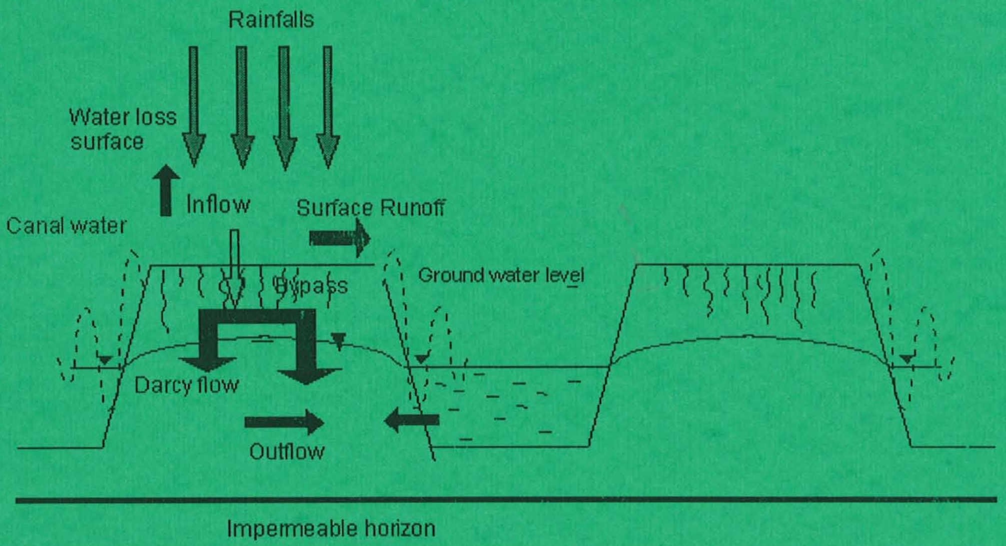
Soil Water Flow Dynamics on Raised Beds in an Acid Sulphate Soil

Field Study at HOA AN station, Mekong Delta, Vietnam

Pham van Quang



Master of Science Thesis
Supervisor: Per-Erik Jansson

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Avdelningen för lantbrukets hydroteknik

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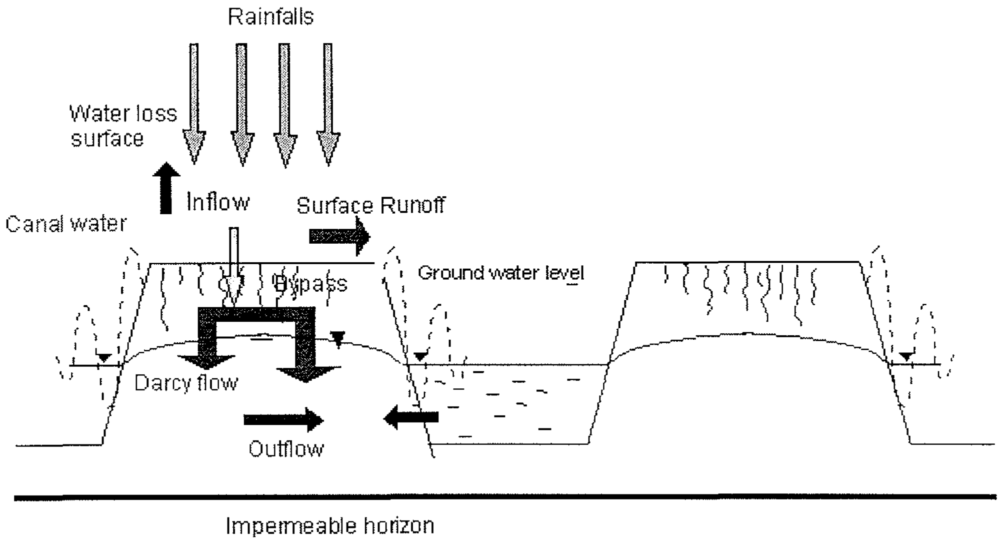

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ABSTRACT

Soil water flows and soil moisture dynamics from raised bed system with and without sugarcane crops during the period January to October 1997 was studied. Measurements were made on soil water contents and ground water level. Soil samples were taken once a week from the beds randomly. Meteorological conditions were collected at Can Tho meteorological station. Cumulative precipitation during the investigation period was of 1377.6 mm. The SOIL model has been used as a tool to simulate the soil water flows, and the soil moisture dynamics in the soil profile. The comparison was done on soil water contents and ground water level between simulations and measurements by linear regression. Simulation was successful in reproducing the general pattern of water flow dynamics and water redistribution. Simulated results agreed well with measurements (R^2 - values for linear regressions in a range between 46.7 % to 88 % for soil water contents). Simulated cumulative soil evaporation amounted to 695.8 mm from the system with bare soil, and 412.2 mm from the system with sugarcane crops. Simulated water flows and water redistribution's were governed of soil properties, precipitation and, and evaporation. The capillary flow was dominant during the period from January to April. Infiltration for bare soil exceeded infiltration for sugarcane plots with 77.5 mm and the correspondent total drainage was exceeded with 203 mm during the investigation period. In the raised beds covered with crops reduced infiltration flows and runoff flows.

Tóm lược

Động thái dòng chảy và ẩm độ đất trên đất líp được nghiên cứu trong giai đọan từ tháng 1 đến tháng 10 năm 1997, nhằm (1) ước lượng dòng chảy của nước trong đất và tính cân bằng nước, (2) định lượng sự ảnh hưởng của điều kiện khí tượng đến dòng chảy của nước trong đất. Thí nghiệm được thực hiện trên đất líp tại Hòa An với hai nghệm thức: có trồng mía và đất trống. Mẩu đát để xác định ẩm độ đất và mực nước ngầm được lấy một tuần một lần trên khu thí nghiệm. Các chỉ tiêu về khí tượng được thu thập tại tram khí tượng Cần Thơ bao gồm: lượng mưa, nhiệt độ không khí, độ ẩm không khí, số giờ nắng, và tốc độ gió. Mô hình SOIL được sử dụng để mô phỏng động thái dòng chảy và ẩm độ đất trong phẩu diện. So sánh kết quả thực đo và kết quả thu được từ mô hình được thực hiện bằng phương pháp hồi qui tuyến tính. Kết quả thực đo và mô hình giống nhau có ý nghĩa thống kê (giá trị R^2 nằm trong khỏang từ 46.5% tới 88% đối với ẩm độ đất). Dòng chảy của nước trong đất và sự tái phân bố độ ẩm mô phỏng thì chịu khống chế bởi đặc tính của đất, lượng mưa và lượng bốc hơi từ đất. Dòng mao dẫn chiếm ưu thế trong giai đọan từ tháng 1 đến tháng 4. Lượng thấm đối với đất trống vượt 77.5 mm so với đất trồng mía và tổng lượng lượng nước chảy qua phẩu diện đất trống vượt 203 mm so với đất trồng mía trong suốt thời gian theo dỏi.

INTRODUCTION

The Mekong Delta is the main agricultural production area in Vietnam in which rice is the major crops. The Delta is located from 8°30'' to 11° N and from 104°30'' to 107° E. Its Monsoon climate is influenced by the river flows and diurnal tidal movements of the Western sea and the semi-diurnal tidal of the Eastern sea. The climate is characterized by 1,400 to 2,400 mm of rainfall per year, the average temperature is from 23°C to 25°C during the coolest months (Dec. - Jan.), and 32°C to 33°C during the warmest months (March - May). The soil of the Delta is formed less than 10,000 years Holocene by combined actions of the river and the sea. The Acid Sulphate Soils (ASS) occupies from 1.6 to 1.8 million hectares and is concentrated in the three waste areas (the Plain of Reeds, the Long Xuyen Quadrangle and Ca Mau Peninsula). The soil have been characterized with unfavorable chemical and physical properties that are difficult to cultivate and to improve (Xuan, 1995). Strongly acidity is often formed by oxidation of pyrite (FeS_2) in the acid soil. Adverse conditions for plant growths are caused by low pH, Al-toxicity, Fe-toxicity, P-deficiencies, low N, poor nutrient levels and unfavorable hydrological conditions (Dent, 1986; Pons, 1989).

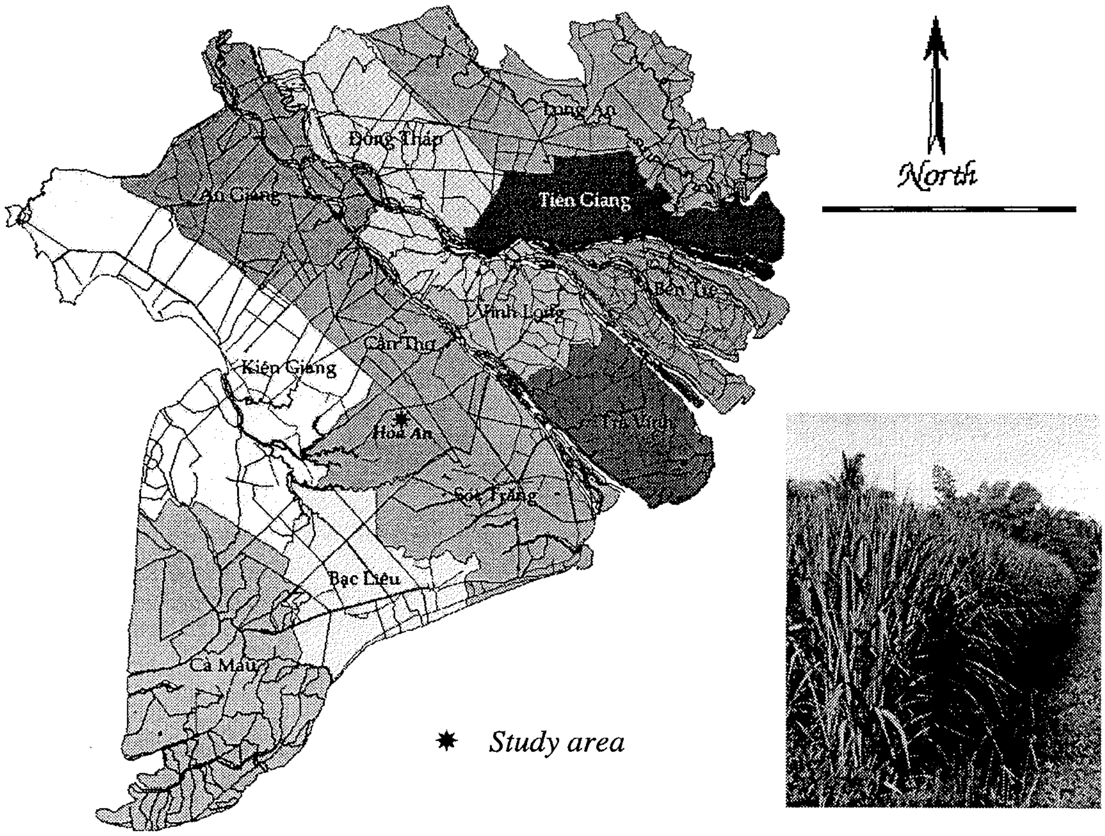


Figure 1. Province administrative border map of the Mekong Delta, Vietnam.

