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OPTIMIZING IRRIGATION AND DRAINAGE RATES IN SRI PADDY FIELDS

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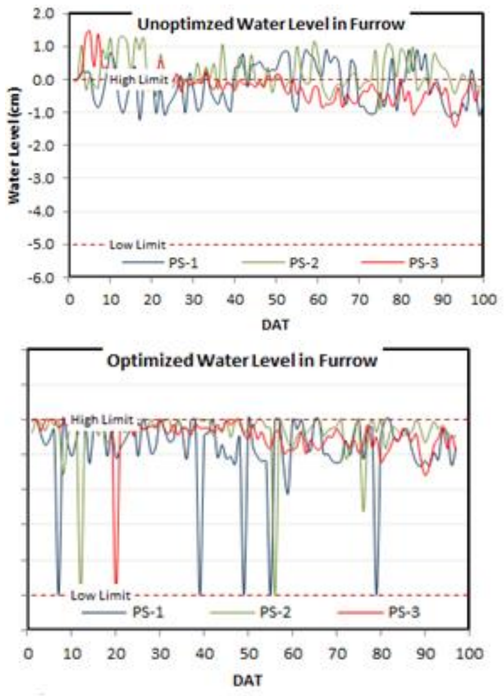
Graphical abstract



Abstract

A quantified study to optimize furrow irrigation and drainage rates for SRI paddy fields has been carried out over three different planting seasons. It is very crucial to maintain soil conditions where the water level sustains soil moisture at around saturation and air-entry values. In the present study we report on a simulator program which applies a saturated water flow equation in one dimension for which boundary conditions at both ends formed water rates (Neumann type). A spreadsheet optimization using an imbedded Solver in MS Excel was employed alongside the simulation. Daily rainfall, evapotranspiration and percolation rates as sink-source functions were incorporated into the equations. Our study shows that optimizing irrigation and drainage rates gives an effective water level for SRI paddy fields within a range of -5 to 0 cm for all planting seasons. The highest value for irrigation rate within the furrow was about 6 mm per day, while the optimizing drainage rate was about 0.5 mm per day. Water table profiles are significantly affected by planting season. Our study confirmed that conserving drained water from one planting season is desirable to provide sufficient irrigation water for the next planting season.

Keywords: SRI paddy field, water level, water table, irrigation, drainage, optimization

1.0 BACKGROUND

Water management in SRI paddy fields is crucial to maintain the water level within a proper soil moisture range. Soil moisture conditions should be kept around or between the soil's saturation and air-entry values. [To condition the water level simply, as it becomes a standard procedure, paddies are planted in a short ridge between two furrows or waterlines [1, 2] – this I cannot understand]. There is no standard number of paddy plants in a specific ridge but commonly there are about 4 to 5 plants with a wider spacing (25 cm x 25 cm) in between compared to the conventional paddy fields [3]. The furrow itself could be the width of an unplanted row. In Indonesia, this practice is well-known as *Jajar Legowo*, called *Jarwo* for short. This practice is also for the plants to intercept more sunshine [4, 5]. Typically, the space between two adjacent furrows ranges from 100 cm to 125 cm, and the width is about 25 cm.

Furrow irrigation [e.g., 6] is commonly applied to moisten the surrounding soils through the process of lateral infiltration. In some occasion the furrow is fully filled with water at the earlier growth stage but in the later stages, the water level is lower than the soil surface [7]. Lowering the water level gradually with time as the root growth has also been introduced to put the water level continually below the root zones [7]. Irrigated water flows down gravitationally in the furrow in which its speed is determined by the slope length of the furrow [8, 9]. It is not uncommon to find a slope of paddy field in the magnitude of 10-4 (in example, 5 cm-height different in 100 m-length). It turns out that furrows are also effective as drainage channels to draw excessive rainwater out of the fields [10].

The water may be supplied through a water gate from a tertiary irrigation box continuously, or intermittently vis-à-vis to the determined purposes or special treatments of irrigation [11]. An alternate wetting and drying (AWD) through surge irrigation practice [12] is also common to acquire more water use efficiency and to condition aerobic-anaerobic dynamics in the root zone which is very important to propagate microorganism activities [13] and to control soil respiration [14].

This study intends to build a simulator program for maintaining water level in the furrows that can minimize irrigation and drainage rates. Herewith, we applied a saturated water flow equation in one dimension over which boundary conditions at both ends formed water rates (Neumann type). A simulation program was built, by using the imbedded Solver of MS Excel with the target of optimization is to minimize irrigation and drainage rates while maintaining water level in the furrows at a certain range. Hence, we employ daily rainfall, evapotranspiration and percolation rates as sink-source function that was incorporated to the equation.

