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WATER TABLE MANAGEMENT FOR UPLAND CROPS: A THEORETICAL MODELLING INVESTIGATION

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Abstract: This study discusses some aspects of water table management for upland crops in the abandoned rice fields of shallow field water tables. As upland crops are gaining importance to rice farmers as part of the crop diversification programme, a technical support on how to manage the water resources optimally for plant growth would be extremely valuable. A theoretical investigation based on soil-water balance model in the root zone and water table draw-down is presented. The result is used to formulate the necessary water table control suitable for upland crops. A practical application is demonstrated by the translation of the concluding formula into a local data.

Keywords: Water table, irrigation, field crop, water balance

Abstrak: Kertas ini membincangkan beberapa aspek pengurusan paras air tanah untuk kegunaan tanaman ladang di kawasan sawah padi terbiar yang mempunyai paras air tanah cetek. Oleh sebab tanaman ladang menjadi lebih penting kepada para petani sebagai sebahagian program mempelbagaikan tanaman, maka sokongan teknikal mengenai bagaimana sumber air ladang dapat dioptimumkan untuk tanaman amat diperlukan. Satu kajian teoretikal berdasarkan model imbangan air tanah pada ruang akar tanaman dan kesannya terhadap penyusutan paras air tanah telah dilakukan. Keputusan pemodelan digunakan untuk merancang kawalan paras air tanah yang sesuai kepada tanaman ladang. Aplikasi yang praktikal telah ditunjukkan dengan menggunakan beberapa data tempatan.

Kata kunci: Paras air tanah, pengairan, tanaman ladang, imbangan air

1.0 INTRODUCTION

Diversified cropping of the modern farming, in which rice and other crops are planted in the same field, has recently been given priority in the Malaysian agricultural planning. The main objective of the programme is to increase farm productivity and thus, the income of the farmers. In the present agricultural system, farmers face numerous difficulties, resulting in low farm productivity. Labour shortages, low rice market price, small farm size, and water shortages during the dry spell are among the major problems that contribute to the low farm productivity. As a result, many rice fields are left fallow because many farmers find it necessary to work in the industries in order to gain cash income. It is reported that, of more than 1.25 million acres of available rice land in the

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country, only 80% were harvested [1]. This also means that thousands of acres of rice land provided with the irrigation and drainage infrastructure are lying idle at least for some part of the year. The programme of crop diversification is designed to remedy this situation.

Malaysian rice fields are located largely in the flat low lying areas along the coast where the water table is shallow. The soil is generally alluvial marine heavy clay. The average rainfall is about 2500 mm/year with high variability in time and place. Malaysia rice fields are subjected to soil moisture deficit during the dry season and excessive rainfall during rainy season, which may result in widespread flooding. These variations result in a fluctuating water table during the different parts of the year. In growing upland crops such as maize and vegetables on rice fields with the existence of this fluctuation water table, the key question is how to manage the soil moisture suitable for crop growth. Since the soil moisture status in these areas is strongly influenced by water table depth, an appropriate water table management design has to be formulated before upland crops can be grown optimally. The main objective of this paper is to formulate a water table management strategy for rice fields to enable upland crops to be produced. Evidence shows that after the harvest of wet season rice, the water table often remains at 0.5 to 1.0 m depth, available to the root zone of the upland crops [2]. At particular root zone depths, if water table is too shallow, it can depress growth. Conversely, if water table is too deep, a large amount of irrigation water will be required.

2.0 FORMULATION OF WATER TABLE CONTROL

2.1 Soil Water Balance at Root Zone Depth

The rate of change in soil moisture content at the root zone can be described with a simple water balance equation as;

$$\frac{\Delta MC}{\Delta t} = I + S - ET \tag{1}$$

where $\frac{\Delta MC}{\Delta t}$ is the rate of change in soil moisture content (cm/d), I is the rate of net infiltrated water through the upper boundary of the root zone (cm/d), S is the rate of net upward flow through the lower boundary (cm/d), and ET is the rate of crop evapotranspiration (cm/d).