Together with experiences of farmers, national and international efforts have been made to ameliorate acid soils in the Delta. Many effective measures have been widely practiced in the Delta, that have allowed a varieties of crops including rice, pineapple, jam, cassava, and sugarcane (Sen, 1987; Tri et al., 1993; Xuan, 1993) to be grown successfully - known as water management practices for leaching and flushing toxicities, controlling of ground water level, reducing capillary rise, raising bed, proper soil nutrient management.

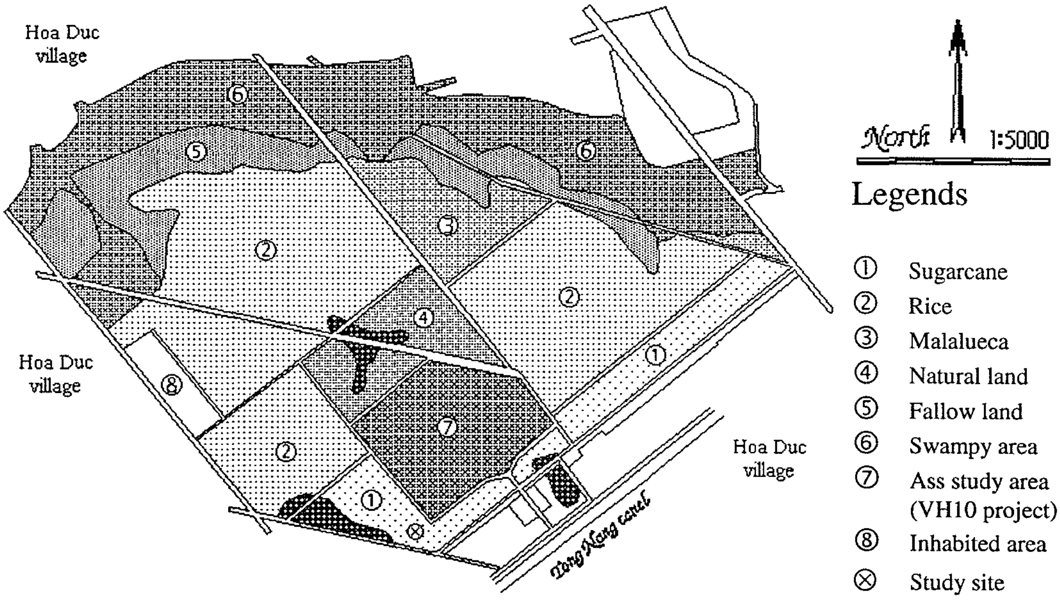


Figure 2. Hoa An station in more detail.

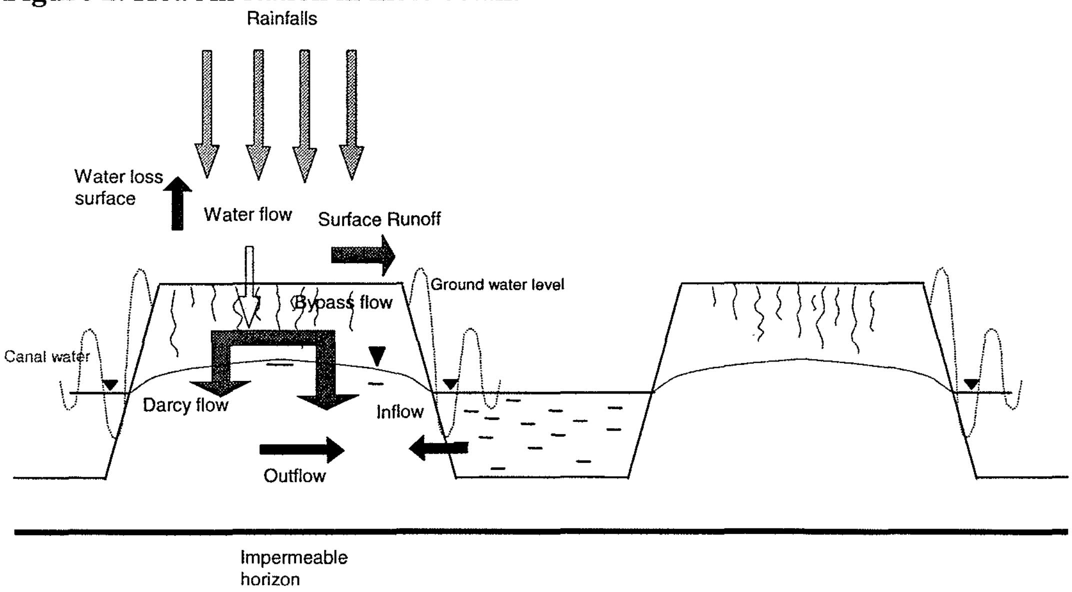


Figure 3. The flow water pattern occurring on the raised beds.

The soil properties on the raised bed are characterized by high hydraulic conductivities, high infiltration capacities, and high bypass flow. Normally, the raised bed is made up by the arrangement of soil blocks dug, moved up. Under dry and wet conditions have caused the soil clots broken to form many aggregates with a well developed interpore space

OBJECTIVES

This study focuses on soil water flow dynamics of raised beds in the acid sulphate soil. The objectives were

- To estimate soil water flows and water balance in the raised bed for a bare soil and a sugarcane crop.
- To quantify the influence of the meteorological conditions on soil water flows.

MATERIAL AND METHODS

The materials and methods used in this study are described in Figure 4.

Location of study area and experiment setup

The experiment site is located at the Hoa An station (10°10' N, 106°15' E), Can Tho, Mekhong Delta, Vietnam. The soil is classified as a Typic Sulphaquept (USDA, Soil Survey Staff, 1975). The sulfiric horizon (with jarosite) is found from 40 cm to 120 cm. A grey permanently reduced sulfuric horizon exists at the depth from 120 cm and more. *Eliocharisdulcis* (a common grass on acid sulphate soil) originally covered the soil.

The raised bed was constructed by digging up the soil profile. This was excavated in the dry season of 1995. With this action, soil of the raised bed is arranged in a reverse order as compared to the natural soil profile (Figure 5). The height of the raised bed is of 0.7 m from the original soil surface. During the rainy season, the soil as it has been under natural conditions, flooded for few months, normally, from the end of July to December.

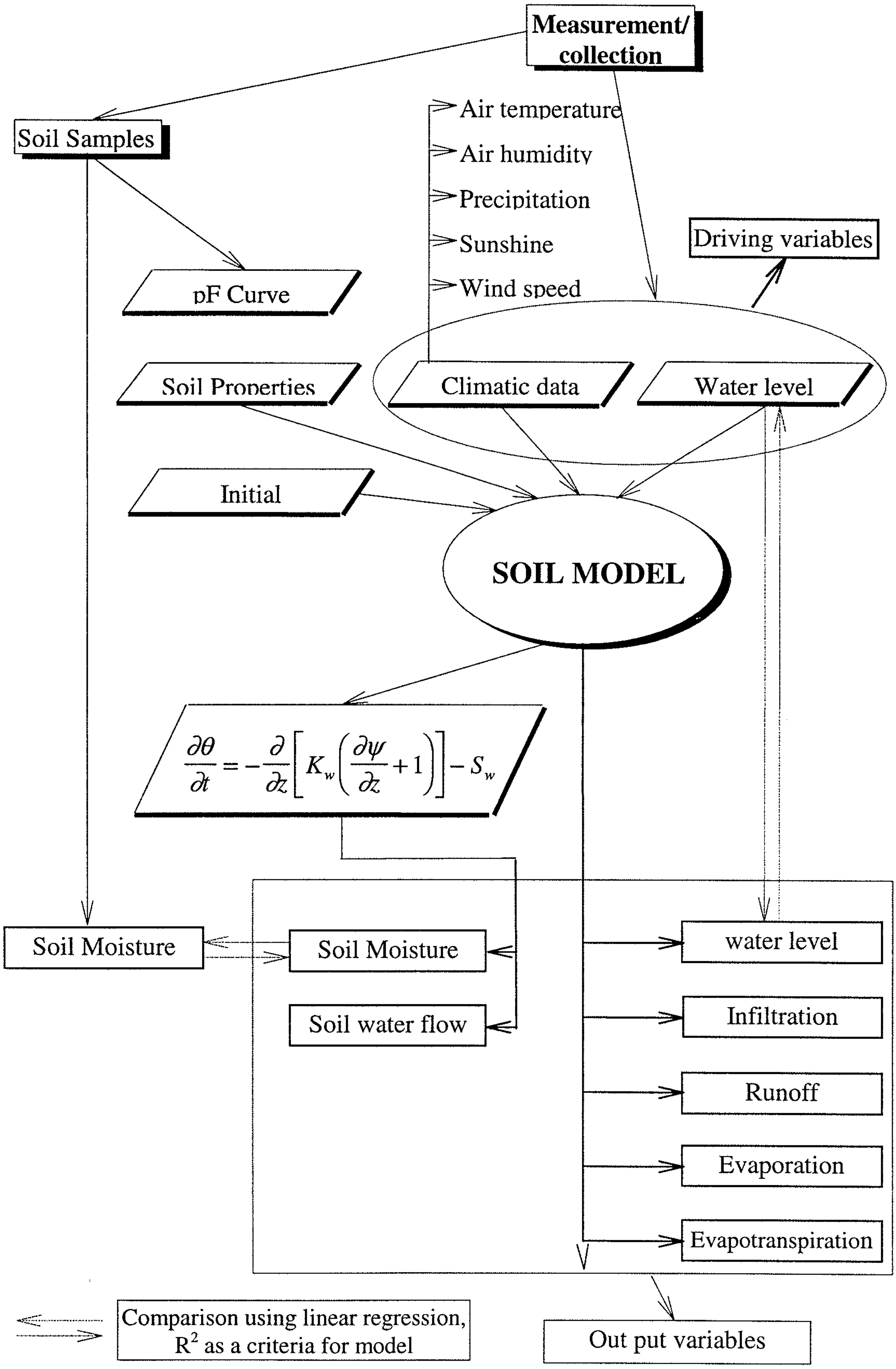


Figure 4. Flowchart of works done on the study.