2.0 THEORETICAL APPROACH

Water flow in saturated porous medium follows the Darcy's Law that can be written in the following equation [15].

$$q = -K_s \frac{dh}{dx} \qquad (1)$$

Where, q is water flux (m d^{-1}); Ks is saturated hydraulic conductivity (m d^{-1}); h is static pressure head (m H_2O); and x is distance (m).

In the form of the unsteady state, Equation 1 can be transformed into the following continuity equation [e.g., 16].

$$S\frac{\partial h}{\partial t} = T\frac{\partial^2 h}{\partial x^2} + s \qquad (2)$$

Where, S is storativity; s is water sink and source (m d^{-1}); t is time (d); and T is transmissivity (m^2 d^{-1}) in which was defined by the following equation.

$$T = K_s h \qquad (3)$$

The water sink and source herewith is in the form of the following equation.

$$s = re - et \qquad (4)$$

Where, re is effective rainfall intensity (m d^{-1}); et is evapotranspiration rate (m d^{-1}).

The effective rainfall intensity denotes rainwater that is potential to percolate into the soil layer.

$$re = \begin{Bmatrix} r & r \le p \\ p & r > p \end{Bmatrix} \qquad (5)$$

Where, p is percolation rate of the soil layer (m d^{-1}). Excessive water is calculated by the following equation.

$$ro = \begin{Bmatrix} 0 & r \le p \\ r - p & r > p \end{Bmatrix} \qquad (6)$$

Where, ro is run-off or surface drainage (m d^{-1}).

Boundary conditions are in the form of horizontal fluxes (Neumann type [e.g., 17]) specified by the following equations.

$$q_0 = -K_s \left.\frac{\partial h}{\partial x}\right|_0 \qquad (7)$$
$$q_L = -K_s \left.\frac{\partial h}{\partial x}\right|_L \qquad (8)$$
$$h(L,t) = h_L(t) \qquad (9)$$

Where, L is length of the domain (m); and h_L is known as time function of pressure head (m) at x=L.

An initial condition is given by the following equation.

$$h(x,0) = h(x) \qquad (10).$$

3.0 METHODS AND MATERIALS

3.1 Numerical Solution

By applying an explicit type of Finite Difference Method, Equation 2 was transformed into the following equations:

$$h_i^{t+1} = ah_{i-1}^t + bh_i^t + ch_{i+1}^t + ds^t \qquad (11)$$
$$a = c = \frac{T_i\Delta t}{S\Delta x^2} \qquad (12)$$
$$b = 1 - 2a \qquad (13)$$
$$d = \frac{\Delta t}{S} \qquad (14)$$

Where, i is index for spatial increment {i=1…n}, t is index for temporal increment, and n is the total number of spatial increments.

The boundary conditions of Equation 7 and Equation 8 were transformed into the following equations.

For i=1:

$$h_1^{t+1} = ah_0^t + bh_1^t + ch_2^t + ds^t \quad (15)$$

$$h_0^t = h_1^t - q_0 \frac{\Delta x}{K_s} \quad (16)$$

For i=n;

$$h_{n-1}^{t+1} = ah_{n-2}^t + bh_{n-1}^t + ch_n^t + ds^t \quad (17)$$

$$h_n^t = h_{n-1}^t - q_n \frac{\Delta x}{K_s} \quad (18)$$

Where, h_0 and h_n are the water level in each furrow, and q_0 and q_n are the associating fluxes from the furrow to the soil (positive sign), or vice versa (negative sign). Since the water flow domain was symmetrical then q_0 was equal to q_n.

The flux, q_0 was optimized using Solver in MS Excel with the following conditions:

$$\text{Minimize } \mathrm{SUMSQ}(q_0^t) \text{ for } t = t_0 \text{ to } t_m \quad (19)$$

$$h_{min} \le h_0 \le h_{max} \quad (20)$$

Where, h_{min} and h_{max} are the lowest and the highest values of water level in furrows (cm).

The initial condition was given by equaling the water table with the soil surface.

$$h_i^0 = 0 \quad (21)$$

Since Equation 11 is conditionally stable, the maximum time step was determined by the following equation.

$$\Delta t \le \frac{S\Delta x^2}{2T} = \frac{S\Delta x^2}{2K_s h_{max}} \quad (22)$$

Table 1 shows values of numerical parameters used in the simulation. Length of the water flow domain (L) was 150 cm divided by 15 numbers of spatial increments (Δx). Based on the soil properties shown in Table 1 and Equation 22, the resulted Δt was 1.2 days. In this study however, Δt was set to 1 day in order to achieve the stability of calculation.

