-1}), n (–) and m (–) are soil-specific shape factors.

2.4. Simulations

SAWAH was used to simulate the depth of ponded water and pressure head gradients within the profile as dynamic variables. Depth of the muddy layer in the simulations was 15 cm, i.e. the average depth as determined by the thickness of easily removed soft mud at the 12 measurement sites used for hydraulic conductivity (see above). The measured daily values for rainfall, irrigation supply and evapotranspiration were used as driving variables, and the measured water table depths served as boundary conditions. All simulations were conducted using the measured hydraulic properties of puddled topsoil and non-puddled subsoil as input parameters. For k_s of the plow sole, the average value and the lowest and highest values observed at the 12 measurement sites were used. For the hydraulic conductivity and water retention data of the subsoil, average, lower and upper extremes reported by Wopereis et al. (1993b) were used. Simulated values of ponded water depth and pressure head were compared with observed values.

3. Results and discussion

3.1. Measurements

The field experiment was divided into four stages. Stage I was the period after transplanting and before plastic sheets were installed to stop seepage near the bunds of the field (calendar days 39–49). Stage II occurred between the installment of the sheets and the disturbance of the soil by weeding (calendar days 50–75). Stage III was after the disturbance of the soil (calendar days 76–103), and stage IV started after the field had been divided by a plastic sheet into two subplots at the end of the season (the test plot still being irrigated, the other plot drying out, calendar days 103–120).

Percolation rates were determined from the double-rings within the field, and for the area near the bunds (Table 1). For each stage, the combined field-average SP rate was derived from sloping-gauge readings at the beginning of the stage (Table 1). The percolation rate within the field (P′) was comparable with the percolation rate measured near the bunds (P″) during stage I, indicating that the puddling of the soil was as effective in the middle of the field as close to the bunds (Table 1). During stage II, the average percolation rate determined from the double-rings was of similar magnitude as the field-average percolation rate determined from the sloping-gauge readings. Between stage II and III, the plow sole was disturbed by hand-weeding, and measured field-average SP rates nearly tripled. The difference in field-average SP rates between stages I and II, and between stages III and IV illustrate the large effect of seepage on total water loss. In stage II the blocking of seepage through and underneath the bunds reduced the SP rate 10-fold. The drying of the neighbouring plot in stage IV induced seepage from the test plot underneath the plastic barrier through the (permeable) subsoil, thus increasing the field-average SP rate 2.2-fold. In stage I, the ratio of bund length over surface area was 0.20, and in stage IV, the ratio of plastic barrier over surface area was 0.07.

Table 1
Measured field-average seepage and percolation (SP), percolation (P′ within field; P″ near bund), and saturated hydraulic conductivity of the plow sole (k_s obs) for the four stages distinguished in the field experiment

Stage	SP	P′	P″	k_s obs*
I	3.62	0.41	0.46	0.082 (0.030, 0.122)
II	0.40	0.43	0.53	0.082 (0.030, 0.122)
III	1.46	–	–	–
IV	3.26	–	–	–

* Values between bracket are minimum and maximum encountered values.
All values are in $cm \cdot d^{-1}$.

Evaporation measured with the class A pan (E_{pan}), and evaporation (E) and evapotranspiration (ET), derived from the pots are plotted in Fig. 2. E derived from the pots without plants became gradually lower than E_{pan}, due to shading effects of the growing rice plants surrounding the pots. ET was consistently higher than E_{pan}. Because ET measurements started 34 DAT and continued for 25 consecutive days, this holds for a closed canopy situation. The following equation related ET to E_{pan}:

$$\mathrm{ET} = 1.44 E_{pan}, \quad r^2 = 0.56 \tag{4}$$

Total water consumption from the beginning of stage I to the end of stage IV is presented in Table 2. Calculations were also made of water losses for the hypothetical situations where the four different stages would have lasted for the whole duration of the experiment. The