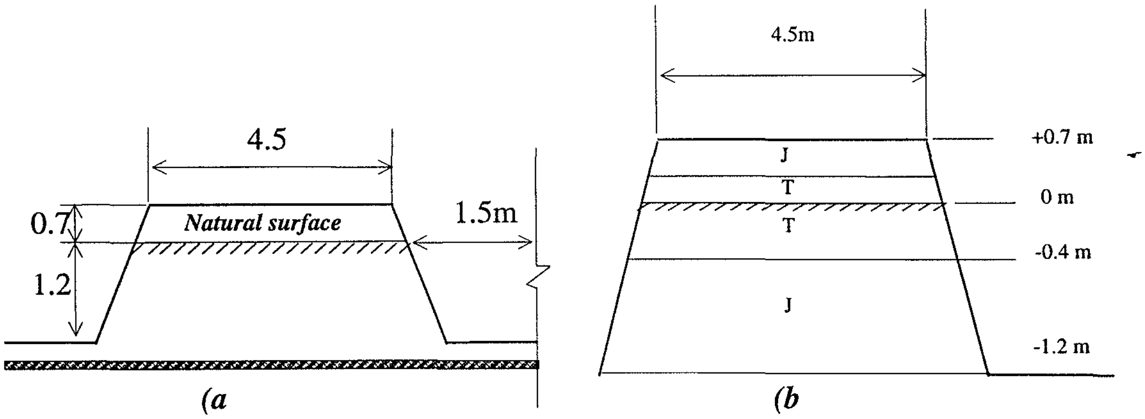


Figure 5. Cross section of raised beds (a); soil material for raised bed construction (b) was indicated by T (top soil), J (sulfuric material).

The experiment was carried out from January to September 1997 on two beds at the Hoa An station, which included the bare soil and the sugarcane crops. Each bed has a dimension of 4.5 m wide and 52 m long and separated by a 3m wide ditch. When the water level dropped below the soil surface, land preparation was begun for experiments. For bare soil treatment, the soil surface was kept clean for whole period of experiment by removing weeds periodically.

Sugarcane treatment:

Cane seeds were first selected to obtain homogeneity by collecting the same length with three to four buds. The cane seeds were placed in the furrows and are covered with a thin layer of soil (See Figure 5 for detail of furrow size and arrangement.). Fertilizers were applied by broadcasting in the furrows with an amount of 200-100-120 kg.ha^{-1} N, P, K respectively. Irrigation was only done at the beginning of the crop season to keep enough moisture for development of shoots and roots and with fertilizer application.

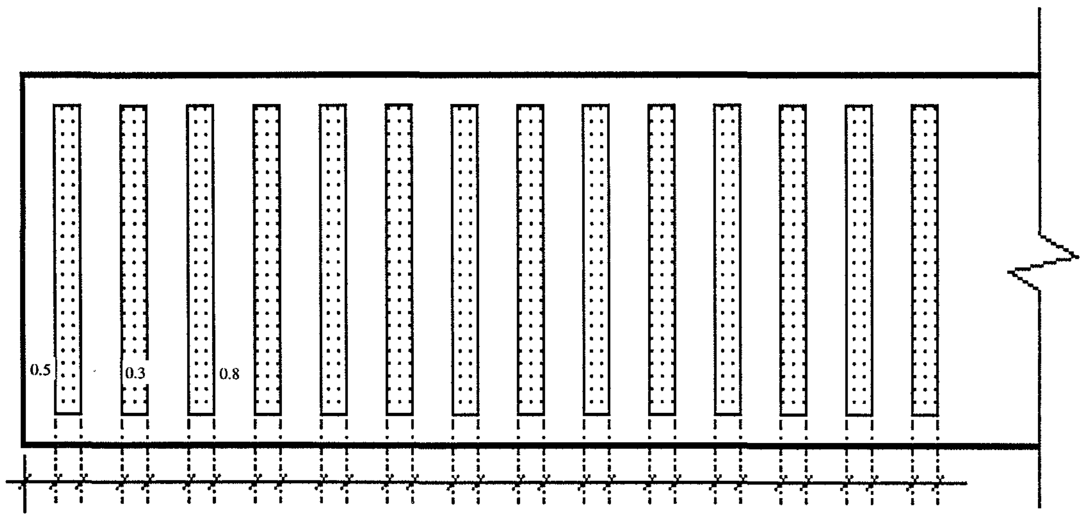


Figure 6. Furrows' layout for sugarcane treatment (distances given in meters).

Measurement of soil water content and ground water level

Soil samples were taken repeatedly once a week for measuring soil water content and water retention curve in the laboratory, ground water level was also measured at the same time as well. Sampling started after planting (February) and ended when water level move up to near the soil surface (August). The following table show how the samples are taken.

Table 1. Soil sampling scheme

	Water content	
	Bare soil	Sugarcane
Period of taking samples (days)	7	7
Position of sampling	random	random
Number of compartment	8	12
Number of samples for each time	3 x 8	3 x 12
Sample size	ϕ 5 cm x 2.5 cm	ϕ 5 cm x 2.5 cm
Maximum depth of sampling	20 cm	30 cm

Description of simulation model

In this study, the physically based model of water and heat flow (Jansson, 1998) has been used as a main tool to simulate soil water dynamics in a soil profile.
The SOIL model is based on one-dimensional numerical solutions which is performed with finite difference method. The soil profile is divided into a finite number of soil layers. Driving variables for the model were daily values of meteorological variables, i.e. air temperature, air humidity, wind velocity, precipitation, and duration of sunshine.

Soil water flow

Water flow in the soil profile is based on the partial differential equation by combining Darcy's law and the law of mass conservation (Richards, 1931).

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left[K_w\left(\frac{\partial \psi}{\partial z}+1\right)\right]-S_w \qquad (1)$$

where θ is soil water content, t is time, ψ is the water potential, z is the depth from the soils surface downward, K_w is the unsaturated hydraulic conductivity, and S_w is a sink term representing the net outflow.

Bypass flow and surface runoff can occur when rainfall intensity exceeds the infiltration rate of the top soil (Horton, 1993). Bypass flow is considered as rapid downward free water flow along macropores during conditions when smaller pores are only partially filled with water. Bypass flow in a soil profile can be calculated from the infiltration flow rate at soil surface or vertical flow in the macropores at any depth, q_{in}, and the ordinary Darcy flow, q_{mat}:

$$q_{mat} = \max\left(k_w(\theta)\left(\frac{\partial\psi}{\partial z}+1\right), q_{in}\right) \qquad 0 < q_{in} < S_{mat} \qquad (2)$$

$$q_{bypass} = 0 \qquad 0 < q_{in} < S_{mat} \qquad (3)$$

$$q_{mat} = S_{mat} \qquad q_{in} \geq S_{mat} \qquad (4)$$

and

$$q_{bypass} = q_{in} - q_{mat} \qquad q_{in} \geq S_{mat} \qquad (5)$$

where $k(\theta)$ is the unsaturated conductivity at a given water content, Ψ is the water potential and z is the depth co-ordinate. At all depths in the soil q_{in} is the vertical flow rate in the macropores (q_{bypass}) from the layer immediately above. S_{mat} (sorptivity capacity of aggregates) is defined as:

$$S_{mat} = a_{scale} . a_r . k_{mat}. pF \qquad (6)$$

where k_{mat} is the maximum conductivity of smaller pores (i.e. matric pores), a_r is the ratio between compartment thickness and the unit horizontal area represented by the model, pF is ${}^{10}\log$ of ψ and a_{scale} is an empirical scaling coefficient accounting for geometry of aggregates.

Soil hydraulic properties

The relationship between volumetric water content and water tension is calculated by Brooks and Corey expression (1964). The unsaturated hydraulic conductivity which is related to pore size distribution is calculated by Mualem equation (1976).

The function by Brooks & Corey (1964) is given by:

$$S_e = \left(\frac{\psi}{\psi_a}\right)^{-\lambda} \qquad (7)$$

where ψ_a is the air-entry pressure and λ is the pore distribution index. S_e (effective saturation) which is defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (8)$$

where θ_s is the porosity and θ_r is the residual water content.

Following Mualem equation (1976), and using the analytical expressions according to Brooks & Corey (7) and (8), the unsaturated conductivity is given by:

$$k_w = k_{mat}\left(\frac{\psi_a}{\psi}\right)^{2+(2+n)\lambda} \qquad (9)$$

k_{mat} is saturated conductivity and n is parameter accounting for pore correlation and flow path tortuosity.

To account for the contribution of macropores, an additional contribution the hydraulic conductivity is considered when water content exceeds θ_s - θ_m.

$$k_w = 10^{\left(\log(k_w(\theta_s-\theta_m)) + \frac{\theta-\theta_s+\theta_m}{\theta_m}\log\left(\frac{k_{sat}}{k_w(\theta_s-\theta_m)}\right)\right)} \tag{10}$$

where k_{sat} is the saturated conductivity which includes the macropores, $k_w(\theta_s - \theta_m)$ the hydraulic conductivity calculated from Eqs. (9-10).

Groundwater flow

Water movement from ground water level to the root zone of plants or the upper layers of soil profile is unsaturated flow. The capillary fringe always exists above the ground water level.

The ground water flow may be considered as a dynamic sink term in the one dimensional structure of the model. Based on the equations presented by Hooghout (1940), the total flow to drains is given by:

$$q_{wp} = \frac{4k_{s1}\left(z_{sat} - z_p\right)^2}{d_p^2} + \frac{8k_{s2}z_D\left(z_{sat} - z_p\right)}{d_p^2} \tag{11}$$

where k_{s1} and k_{s2} are saturated conductivities in the horizon above and below drainage canals respectively, z_D the thickness of the layer below the drains and d_p is the spacing between parallel drain canals.

In the model, flow for specific layers above the drain depth are calculated based on the horizontal seepage flow for heterogeneous aqifers (Youngs, 1980), corresponding to the first term in the Hooghoudt equation:

$$q_{wp1}(z) = \frac{8k_s(z)\left(hu - hl + \frac{(hl^2 - hu^2)}{2(z_{sat} - z_p)}\right)\left(z_{sat} - z_p\right)}{d_p^2} \tag{12}$$

where *hu* and *hl* are the height of the top and the bottom of the compartment above the drain level z_p. Below the drain depth the flow is calculated for each layer as:

$$q_{wp2}(z) = \frac{8k_s(z)\left(z_{sat} - z_p\right)r_{corr}(z)}{d_p^2} \tag{13}$$

where the correction factor r_{corr} may be calculated based on the equivalent layer thickness (z_d) as:

$$r_{corr1}(z) = \frac{z_p \Delta z}{z_D} \quad (14)$$

For this study, the soil compartment was assumed that there was an existental impermeable layer at the bottom of the profile.