Table 1 Numerical parameters

Parameters	Symbol	Unit	Value
Length of Flow Domain	L	cm	150
Hydraulic Conductivity	Ks	cmd-1	0.5
Storativity	S		0.6
∑Spatial Increment	b		15
Spatial Increment	Δx	cm	10
Highest Water Level	hmax	cm	50
Time step	Δt	d	1.2
Maximum Transmissivity	Tmax	cm2d-1	25

3.1 Study Site

The paddy field selected for this study was at the Rice Research Center of the Ministry of Agriculture located in Sukamadi, West Java (Figure 1), Indonesia. It has about 300 ha of paddy field which is used mainly to test newly developed rice breeds and cultivation techniques.

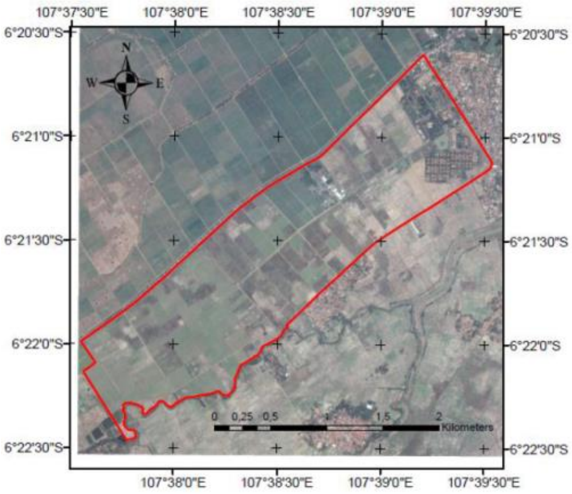


Figure 1 Location of the study site

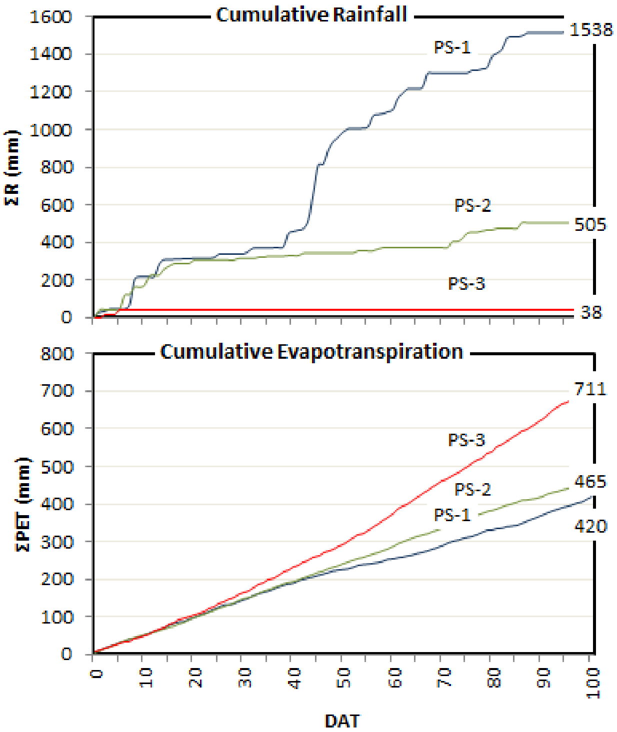


Figure 2 Rainfall and evapotranspiration at different planting season

Based on a decadal weather recorded in the location, there was a distinct transition of wet and dry seasons, and there was also temporal shifting on the beginning and length of dry season. The earliest and latest dry seasons were 50 days and 160 days of Julian date calendar, and the shortest and longest dry seasons were 170 days and 300 days [18]. This area is classified as dry land where the availability of rainwater is sufficient only for one planting season of paddy. However due to the irrigation, paddy can be planted up to 3 times a year. The first planting season is from December to the middle of March, the second season is from April to the middle of July, and the third season is from August to the middle of November.

In this study, we used whether data recorded from 2013 and 2014. As shown in Figure 2, the cumulative rainfall (ΣR) and potential evapotranspiration (ΣPET) in each planting season was significantly different. Total rainfall and evapotranspiration in the first planting season (PS-1) were 1538 mm and 711 mm, in the second planting season (PS-2) were 505 mm and 465 mm, and in the third planting season (PS-3) were 38 mm and 420 mm, respectively. It is clear that PS-2 and PS-3 are the seasons having deficit water while excessive water occurred in PS-1.