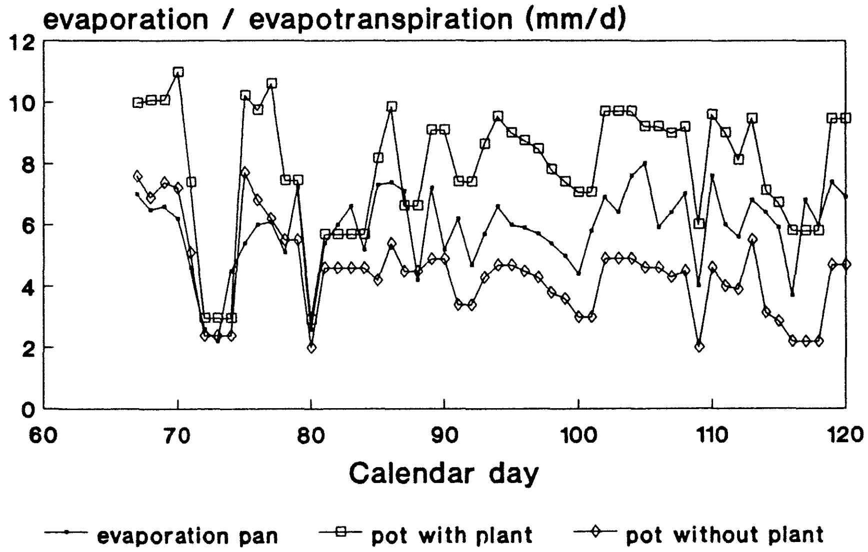

Fig. 2. Evapotranspiration (ET), evaporation (E) and class A pan evaporation (E_{pan}) measured in the field experiment.

Table 2
Measured cumulative water use for the field experiment, and calculated values for four hypothetical situations based on SP rates of the four individual stages (see text)

	ET	SP	SUM
Measured	55.5	74.9	130.4
Calculated			
situation 1	55.5	296.8	352.3
situation 2	55.5	32.8	88.3
situation 3	55.5	119.7	175.2
situation 4	55.5	267.3	322.8

ET = evapotranspiration; SP is seepage and percolation; SUM = cumulative water use for one crop cycle. All values in cm.

Table 3
Fitted parameter values k_s and p of the hydraulic conductivity curve (Eq. 1); and θ_r, θ_s, α and n of the water retention curve (Eq. 2) of the subsoil horizon

	Hydraulic conductivity		Water retention			
	k_s ($m \cdot d^{-1}$)	p (–)	θ_r ($m^3 \cdot m^{-3}$)	θ_s ($m^3 \cdot m^{-3}$)	α (cm^{-1})	n (–)
On-site	0.60	−2.41	0.01	0.56	0.0554	1.1121
Upper extreme	4.82	−2.49	0.01	0.58	0.1099	1.0623
Average	0.77	−2.32	0.01	0.55	0.0468	1.0954
Lower extreme	0.08	−2.00	0.01	0.52	0.0152	1.1429

Average, upper and lower extreme values are taken from Wopereis et al. (1993b).

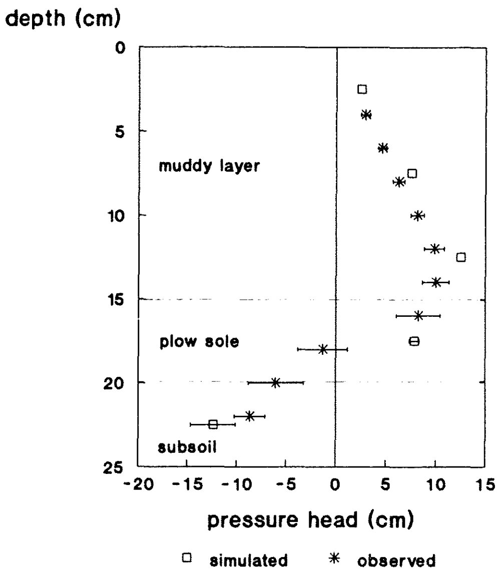

Fig. 3. Measured (12 sites) and simulated pressure head distribution in the field experiment (calendar day = 63). Simulations were conducted for six different scenarios, comprising three different values of k_s of the plow sole at the interface of puddled and non-puddled soil and average, lower and upper extremes for the hydraulic conductivity of the subsoil (see text). The bars represent the standard errors of the means.