Potential transpiration and evaporation

The combination of Penman method proposed by Monteith (1965) is used to estimate potential transpiration as well as potential evaporation rate for intercepted water and evaporation from soil separately

$$\lambda E_p = \frac{\Delta R_n + \rho_a c_p \frac{(e_s - e)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \quad (15)$$

where λ is the latent heat of vaporization, γ the psychrometric coefficient, Δ the slope of vapour pressure and temperature relationship, ρ_a the air density, c_p the coefficient of specipic heat for moist ambient air at constant pressure, (e_s - e) the vapour pressure deficit, r_a the aerodynamic resistance, r_s the canopy resistance, and R_n is the net radiation.

The amount of energy reaching the soil surface is calculated as a function of the net radiation above the canopy according to Beer's law

$$R_{ns} = R_{na} e^{-k_m LAI} \quad (16)$$

where R_{ns} is the net radiation at the soil surface, R_{na} is the net radiation above canopy, k_{rn} is the extinction coeffecient, and *LAI* is the leaf area index.

Transpiration

The potential transpiration demand, E_{pT}, is calculated according to equation (15) with the remaining net radiation, R_{na} - R_{ns}. The aerodynamic resistance between the canopy and the reference height, r_{ac}, is calculated as

$$r_{ac} = \frac{\left[\ln\left(\frac{z_{ref} - d}{z_0}\right)\right]^2}{k^2 u} \quad (17)$$

where *u* is the wind velocity at reference height, *k* is von Karman's constant, *d* is the zero plane displacement. The roughness length, z_0, is estimated with functions derived by Shaw and Periera (1982).

The surface resistance of the canopy is calculated as a function of leaf area index (*LAI*), global radiation (R_g) and vapour pressure deficit (e_s-e_a)

$$r_{sc} = \frac{1}{g_s LAI} \quad (18)$$

where g_s is the stomatal conductance which is given by the Lohammar equation (Lindroth, 1985) as:

$$g_s = \frac{R_g}{R_g + R_0} \frac{g_{\max}}{1 + \frac{(e_s - e_a)}{g_{vpd}}} \tag{19}$$

where R_0, g_m, and g_{vdp} are parameter values.

Water uptake by root is assumed to equal actual transpiration. Actual transpiration is estimated from the potential transpiration, the soil temperature R_T, the normalized root density for each soil layer $r(z)$, and the water tension response $R\psi$.

$$E_T = E_{Tp} \int_0^{z_r} R_\psi(z) R_T(z) r(z) dz \tag{20}$$

where z_r is the maximum root depth. Water uptake is reduced by dry soil that is supposed to act through the stomatal mechanism and xylary tissue resistance.

$$R_\psi(z) = \left(\frac{\psi_c}{\psi(z)} \right)^{p_1 E_{Tp} + p_2} \tag{21}$$

where p_1 and p_2 are parameters as well as ψ_c is a critical tension where reduction begins. The analytical form of the soil temperature response R_T is given as the exponential function proposed by Axelsson and Ågren (1976). The compensatory water uptake is accounted for when calculating the total transpiration

$$E_{Ta} = E_T + f_{umov}(E_{Tp} + E_T) \tag{22}$$

where f_{umov} is the degree of compensation.

Soil evaporation

The soil surface evaporation, E_s, is calculated according to the Penman combination equation using the amount of radiation energy reaching the soil surface, R_{ns}:

$$\lambda E_s = \frac{\Delta(R_{ns} - q_h) + \rho_a c_p \frac{(e_s - e)}{r_{as}}}{\Delta + \gamma\left(1 + \frac{r_{ss}}{r_{as}}\right)} \tag{23}$$

where r_{as} is the sum of the aerodynamic resistance, r_{ss} is the surface resistance at the soil surface, and q_h is the heat flow to the soil.

$$r_{as} = r_{ac} + r_{alai} LAI \tag{24}$$

$$r_{ss} = r_\psi(\log\psi - 1 - \delta_{surf}) \qquad \psi > 100 \tag{25}$$

$$r_{ss} = r_\psi(1 - \delta_{surf}) \qquad \psi < 100$$

where r_ψ is an empirical coefficient, ψ is the tension in the uppermost layer and δ_{surf} is the mass balance at the soil surface.

Parameterisation of the simulation model

Simulation was made for the period January to October 1997. The following are some of the most important inputs. See Table 2 for details on parameter inputs and literature references.

Meteorological variables

Meteorological variables were obtained at Can Tho meteorological station for the period from 19970101 to 19971031 as air temperature, precipitation, relative humidity, wind speed, and sunshine. Data were in average of daily values. See Figure 7.

Ground water level and initial conditions

Canal water level is considered as driving variables, and thereby as a factor controlling the water flow dynamics in the soil profile. The value of D-layer in the Houghoudt formula was found by calibration. The canal water level which was of 0.3m at the beginning of experiment was considered as initial ground water level in the model, it reached to the deepest level of 1.4 m at April. Initial conditions of soil water potentials for simulation have been considered as a profile in equilibrium with ground water level. The water potential value was of 20cm. The soil surface was flooded in the end of July.

Soil hydraulic properties

The soil profile was divided into 20 layers down to 2.2m depth. Based on measurement of water retention curve, which were obtained from analyses of soil cores from the field, the Brooks & Corey water retention curves and unsaturated hydraulic conductivity were calculated for 20 different soil layers. The parameters λ, ψ_a, and θ_r in Brooks and Corey equation were obtained by least-squares fitting to experimental data (using the PLOTPF program).

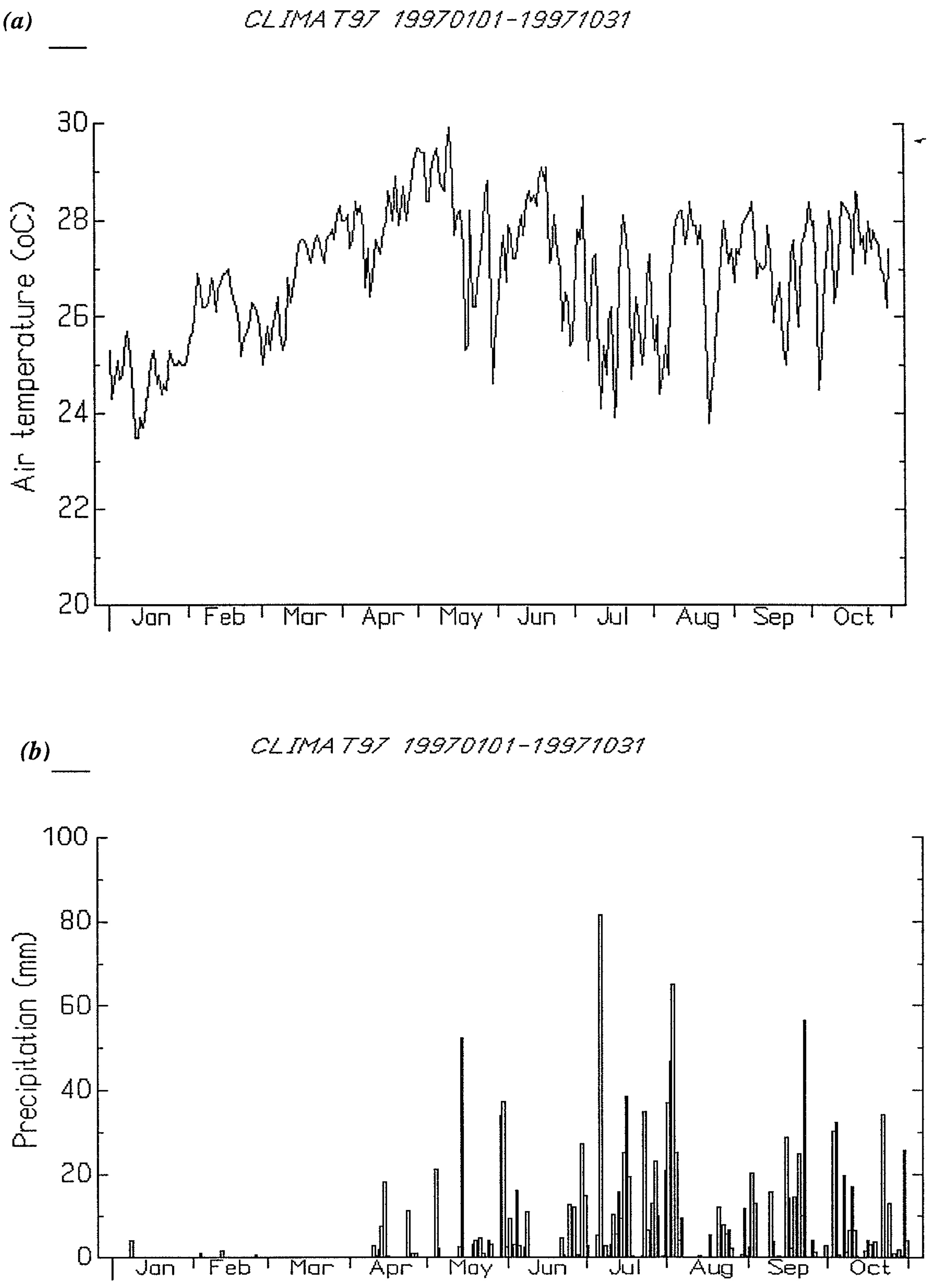


Figure 7. Daily mean temperature (a), and frequency of rainfall (b) during the period January to October 1997 at Can Tho meteorological station.