Based on Equation 4, Equation 5 and Equation 6, and by applying averaged percolation rate 5 mm per day, the rates of water sink and source for each season are shown in Figure 3. The rates clearly fluctuated with season and days of transplanting (DAT). The maximum range of sink and source was found in PS-2 which vary from -8.9 mm to 7.6 mm per day. The minimum range was found in PS-3 which vary from -5.4 to 5.6 mm per day.

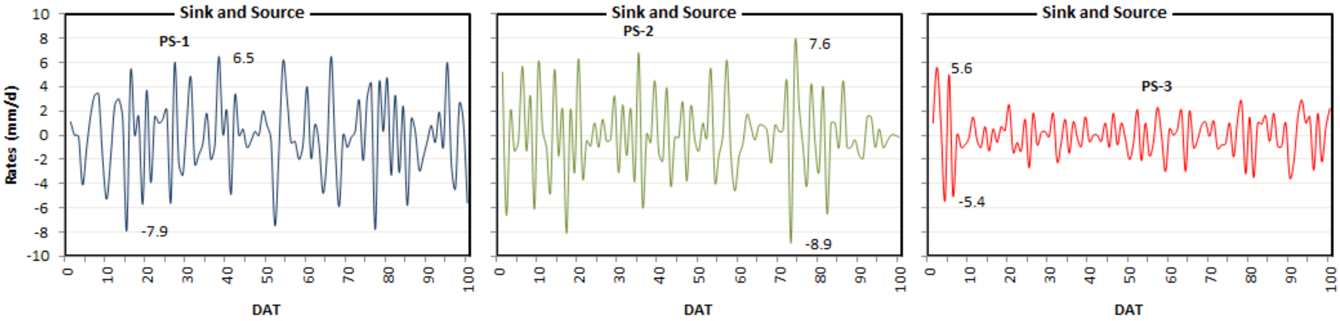


Figure 3 Rates of water sink and source at different planting season

4.0 RESULTS AND DISCUSSION

4.1 Water Level in the Furrow

Figure **4** shows water level in the furrow with and without optimization of irrigation and drainage during all planting seasons (PS-1, PS-2 and PS-3). As stated earlier that the target of optimization was to minimize irrigation and drainage rate which enable to maintain water level in the furrow in between 0 cm (high limit) to -5 cm (low limit). As clearly indicated in the left figure, without optimization, water level in many occasions for all planting seasons exceeded the soil surface (high limit). There was a general tendency that water level decreased gradually with time. Whereas, after applying optimization (right figure), water level in all occasions are between the expected high and low limits. In some cases, water level reached the low limit that shows responsiveness of the optimization process.

4.2 Furrow Irrigation and Drainage Rates

Figure 5 shows irrigation and drainage rates, and theirs accumulations resulted from the optimization process in all planting seasons. Comparing to the drainage (negative value), irrigation rate (positive value) was more responsive even in the wet season (PS-1) indicating that the optimization process preferred to maintain the water level closed to the high limit (soil surface). This preference might be due to the given initial condition that was at the soil surface. Therefore, when the water level has dropped below the soil surface, irrigation rate amplified immediately to put back the water level position to the initial value. This trend resulted in higher cumulative irrigation (middle curves) in PS-1 (56 mm) rather than in PS-2 (43 mm) and in PS-3 (17 mm). Similarly, a higher cumulative drainage (bottom curves) occurred in PS-1 (1.5 mm) rather than in PS-2 (0.4 mm) and in PS-3 (0.04 mm).