values in Table 2 correspond well with the ranges found in experimental field studies in the Philippines by Tabbal et al. (1992). They measured irrigation needs, rainfall and drainage and estimated evaporation and transpiration to derive water losses over a cropping season for a large number of rice fields. Water requirements ranged from 1000 to 4000 mm per rice crop. The saturated hydraulic conductivity of the plow sole varied between 0.03 and 0.12 $cm \cdot d^{-1}$ (Table 1). Water retention and hydraulic conductivity data of the non-puddled subsoil horizon, determined for one site within the field fell within the range of extremes reported by Wopereis et al. (1993b) for the same soil horizon (Table 3).

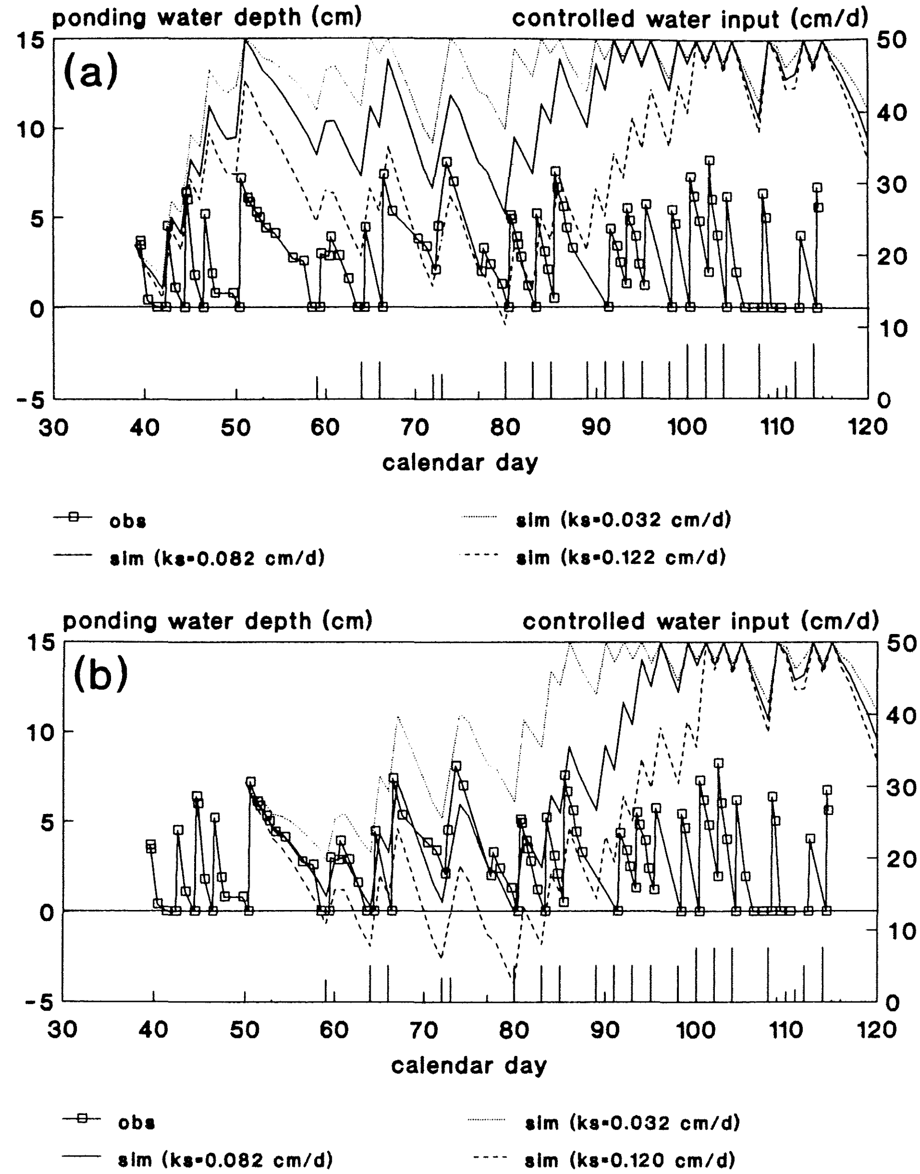

Fig. 4. Observed and simulated ponded water depths in the field experiment. (a) Start of simulation is on the first day of the experiment. (b) Start of simulation on first day of stage II (see text).

3.2. Simulations

Simulations were conducted using measured hydraulic properties of puddled top- and non-puddled subsoil as input parameters. For k_s of the plow sole, the average value and the lowest and highest values were used (Table 1). For the hydraulic conductivity and water retention data of the subsoil, average, lower and upper extremes reported by Wopereis et al. (1993b) were used (Table 3).

Pressure head distributions in the puddled layer of the profile were determined at 30

DAT, i.e. on calendar day 63, when there was almost no ponded water on the field. Simulations agreed well with observed data (Fig. 3). The shape of the curve is similar to observations made by Iwata et al. (1988), Adachi (1990), Tabuchi et al. (1990) and Wopereis et al. (1992).

Simulated values of ponded water depth were very much affected by the differences in k_s of the plow sole, whereas the variation in measured hydraulic properties of the subsoil had no effect. When simulation was started at the beginning of stage I, water losses were underestimated and simulated ponded water depths were much higher than observed (Fig. 4a). This was caused by the fact that SAWAH is a one-dimensional flow model that does not account for seepage. When simulation was started in stage II, simulated ponded water depths using the average k_s of the plow sole were in good agreement with observed values during that stage (Fig. 4b). With the damaging of the plow sole in stage III, however, the effective, field-average k_s of this layer increased and water losses were again underestimated.