With the presence of shallow field water table,

$$S = CR - D \tag{2}$$

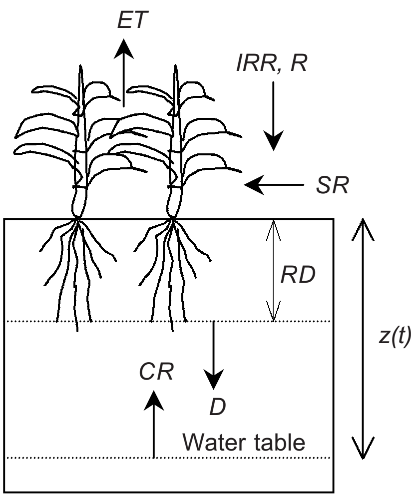
Where CR is the rate of capillary rise from the phereatic layer (cm/d) and D is the net downward flow from the root zone (cm/d).

Under the rice field environment, during the dry season, the magnitude of D might not be given emphasize because of its minor practical value, when the rainfall amount is generally small. During the dry season, when upland crop is normally grown, the field are always under unsaturated condition. Under such field condition, capillary rise is more obvious, thus S would be considered equal to CR in most cases.

The net amount of water that infiltrates the root zones, I, can be calculated as,

$$I = R + IRR + DS - SR \tag{3}$$

Where R is the rate of rainfall (cm/d), IRR is the rate of irrigation (cm/d), DS is the rate of surface storage, and SR is the surface runoff. Figure 1 presents the various incoming and out-coming flow of water in the soil-plant system in the presence of shallow water table.



IRR: Irrigation, *R*: Rainfall, *ET*: Evapotranspiration, *SR*: Surface runoff, *CR*: Capillary rise, *D*: Deep percolation, *RD*: Root zone depth

Figure 1 Soil water balance in the presence of shallow water table

The individual terms in Equations (1), (2), and (3) can be obtained from the literature except for CR and SR. The value of CR with respect to the distance of the capillary flow and the soil moisture tension can be estimated using Darcy Law and described in Equation (4) [3].

$$CR = -k(h)\left(\frac{dh}{dz} + 1\right) \tag{4}$$

where CR is the capillary rise, $k(h)$ is the unsaturated hydraulics conductivity, h is the pressure head, and z is the vertical coordinate from the datum.

Integrating Equation (4) yields,

$$\int_{z_1}^{z_2} dz = \int_{h_1}^{h_2} \frac{-dh}{1+\dfrac{CR}{k(h)}} \tag{5}$$

Starting at the groundwater table level (*h=0*), it is possible to calculate the pressure head profile with depth for various values of capillary rise rate, *CR*. The relationship between these parameters for typical heavy clay soil of rice field is presented in Table 1.

Table 1 The vertical distance of capillary rise (CR) in relation to flow rate and matric potential of typical heavy clay of rice soil [4]

Matric potential (cm)	**Capillary rise (cm/d)**							
	0.50	**0.40**	**0.30**	**0.20**	**0.15**	**0.10**	**0.06**	**0.02**
	Vertical distance of flow, *z* (cm)							
20	4.7	5.5	6.7	8.6	10.0	12.0	14.3	17.6
50	7.9	9.5	11.7	15.5	18.5	23.1	29.0	39.8
100	9.4	11.3	14.1	19.0	23.0	29.5	38.7	60.1
250	10.4	12.6	15.5	21.6	26.5	34.6	47.0	82.2
500	11.0	13.3	16.8	23.0	28.4	37.5	51.7	95.9
1000	11.4	13.8	17.6	24.1	29.9	39.7	55.4	106.8
2500	11.8	14.3	18.2	25.1	31.1	42.5	58.5	116.1
5000	12.0	14.6	18.5	25.6	31.8	42.6	60.3	121.5
10000	12.2	14.8	18.8	26.0	32.4	43.5	61.8	125.9
16000	12.3	14.9	19.0	26.3	32.7	44.0	62.6	128.3

In this particular study, the values of *DS* and *SR* were neglected because of their limited practical value in the dry season period. The value of effective rainfall is based on various factors such as duration and intensity of rainfall, crop cover, antecedent soil moisture, and infiltration capacity of the soil.

By knowing the physical parameters in Equations (2) and (3), the water balance of Equation (1) can be simply solved. It produces the rate of change in *MC* of the root zone depths. Mathematically, the *MC* at the end of any time interval can be written as,

$$MC_{(t+\Delta t)} = MC_{(t)} + \frac{\Delta MC}{\Delta t}\Delta t \tag{6}$$

where $MC_{(t+\Delta t)}$ is the soil moisture at time $(t+\Delta t)$, $MC_{(t)}$ is the soil moisture at time t, $\Delta MC / \Delta t$ is the rate of change in soil moisture, and Δt is the time interval.