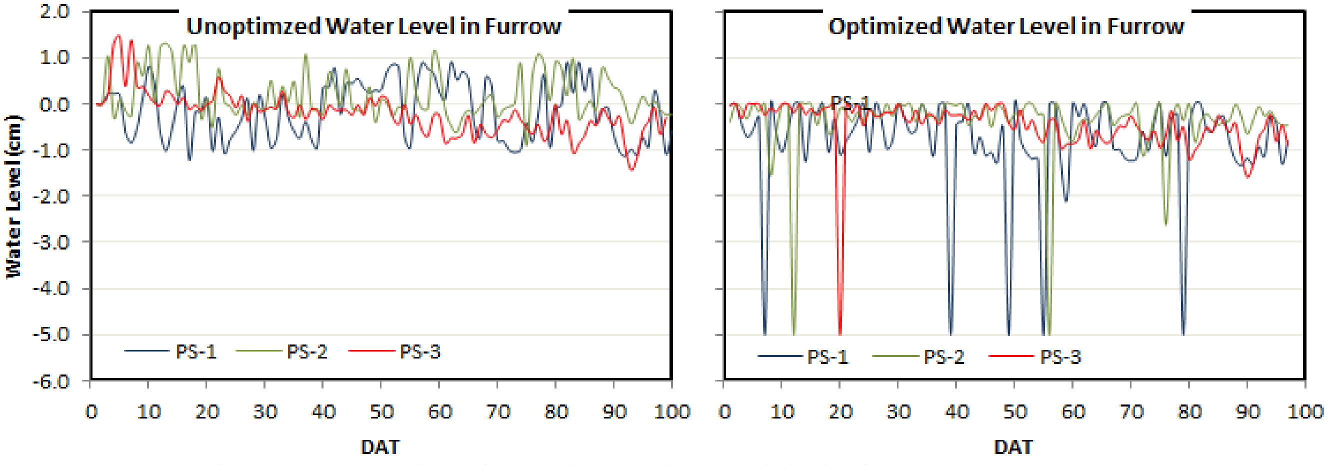


Figure 4 Water level in the furrow with and without optimization for all planting seasons

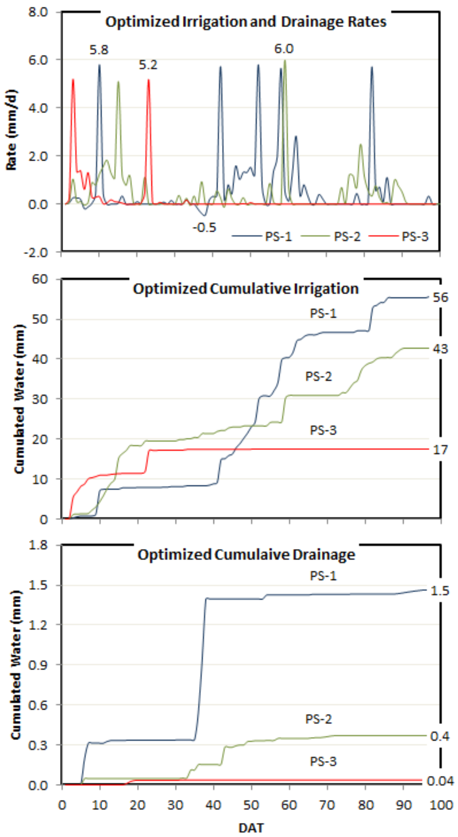


Figure 5 Optimized irrigation and drainage for all planting seasons

As shown in the Figure 5, the highest value of irrigation rate in the furrow was 6 mm per day, and that of drainage was 0.5 mm per day. These values are very important to determine the capacities of irrigation and drainage infrastructures in the field scale that may consists of many furrows with different width and length. These values would change depending upon soil properties and interval between two adjacent furrows. Prior to the optimization process, it is important to find the optimum spacing between two furrows. For this purpose, Hooghoudt equation [19] might be applicable.

4.3 Water Table in the Soil Profile

Figure 6 shows water table profiles in the soil layer between two adjacent furrows in all planting seasons. With and without the optimization process, the water table profiles in the same planting season were lookalike except those at the distance closer to the furrows in which the effects of the water level became significant. Farther than the furrow, fluctuations of water table occurred as direct responses to the sink and source rates.

For comparison purpose, the curve lines were selected on DATs that could represent the minimum and maximum values of the water table occurring in the PS-1. We found that the minimum water table of -1.0 mm occurred on 12 DAT and the maximum of 1.0 mm on 81 DAT in PS-1. This range of water table is sufficient for cultivating SRI paddy fields. All curve lines in PS-1 laid between these two lines but not the case for those curve lines in PS-2 and PS-3. Higher and more intense rainfall affected the water table profiles fluctuated more than the others. In PS-2 and PS-3, water table profiles were more concentrated and stable around the soil surface. It turns out that maintaining water table in the soil layers with lesser rainfall is easier because ones might deal only with irrigation though a sufficient irrigation which must be readily available.