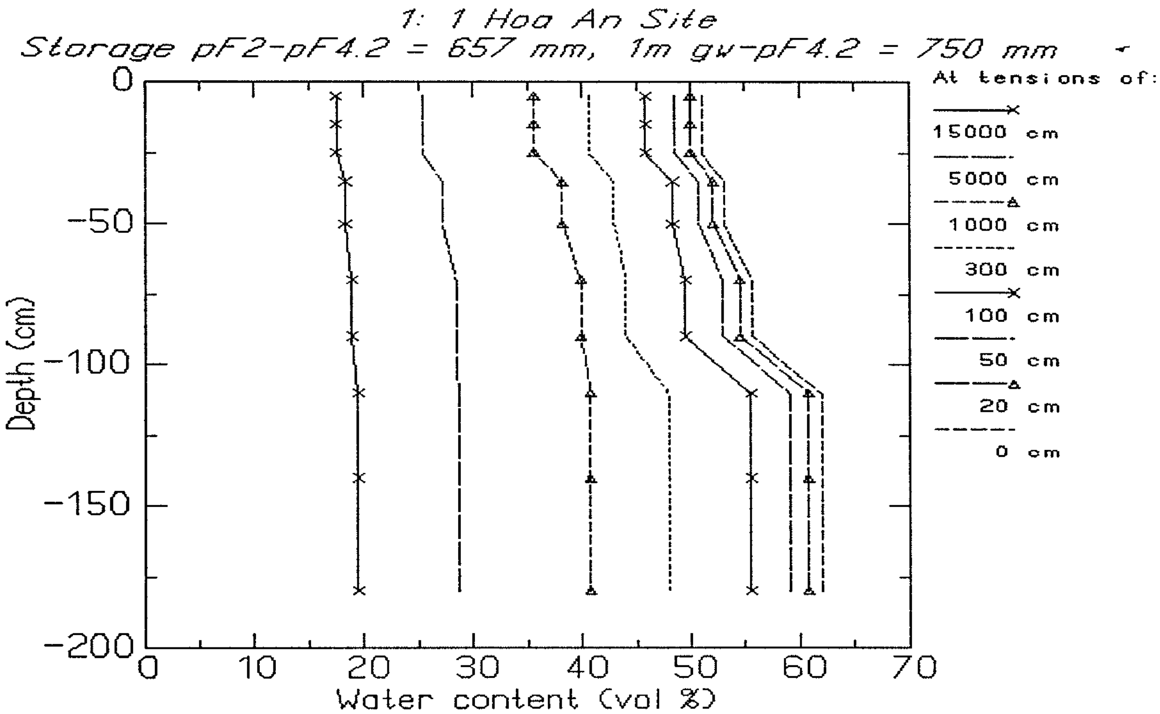
Table 2. Parameter values in the simulations of water flow for bare soil and sugarcane crops

Parameters	Equation	Symbol	Unit	Parameter values		Method
				Bare soil	Sugarcane	(*)
Meteorology						
Reference Height	17	z_{ref}	m	10-12	10-12	c
Air temperature mean		T_{amean}	°C	27.5-29	27.5-29	c
Soil hydraulic						
Minimum conductivity			$mmday^{-1}$	0.0035	0.0035	d
Radiation properties						
Soil albedo dry		α_{dry}	%	20	20	a[1]
Soil albedo wet		α_{wet}	%	10	10	a[1]
Extinction factor	16	k_m	-	0.5	0.5	b
Soil evaporation						
Roughness length	17	z_o	m	0.011	0.011-0.08	a[2]
Increase of aerodynamic resistance below canopy per LAI of canopy	24	r_{alai}	$s\ m^{-1}$	not use	50	b
Surface resistance coefficient	25	$r_{\psi 1}$	0.01s	1	1	b
Surface resistance coefficient	25	$r_{\psi 2}$	cm water	300	300	b
Surface resistance coefficient	25	$r_{\psi 3}$	0.001 s	100	100	b
Soil water flow						
Aggregates, scaling	6	a_{scale}	-	0.2	0.25	d
Drainage deep percolation						
Thickness of the layer below the drainage canal	11, 14	z_D	m	1	1	d
Characteristic distance	11, 12, 13	d_p	m	4.5	4.5	c
Canopy						
Leaf area index	18	LAI	-	not use	0-7	a[2]
Water uptake						
Root depth	20	z_r	m	not use	0-0.7	a[2]
Critical pressure head for reduction	21	ψ_c	cm	not use	100-400	b
Compensatory uptake of water	22	f_{umov}	-	not use	0.6	b

(*) *a: Literature*
b: Default value model
c: Site specific adjustments based on independent observations
d: Calibration

[1] *Burman, R., L. O. Pochop, 1994. Evaporation, evapotranspiration and climate. Imprint. Amsterdam Elsevier, 1994.*
[2] *Fageria, N. K., V.C. Baligar and Charles Allan Jones, 1991. Growth and mineral nutrition of field crops. Chapter 12.*

(a)



(b)

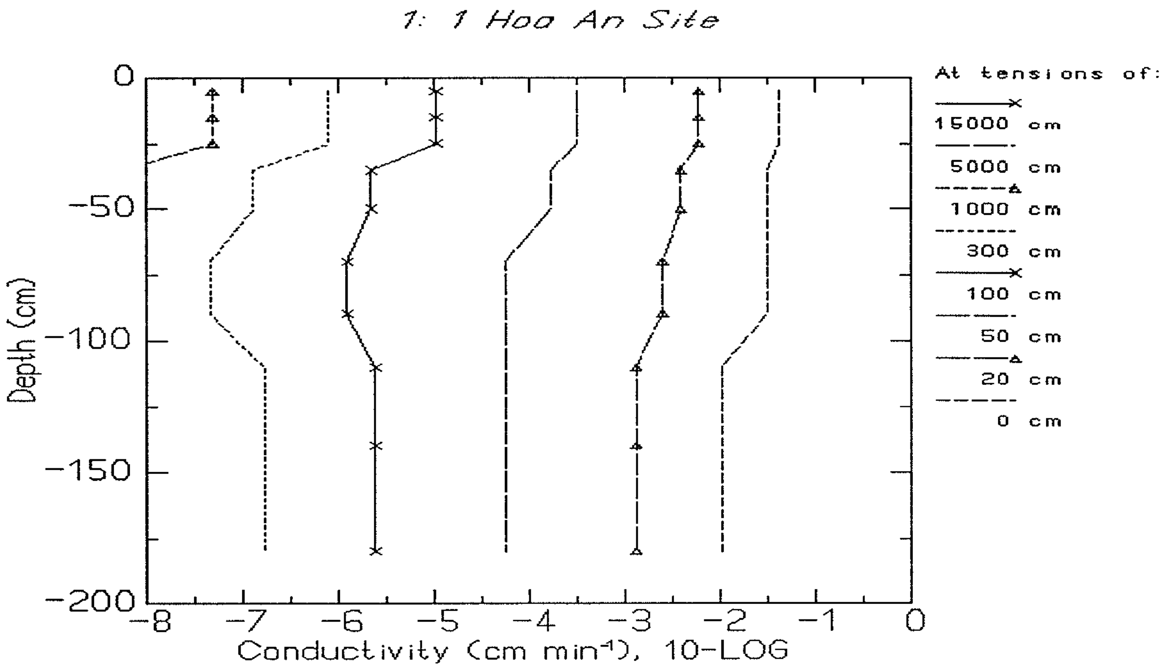


Figure 8. Soil physical properties at the HOA AN station,(a) water retention curves and (b) hydraulic conductivity curves.

Validation variables

Soil water content (volumetric %) and ground water level were the validation variables.

Criteria for model acceptance

Comparison between simulation and measurement should be made to show that they differ or that they do not differ. This can be done by using regression analysis. The simple linear regression analysis deals with the estimation and tests of significance concerning the two parameters α and β in the equation $Y=\alpha+\beta X$.

R-square is considered as a commonly summary measure of the regression. It measures the percentage of the total variability in the data.

$$R^2 = \frac{\left(S_{xy}\right)^2}{S_{xx}S_{yy}} \qquad (26)$$

where S_{yy}, S_{xx}, and S_{xy} are calculated as following

$$S_{yy} = \sum_{i=1}^{n}\left(y_i^2\right) - \frac{\left[\sum_{i=1}^{n}\left(y_i\right)\right]^2}{n} \qquad (27)$$

$$S_{xx} = \sum_{i=1}^{n}\left(x_i^2\right) - \frac{\left[\sum_{i=1}^{n}\left(x_i\right)\right]^2}{n} \qquad (28)$$

$$S_{xy} = \sum_{i=1}^{n}\left(x_i y_i\right) - \frac{\sum_{i=1}^{n}\left(x_i\right)\sum_{i=1}^{n}\left(y_i\right)}{n} \qquad (29)$$

RESULTS AND DISCUSSION

Measurement of soil water content

Soil water content for bare soil and sugarcane crops were obtained by measuring soil samples taken from the field in the laboratory. The results has shown that water content in the bare soil was normally lower than in the sugarcane crops at the uppermost layers. However, in deeper horizons the bare soil showed higher water contents.

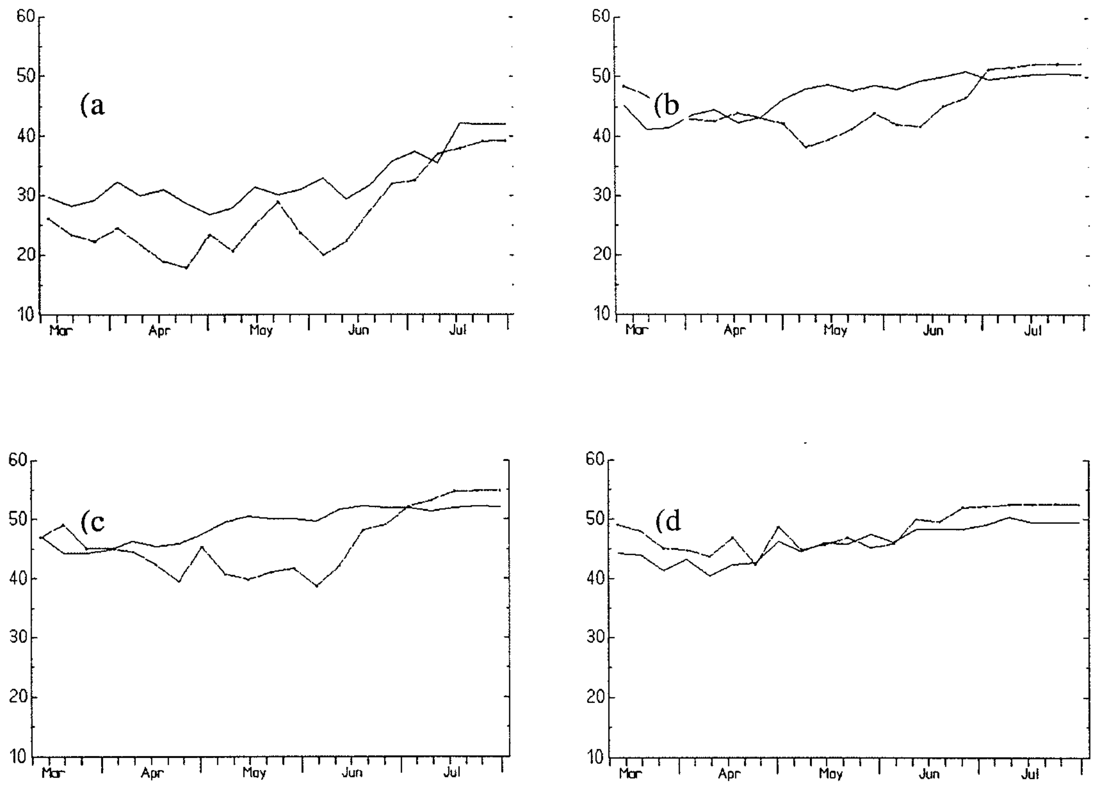


Figure 9. Measured water content from 13 March 1997 to 31 July 1997 of layers 0-2.5 (a), 10-12.5 (b), 12.5-15 (c), and 17.5-20 (d): solid line- sugarcane, broken line - bare soil

Regression analysis was made between bare soil and sugarcane crops to test the significant correlation. There was a significant correlation between the soil water contents of two uppermost layers 0-2.5, 2.5-5.0cm and the layer 17.5-20cm with rather high values of R^2_{Ad}. The other layers such as 5-7.5, 7.5-10, 10-12.5, 12.5-15 and 15-17.5 cm with lower values of R^2_{Ad} indicated that the correlation was not significant (Table 3).