2.2 Soil Moisture and Water Table Depth

The net flow through the lower root zone boundary in Equation (2) would induce a change in water table depth, Δz, as illustrated in Figure 2. [5] wrote the relationship as,

$$\Delta z = \frac{\{2(CR - D)\Delta t\}}{(MC_0 - MC_i)} \tag{7}$$

where Δz is the change in water table depth, MC_0 is the volumetric saturated soil moisture, MC_i is the soil moisture at lower boundary, and (CR-D) is the net unsaturated flow.

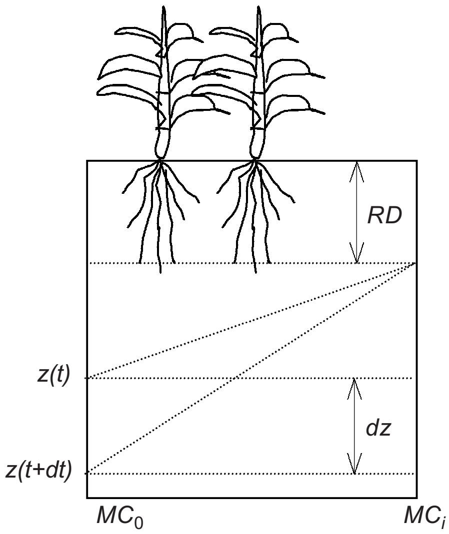


Figure 2 Schematic representation of the value of matric suction at various soil depths

In the rice fields where the water table is controlled by the water level of the irrigation ditches, adjustable weirs or check structures are normally used. Under a steady state condition with homogenous soil type, the drainage rate (q) of the field can be estimated as [6],

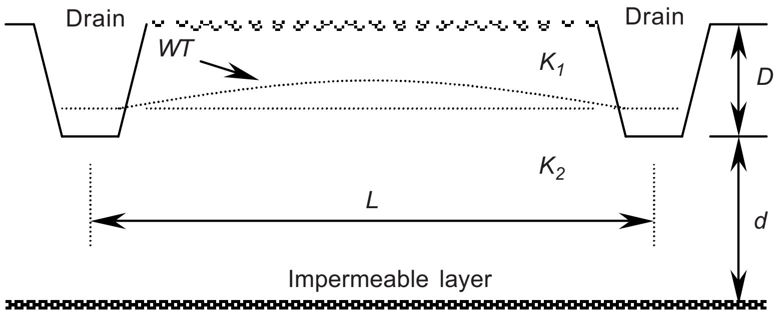
$$q = \frac{4Km(2d + m)}{L^2} \tag{8}$$

where q is the drainage rate, K is the saturated hydraulic conductivity, L is the drain spacing, m is the hydraulic head midway between drain, and d is the depth of impermeable layer below the drain base.

However, for shallow impermeable soil layer such as found in most Malaysia paddy soil, the value of q is best estimated using Fukuda's formula [7],

$$q = (1.5Km)/L \tag{9}$$

The schematic cross section of a rice field facilitated with open drainage system is shown in Figure 3.



WT: Water table, *L*: Drain spacing, *D*: Drain depth *d*: Depth to impermeable layer, *m*: Hydraulic head midway, K_1 & K_2: Hydraulic conductivity at layer 1 and 2

Figure 3 Cross-section of field drain with the presence of water table

In the presence of open drainage system, Δz in Equation (7) will depend not only on unsaturated upward flow, i.e. *(CR-D)*, but also on the removal of *MC* by the internal drainage processes, *q*. Therefore, Equation (7) must be extended into,

$$\Delta z = \frac{2\Delta t\{q + (CR - D)\}}{MC_0 - MC_i} \tag{10}$$

Thus, the water table depth at the end of each time interval can be computed as,

$$z_{(t+\Delta t)} = z_{(t)} + \Delta z \tag{11}$$

where $z_{(t+\Delta t)}$ is the water table depth at time $(t + \Delta t)$ and $z(t)$ is the water table depth at time t.

3.0 NUMERICAL EXAMPLE

This numerical example is used to demonstrate the application of the mathematical investigation described in the previous section. The input data used are from various reports in the literature that are relevant to the rice field condition found in this country. Table 2 presents the input data used.