4. Conclusions

Water use efficiency of puddled rice fields is determined by SP losses. Seepage through and underneath bunds can have a dramatic impact on total SP losses. In our field experiment, SP in a well-puddled soil varied from 0.4 $cm \cdot d^{-1}$ without seepage to 3.62 $cm \cdot d^{-1}$ with seepage through and underneath all four bunds (bund length/surface area ratio of 0.20). Extended over a complete growing season, cumulative SP losses varied between 88 and 350 cm, compared to 55 cm cumulative evapotranspiration. These values compare well with observations in the Philippines by Tabbal et al. (1992). Proper maintenance of bunds may greatly improve water use efficiency, especially if a rice field is next to a drain or a creek, or if neighbouring fields are not flooded.

The vertical profile of puddled rice soil can schematically be described by a layer of ponded water, a muddy layer with no resistance to water flow, a plow sole with large resistance to water flow, and the non-puddled subsoil. Using this concept, the one-dimensional flow model SAWAH accurately simulated the water balance of a test field without seepage using measured input data for the hydraulic properties of the plow sole and the underlying subsoil. In the experiment, water loss by percolation was determined by the saturated conductivity of the plow sole. It was not affected by the hydraulic characteristics of the (permeable) subsoil.

Because of its high degree of detail, SAWAH is very suitable for in-depth analyses of the water balance of puddled rice fields. It is also suitable for exploration and prediction of the effects of various soil-hydraulic properties on the components of the soil-water balance. In Part II of this paper (Bouman et al., 1994), SAWAH is used to investigate magnitude and variability of percolation rates through puddled soils with different soil physical and hydraulic properties, under varying hydrological conditions.

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