Table 3. Regression analysis of water content between respective soil layers (0 - 20 cm) for bare soil and sugarcane crop

	Different layers (cm)							
	0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15	15-17.5	17.5-20
Adjusted R square	75.90	73.40	56.70	33.60	8.80	11.60	56.30	67.90
Slope	1.267	0.770	0.899	0.651	0.498	0.739	0.840	0.936
Intercept.	- 14.503	5.105	0.230	14.871	21.859	9.873	7.585	4.995
N° of observation	21	21	21	21	21	21	21	21
P	<0.001	<0.001	<0.001	<0.003	<0.103	<0.073	<0.001	<0.001

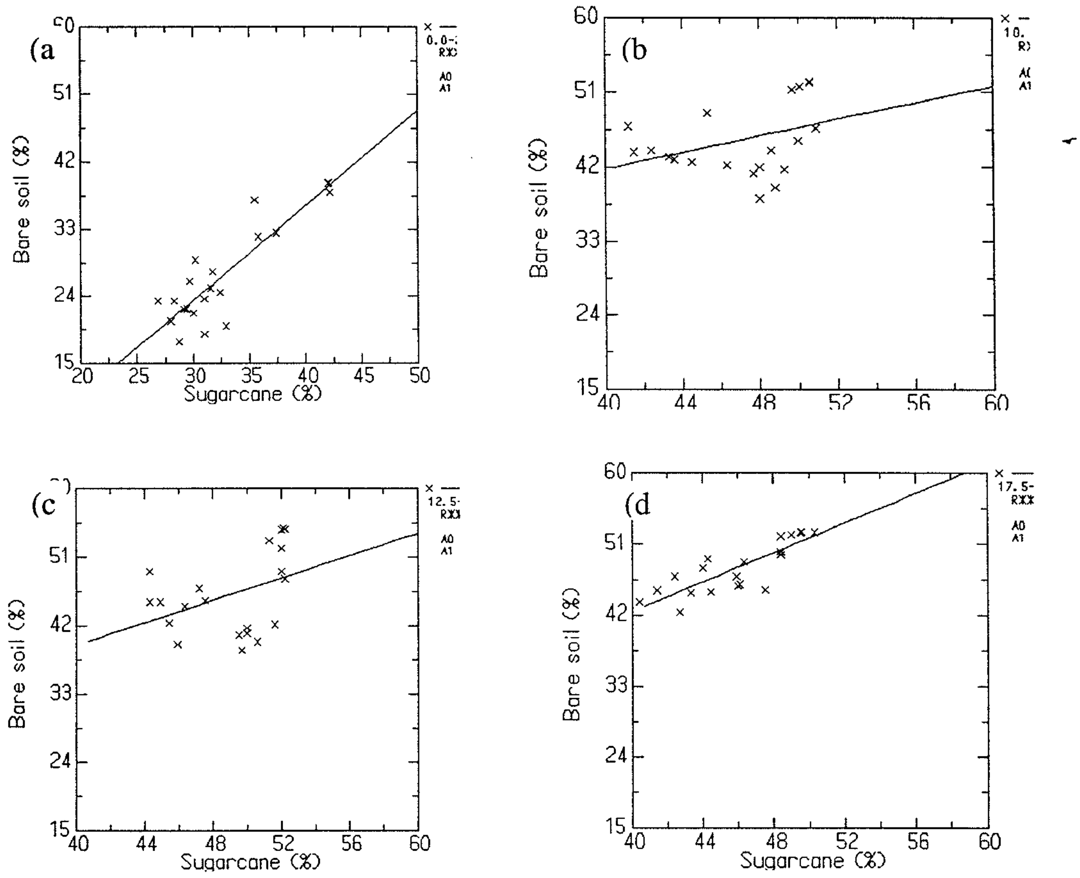


Figure 10. Regression analysis of measured water content of layers 0-2.5 (a), 10-12.5 (b), 12.5-15 (c), and 17.5-20 (d); R-squared values are 0.771, 0.134, 0.160, 0.635, respectively.

In general, there were variation in water contents among the soil layers, especially the layers near the soil surface (Figure 10). More deeper was more higher in water contents. This may cause the differences of potential gradient, and capillary flow may occur.

Making the furrows and planting the cane seeds destroyed the capillary fringe. On the other hand, irrigation was done at the beginning of the crop season and at after applying fertilizer. This may partly explain the higher water content at the uppermost layers in sugarcane crops. See Figure 11.

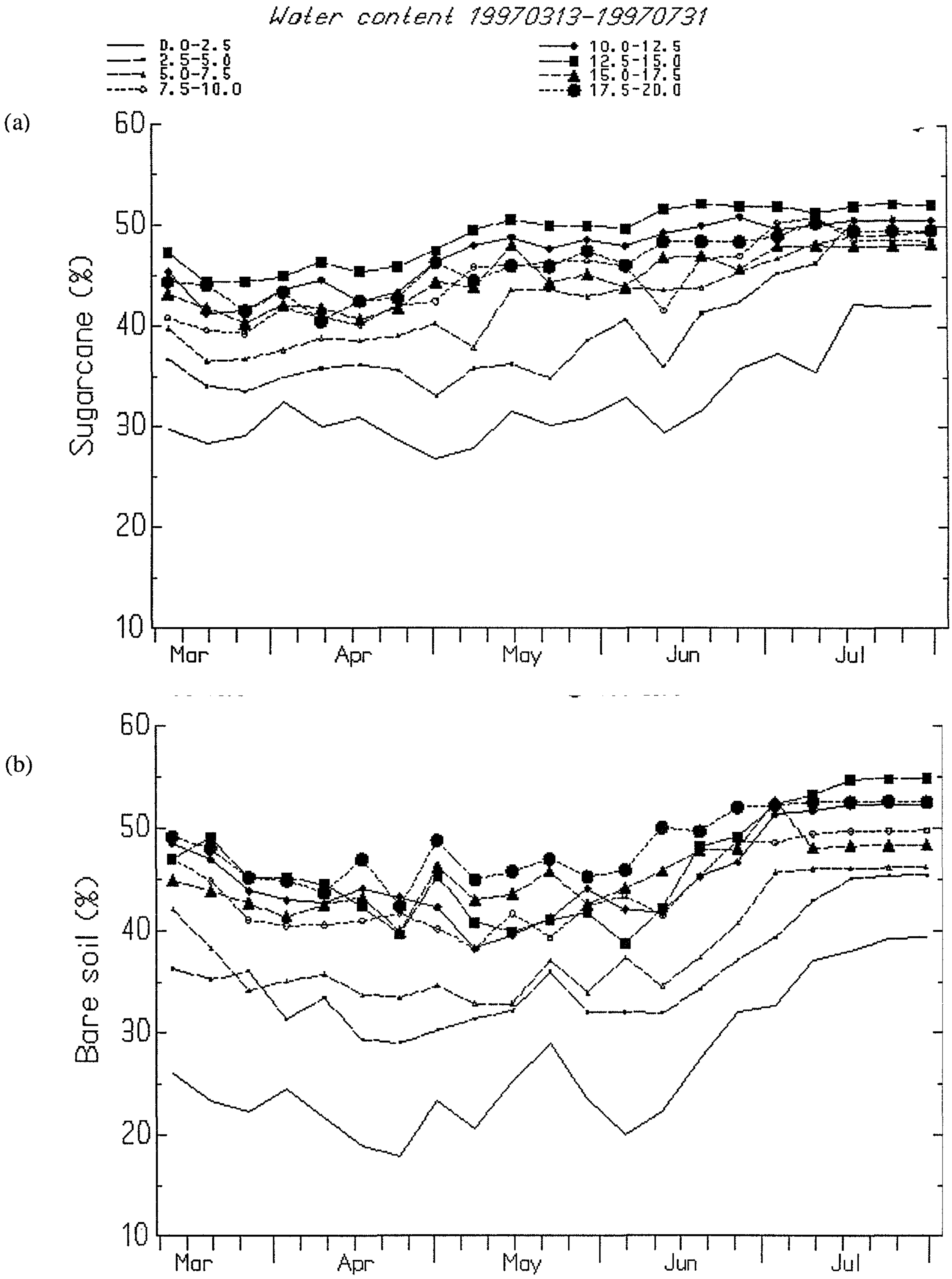


Figure 11. Measured water contents of layers (a) sugarcane crop, (b) bare soil.

Simulated evaporation

Evaporation from the soil was calculated by Penman-Monteith equation (Monteith, 1965). The surface resistance of the soil was estimated by a simple function using an estimated surface storage and three governing parameters. Surface temperature was estimated by using implicitly the soil evaporation rate as calculated by P-M equation. Simulated potential evaporation and air evaporation (Piche evaporation) were significantly correlated. The average was of 2.88 mmday^{-1} and 2.76 mmday^{-1} for simulation and air evaporation, respectively. The mean evapotranspiration was 2.75 mmday^{-1} to which soil evaporation contributed about 46%.