Table 2 Soil, crop, water table and rainfall data used in the numerical example

A)	Soil data [8]: a) Location: MUDA Irrigation Scheme, Kedah b) Soil type: Heavy clay c) Saturated soil moisture, $MC_0 = 0.62$ cm/cm d) Field capacity of soil, $FC = 0.50$ cm/cm e) Wilting point of soil, $WP = 0.22$ cm/cm f) Total available water, $TAW = 0.28$ cm/cm g) Moisture curve of the soil (Figure 4)
B)	Crop data: a) Crop type: Corn b) Root zone depth: 30 cm at 14 days after planting c) $ET = 0.5$ cm/d
C)	Water table depth: Three initial water table depths, $z_{(t)}$, were used, $z = 45$, 60, and 75 cm from the field surface

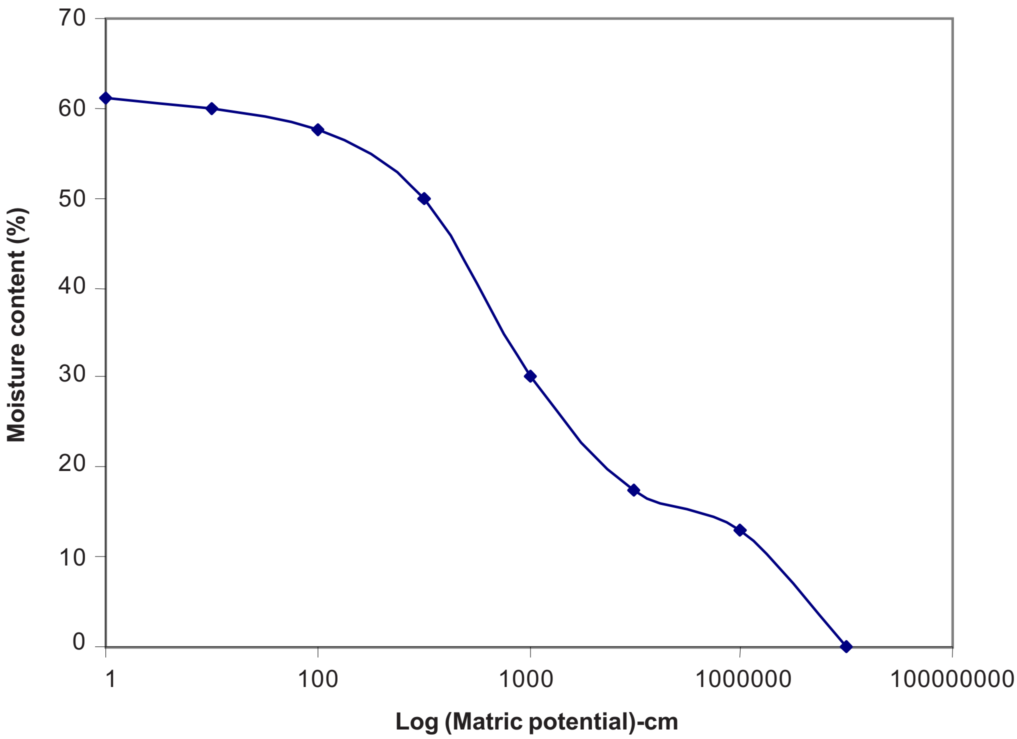


Figure 4 The soil moisture curve

4.0 RESULTS AND DISCUSSION

Knowing the basic cross-section of the rice field drainage system as shown in Figure 3 has enabled us to estimate the drainage outflow of the field. Having known the saturated hydraulic conductivity of the soil layers (K) and the hydraulic criteria of the ditch, the drainage outflow rate (q) can be estimated using Equation 9. The soil generally consists of clay to clay loam in the upper 30 cm, which is also the plow layer, with K value of around 40cm/day and overlays a poorly permeable clay subsoil of K around 0.001 cm/day, which is also called a hard pan layer. Due to the existence of shallow impermeable layer, the Fukuda equation [(Equation (9)] is appropriate. At maximum water table head, that is, when the water table is at the soil surface, the maximum inter flow discharge (q) is estimated as,

$$q = (1.5Km)/L = q = (1.5 * 0.4 * 0.3)/60 = 0.003m/d$$

Using the numerical data in Table 2, the simulation of the MC level and water table depths was made for two cases, i.e. under no influence of rainfall and under the influence of rainfall. Table 3 provides an example of the computation.