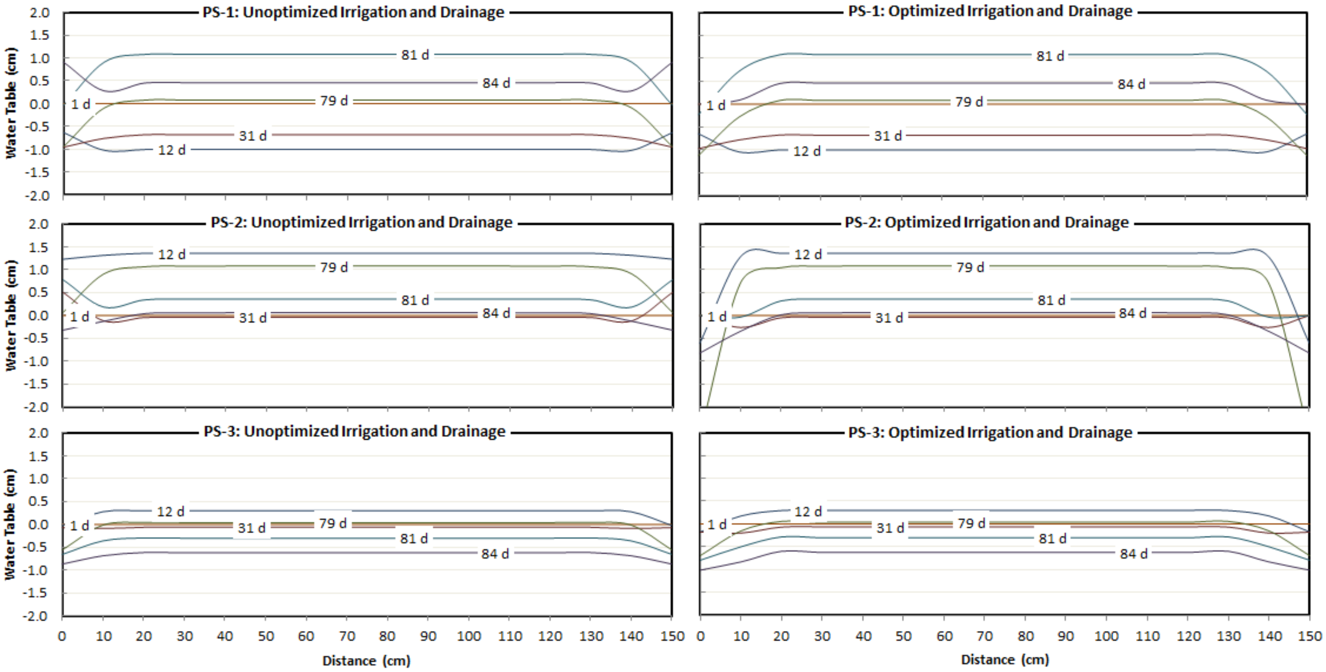


Figure 6 Profile of water table in the soil layers with (right) and without (left) the optimization process for all planting seasons

Table 2 Water balance components

Water Balance Components	Unit	Planting Season-1	Planting Season-1	Planting Season-1
Rainfall	mm	1538	505	38
Percolation	mm	505	505	505
Effective Rainfall	mm	264	133	16
Evapotranspiration	mm	420	465	711
Surface Irrigation	mm	156	332	695
Surface Drainage	mm	1274	372	22
Furrow Irrigation	mm	28	21	9
Furrow Drainage	mm	0.73	0.19	0.02

4.4 Water Balance in the Field

Table 1 shows a resume of water balance components comprising rainfall, percolation, effective rainfall, evapotranspiration, surface irrigation and drainage, and furrow irrigation and drainage for all planting seasons. Notice that even total rainfall was very large (1538 mm) in PS-1, however, most of them (1274 mm or 83%) was drained. Conserving drained water is more than enough to supply irrigation for the following two seasons (PS-2 and PS-3). The required water for furrow irrigation could also utilize the drained water. The values of furrow irrigation and drainage in Table represent one unit of furrow. Thus, for a given width (w), length (l) and number (n) of furrow in a specified SRI paddy field, the total required water can be estimated. According to the information (Table), ones can make throughout design and planning of irrigation and drainage schemes.

5.0 CONCLUSION

The present numerical study provides better understanding on conditioning the optimum water level for one unit of furrow of SRI paddy field.

Our study shows that optimizing irrigation and drainage rates has effectively set the water level of SRI Paddy fields into a range of -5 to 0 cm for all planting seasons. The highest value of irrigation rate in the furrow was about 6 mm per day, meanwhile that of drainage rate was about 0.5 mm per day. The different water table profile is significantly affected by planting season. Our study also confirmed that conserving drained water from a planting season is required to provide sufficient irrigation water for the next planting seasons.

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