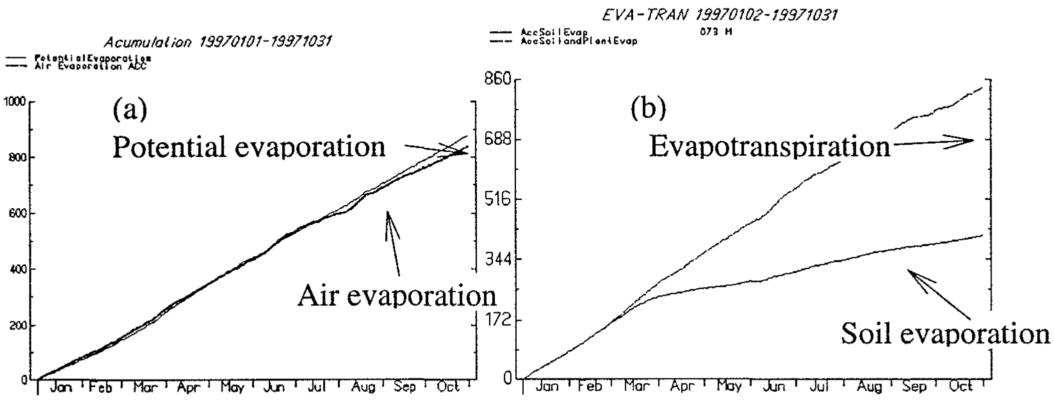


Figure 12. Cumulative simulated potential evaporation and air evaporation (Piche) for the bare soil plot (a), and cumulative simulated evapotranspiration and soil evaporation for the sugarcane plot (b).

Simulated water content

Gravitational, capillary, adsorptive forces affect soil water contents. In unsaturated zone, it is almost only in the capillary range that the unsaturated conductivity is of interest. Water contents in soil profile depend not only on hydraulic conductivity, infiltration and storage capacity but also on the ground water level, the compartment size, and the amount of water flowing into the profile (precipitation). Soil water content has decreased according to the ground water level lowered down and increased when ground water raised up. The driest water content occurred on the uppermost layer at about the middle of May while the deepest ground water level occurred in April. During the dry season, soil water content as well as the pressure head and the hydraulic head decrease near the surface because of evaporation. The upward flow from the ground water table is needed to satisfy the evaporative demand. This flow continues until the surface has became so dry that all flow of water ceases. The formation of dry surface layer, it protects the soil against large evaporation losses.

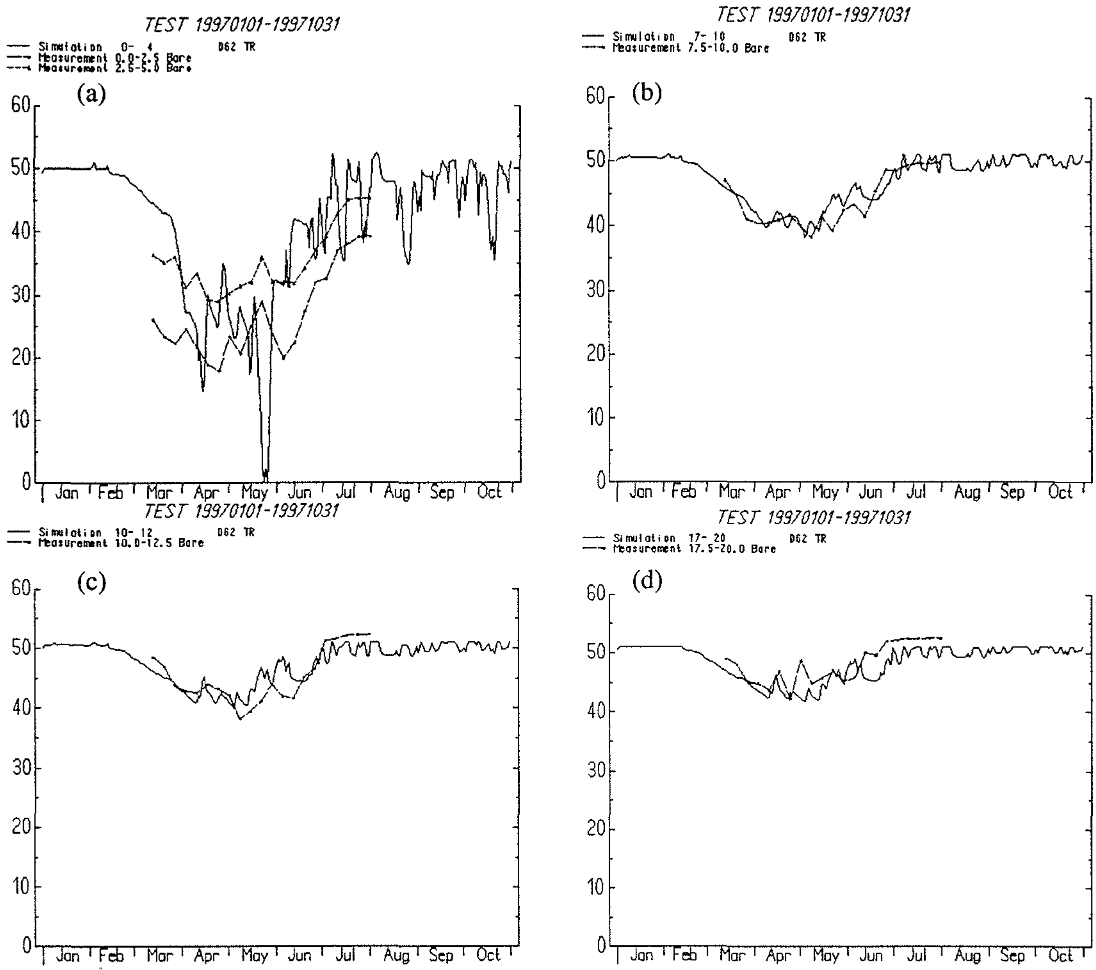


Figure 13. Simulated and measured water content for layers 0-2.5cm from 1 January 1997 to 31 October 1997 (a), 7.5-10cm (b), 10-12.5cm (c), and 17.5-20cm (d) for bare soil: solid line (simulated) and dashed line (measured: (a) upper 0-2.5 cm, lower 2.5-5 cm, (b) 7.5-10 cm, (c) 10 -12.5 cm, and (d) 17.5 - 20.0 cm.

In general, simulated soil water content agreed well with the measurement except for the uppermost layer. Table 4 shows that there were differences in the slope between the soil layers. The highest slope was in the layer 2.5-5cm, this may be caused by redistribution of water in soil profile and capillary rise.

Table 4. Regression analysis of water content between respective soil layers (0 - 20 cm) for bare soil and simulation

	Different layers (cm)							
	0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15	15-17.5	17.5-20
Adjusted R square	46.70	62.60	88.00	88.00	68.60	69.00	53.20	72.90
Slope	0.867	1.213	1.118	0.851	0.586	0.481	0.802	0.692
Intercept.	12.05	-7.180	-1.980	6.810	18.840	23.320	9.900	13.140
N° of observation	19	18	14	18	20	18	19	18
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

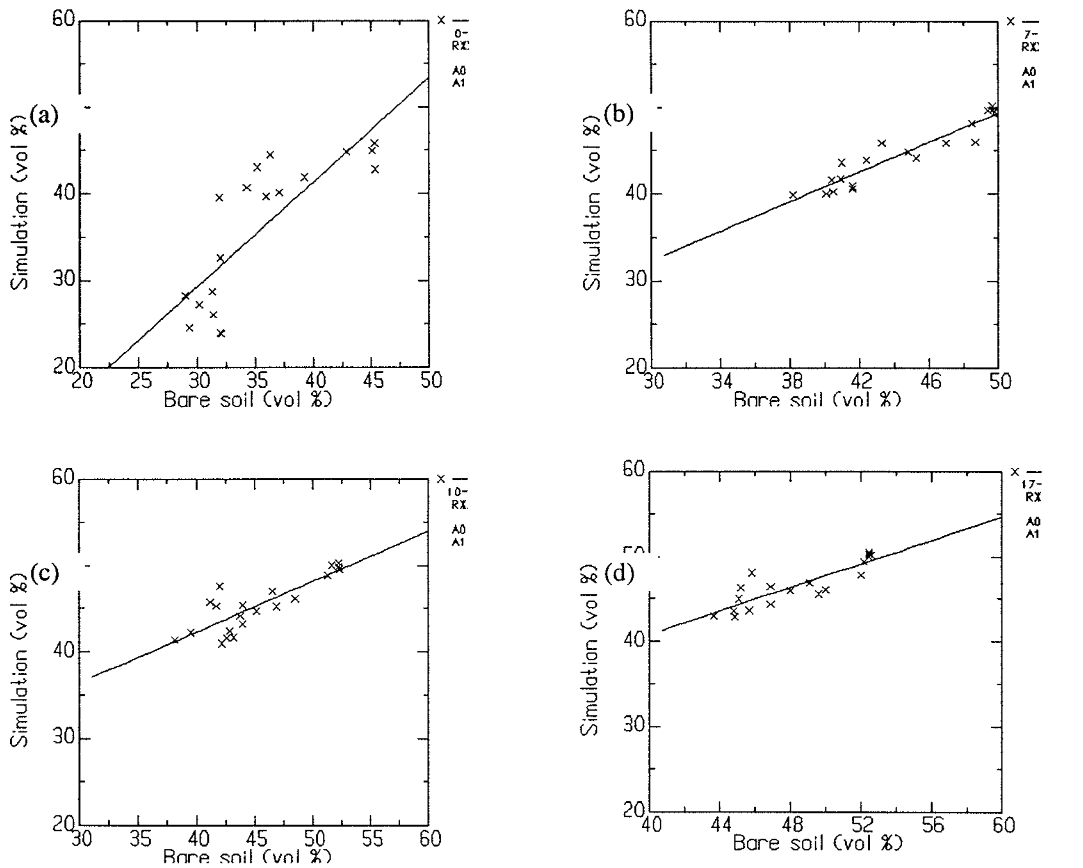


Figure 14. Linear regression between simulated and measured water content from 13 March 1997 to 31 July 1997 for layers 0-2.5 cm (a), 7.5-10 cm (b), 10-12.5 cm (c), and 17.5-20 cm (d) for bare soil. R-squared values are 0.647, 0.886, 0.702, and 0.744, respectively.

Ground water level

Due to the width of the raised bed was rather small (4.5 m wide). Any change of water level in canal, therefore, has immediately affected the ground water table in the bed. In this situation the ground water table in the raised bed was considered to be equal to the canal level. Measurement was done once a week. Consequently, the process of the ground water fluctuation which occurred within the periods was not measured. In addition, the canals in the study area were not connected to the drainage system completely. This increased water level in the canals during a fall of rain and the regulation of water by the infiltration flows to surroundings then decreased the water level again.