Table 3 Numerical example

Crop data:
Type: Maize
Root zone depth (RD): 30 cm
ET rate: 0.70 cm day^{-1}

Soil data:
Initial soil moisture, MC_i : 0.40 cm^3 cm^{-3} ≅ 0.40 cm cm^{-1} ≅ 12 cm/30 cm RD ≅ 5000 cm of matric suction (Figure 4).
Saturated soil moisture, MC_0 = 0.62 cm^3 cm^{-3} ≅ 18.6 cm/30 cm RD

Field data:
Initial water table depth, zt = 60 cm
Distance of capillary flow = (zt – RD)= 60 – 30 = 30 cm
Rate of capillary rise, CR ≅ 0.15 cm/day (Table 1)

Computation table

Day	R(cm)	IRR (cm)	I (cm)	$\frac{\Delta MC}{\Delta T}$	$MC_{(t+\Delta t)}$ (cm)	$MC_{(t+\Delta t)}$ (cm^{-3}cm^{-3})	dz (cm)	$z_{(t)}$ (cm)
0	0	0	0	–	12.00	0.40		60.00
1	0	0	0	–0.55	11.45	0.28	0.13	59.87
2	0	0	0	–0.55	10.90	0.36	0.12	59.75
3	0	0	0	–0.55	10.35	0.35	0.11	59.64
4	0	0	0	–0.55	9.80	0.33	0.10	59.54
5	0	0	0	–0.55	9.25	0.31	0.10	59.44
6	0	0	0	–0.55	8.70	0.29	0.09	59.35
7	0	0	0	–0.55	8.15	0.27	0.09	59.26

Plots of the *MC* in the root zone from various initial water tables depth as predicted by the model are given in Figures 5. Figure 5(a) is the case in which no rainfall has