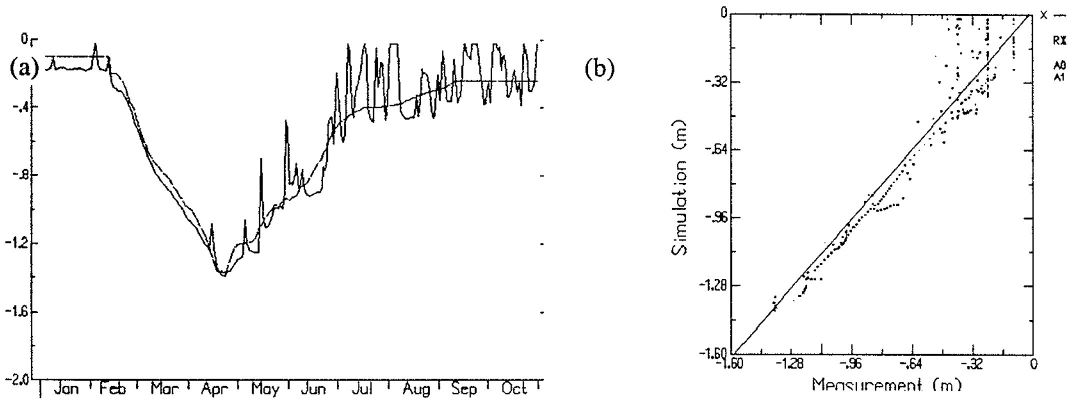


Figure 15. Ground water levels (m) from 1 January 1997 to 31 July 1997: (a) Simulated (solid line) and measured (broken line) ground water level, and (b) linear regression between simulated and measured water level (A0 = 0.020446, A1 = 1.025, R-squared value = 0.903).

The simulated dynamics of the ground water level (GWL) agreed well with the measurements (Figure 15). However, the simulation was discrepancies to observation at somewhere. The simulated level increased higher than measured level, which may be caused, by increasing water level in the canals from rainfall and high infiltration quantity.

Soil water flow and water balance

Water flows in soil depend mainly on precipitation and on evaporation rate from the soil surface. The model was used to estimate soil water flow dynamics in raised beds. Figures below showed the estimation of the partition of water flow components of which included soil water flow, infiltration flow, and runoff flow.

During the period from January to April, there was only some small rainfall. The upward flow or capillary flow was dominant. This process is caused by water losses from the surface, so cracks were created. For the period April to July, it depends on the amount of precipitation that the existence of downward flow and infiltration flow take place. When the soil became almost saturation accompanying with water level moved up near the surface, infiltration flow and runoff flow were dominant within the period from July to October.

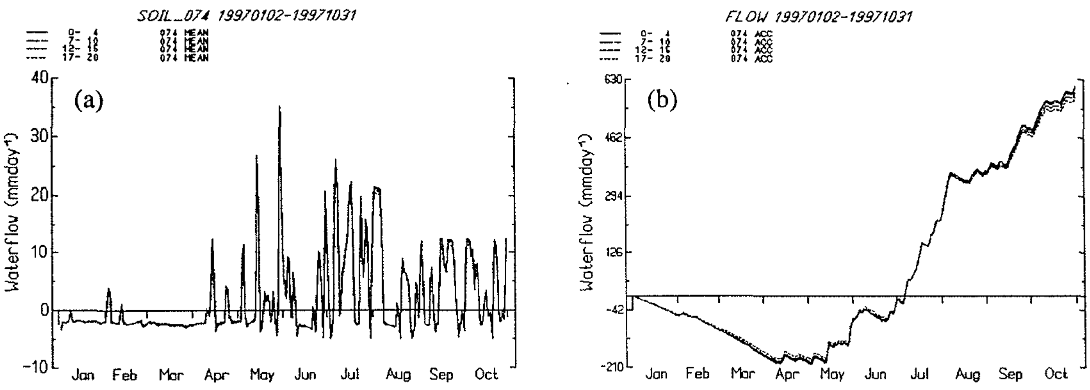


Figure 16. Simulated water flow (a) and cumulative water flow (b).

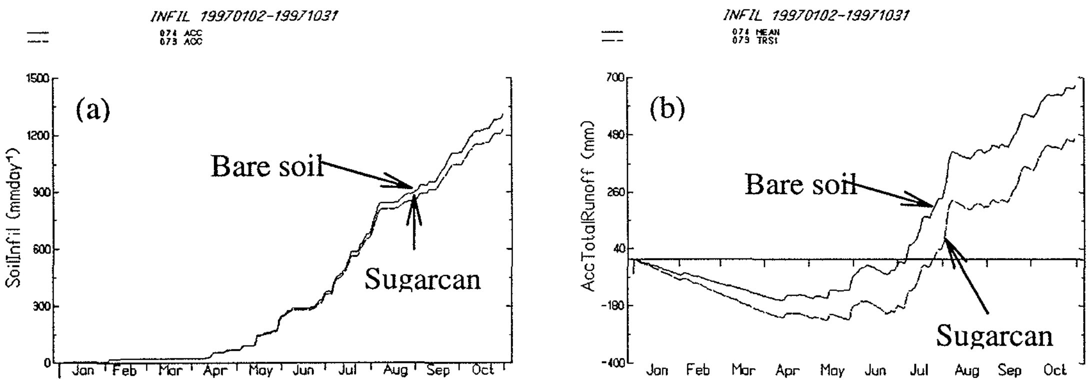


Figure 17. Simulated cumulative soil infiltration (a), and cumulative total runoff (b).

Figure 17 shows in raised bed systems covered with crops reduced infiltration and runoff flows compared to that without crops.

The simulated water balance for the period January to October 1997. The total of precipitation was of 1377.6 mm. The accumulation of evaporation, transpiration and runoff is as the table below

Table 5. Simulated water balance for observed period for bare soil and sugarcane crop

	Evaporation	Transpiration	Runoff
Bare soil	695.8	0	667.0
Sugarcane crop	412.2	485.2	464.0

The amount of runoff in sugarcane crop was lower than bare soil. Total water loss in the bare soil was of 77.5% compared with sugarcane crops. Evaporation contributed 46% in the evapotranspiration for sugarcane crops.

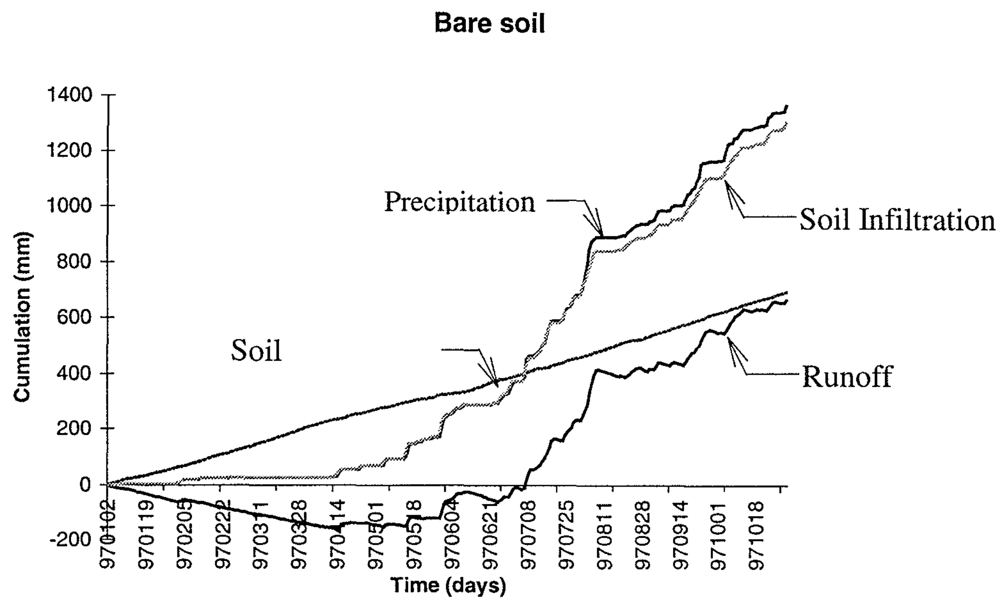


Figure 18. Simulated cumulative precipitation, simulated cumulative soil infiltration, simulated cumulative soil evaporation, and simulated cumulative total runoff for bare soil.

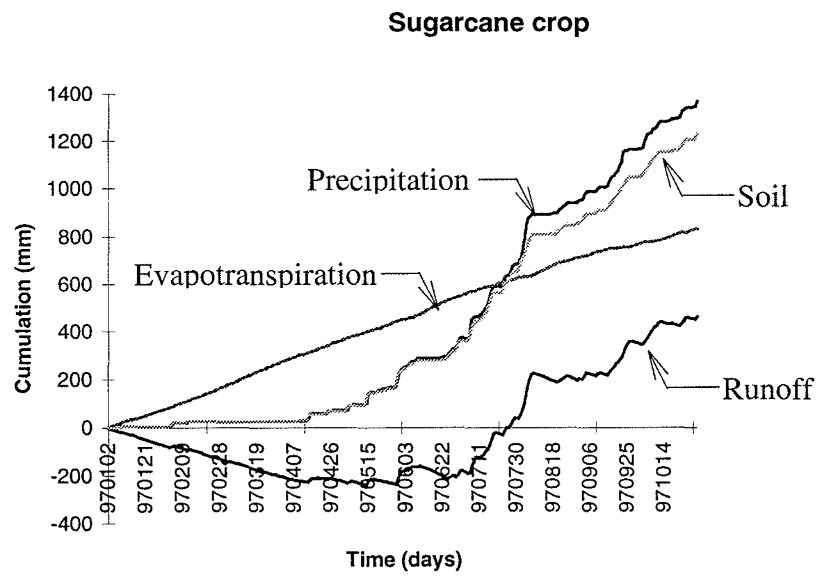


Figure 19. Simulated cumulative precipitation, simulated cumulative soil infiltration, simulated cumulative soil evaporation, and simulated cumulative total runoff for sugarcane crops.

CONCLUSIONS

Simulation was successful in reproducing the general pattern of water flow dynamics and water redistribution during the period from January to October 1997 in the raised bed systems on an acid soil. Simulated results agreed well with measurements (R^2 - values for linear regressions in a range between 46.7% to 88% for soil water contents).

- Simulated water flows and water redistributions were governed by soil properties, precipitation and, and evaporation.
- The capillary flow was dominant during the period from January to April.
- Infiltration for bare soil exceed infiltration for sugarcane plots with 77.5mm and the correspondent total drainage was exceed with 203mm during the investigation period.
- In the raised beds covered with crops reduced infiltration flow and runoff flow.

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