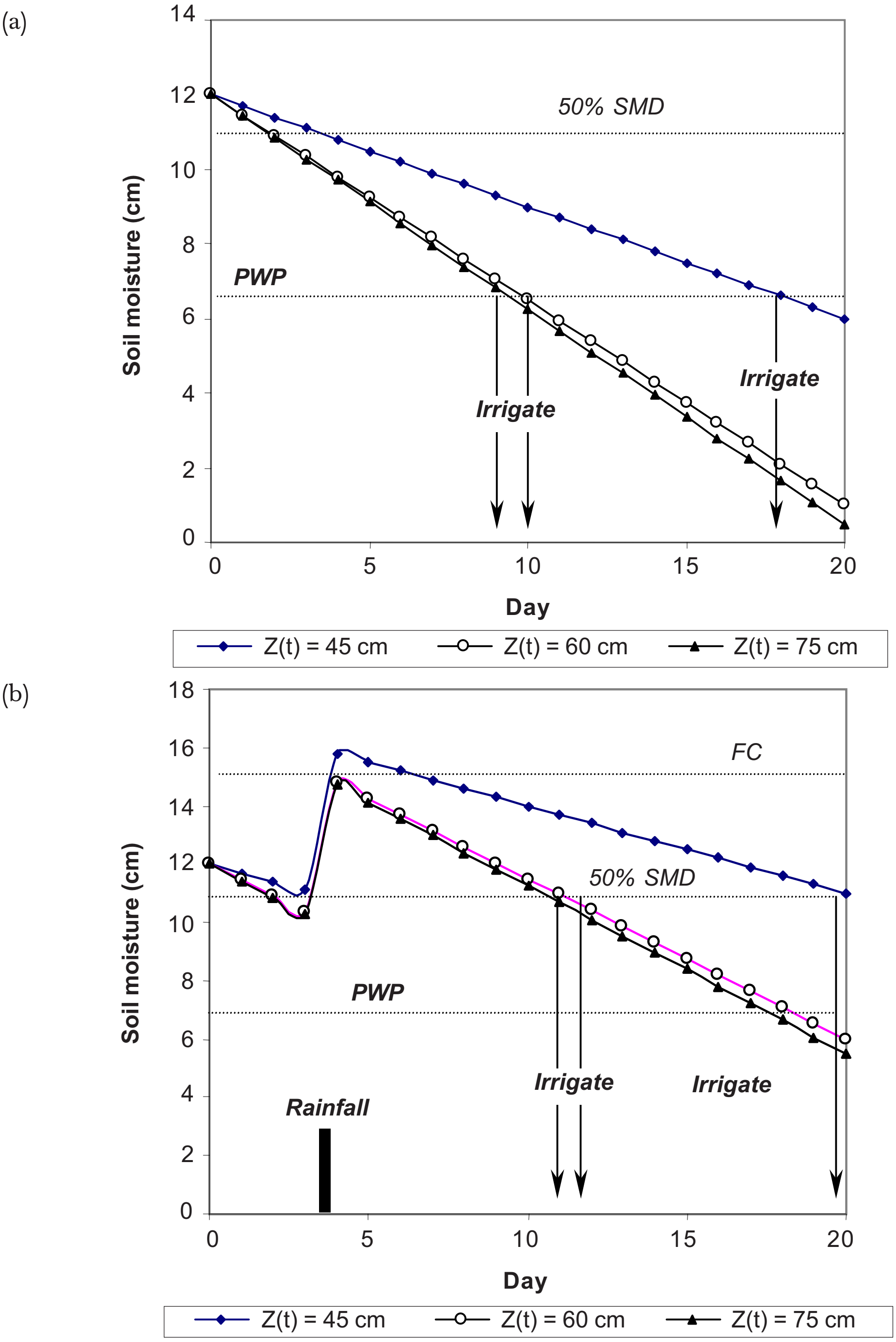


Figure 5 Simulated soil moisture content for various initial water table depths (a) without influence of rainfall (b) with influence of 5 cm rainfall

occurred. Figure 5(b) is the predicted values of soil moisture under the influence of 5 cm rainfall. As shown in Figure 5(b), note that the soil moisture content after the rainfall remained above the field capacity for the next few days. Under such condition, the crop will die. Therefore, it is essential that part of the rainfall be removed by surface drainage and not allowed to infiltrate into the root zone.

The plots of the relation between predicted soil moisture content in the root zone depth and their respective water table for various initial depths are given in Figures 6. Assuming that the crops are to be irrigated when the soil moisture in the root zone reaches 50% of the available soil moisture depletion (50% SMD), the result of the simulation would give a simple technical guideline to irrigation engineers as well as farmers. With the guide of using ground water table in the field, the most common question to irrigation engineers, which is when to irrigate, could be answered by using Figures 6 of the present field condition. For instance, under the field condition as discussed in the numerical example and with no influence of rainfall, irrigation is required when water table reaches 45.5, 60.25, and 75.25 cm for area of initial water table of 45, 60, and 75 cm, respectively.

In rice fields, where the land is almost flat within an irrigation service unit and the field has a good access to irrigation, subirrigation method might be the most practical technique in supplying water to the crops. It can be performed through manipulating the water level in the irrigation ditches [9]. However, according to [10], this method may not be suitable for area with low soil hydraulic conductivity such as found in the present example.

The concept of capillary rise can be of practical importance in growing upland crops in the rice fields during the dry season (off season). [11] found that there was considerable upward flow from a water table located 2.0 meters below the soil surface in clayey soil. However, in heavy clay soil of rice fields, the contribution of the capillary rise to the root zone of the crops could be restricted by the presence of hard pan layers, which are not only low in water holding capacity, but also produce a shallow distribution of roots [12].

Related to the issue of capillary rise irrigation supply from water table, the field water table condition can contribute a significant yield increase to upland crops. [13] found that corn yield grown on a field with 0.5 m water table depth produced 13.8% higher than those grown on a field of 1 m water table depth. Shallower water table field substantially increased soil moisture levels, thus providing a better soil environment to crops. In a similar study, [14] found that the required irrigation interval for corn was significantly affected by the water table condition of the field. In arid condition, as much as 60-70% of crop's water requirement can be obtained from water table supply [15].

The control and utilization of rainfall must be a part of the water table management plan for upland crops in the rice fields. When the water table is shallow, a small amount of rainfall might cause wet injury to the crop, depending on its condition.

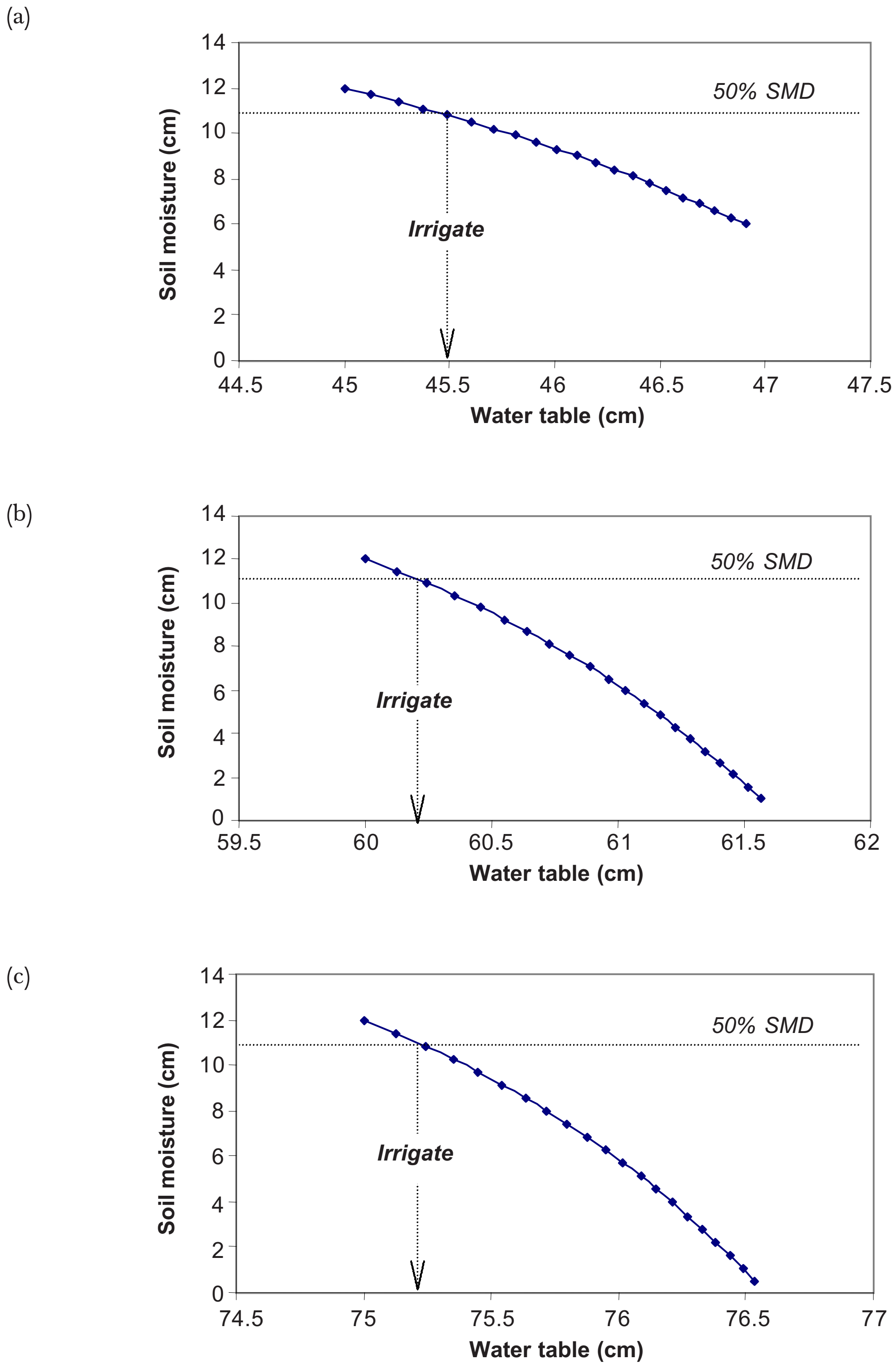


Figure 6 Simulated water table and soil moisture in relation to irrigation requirement (a) Initial WT = 45 cm (b) Initial WT = 60 cm (c) Initial WT = 75 cm

Therefore, a surface drainage system should be able to drain excess water from heavy rainfall.

5.0 CONCLUSIONS

A theoretical model based on the theory of soil water balance in the root zone and water table draw down was presented. The simplified soil water balance was used by neglecting some of the physical parameters, which are not practically important. The model was used as a tool to investigate the required water table depth to support upland crops in a field with shallow water table. It was able to predict the soil moisture in the root zone and consequently, the water table depth after a certain period of time. Using the relation between soil moisture and water table depth for a particular field condition, information about irrigation requirements was obtained as indicated by the water table depth. A simple model based on soil water balance and water table draw down can be usefully applied if appropriate input data is available. A shallow water table in the rice fields can be treated as an irrigation supply to upland crops through capillary rise. Water table depth can be used as an indicator for irrigation requirement of the crops.

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