ARTICLE

Estimation of paddy water productivity (WP) using hydrological model: an experimental study

**S. Govindarajan · N. K. Ambujam ·
K. Karunakaran**

Abstract Water productivity (WP) expresses the value or benefit derived from the use of water. A profound water productivity analysis was carried out at experimental field at Field laboratory, Centre for Water Resources, Anna University, India, for rice crop under different water regimes such as flooded (FL), alternative wet and dry (AWD) and saturated soil culture (SSC). The hydrological model soil-water-atmospheric-plant (SWAP), including detailed crop growth, i.e, WOFOST (World Food Studies) model was used to determine the required hydrological variables such as transpiration, evapotranspiration and percolation, and bio-physical variables such as dry matter and grain yield. The observed values of crop growth from the experiment were used for the calibration of crop growth model WOFOST. The water productivity values are determined using SWAP and SWAP–WOFOST. The four water productivity indicators using grain yield were determined, such as water productivity of transpiration (WP_T), evapotranspiration (WP_{ET}), percolation plus evapotranspiration (WP_{ET+Q}) and irrigation plus effective rainfall (WP_{I+ER}). The highest value of water productivity was observed from the flooded treatment and lowest value from the saturated soil culture in WP_T and WP_{ET}. This study, reveals that deep groundwater level and high temperature reduces the crop yield and water productivity significantly in the AWD and SSC treatment. This study reveals that in paddy fields 66% inflow water is recharging the groundwater. There is good agreement between SWAP and SWAP–WOFOST water productivity indicators.

Introduction

Rice is currently the staple food of about 3 billion people in the world. It is expected that in Asia the population growth will be 1% every year up to 2025 and 0.6–0.9% in the world up to 2050. There is a growing demand for rice in the west and central Africa at the rate of 6% annually. Although large quantity of the rice is being produced and consumed in Asia, Tuong and Bouman (2003) estimated that by 2025, 2 million ha of Asia's irrigated dry-season rice and 13 million ha of its irrigated wet season rice may experience "physical water scarcity and approximately 22 million ha of irrigated dry-season rice in south and South-East Asia may suffer economic water scarcity". To solve these, farmers need to cultivate more area per drop or produce more per drop of evapo-transpiration (ET). According to Molden (1997), Molden and Sakthivadivel (1999) and Molden et al. (2003), water productivity means quantum of production per unit water used. Water productivity concept aims at "more crops per drop". For rice crop, researchers have developed alternative wet and dry and continuous soil saturation methods of irrigation aiming at increasing water productivity. In these methods, moisture content in the root zone of the rice crop was kept around saturated condition.

To measure the water productivity, water accounting is important; it is based on domain. By definition, domain is bounded in three-dimensional space and time; at field scale this could be top of the plant structure to the bottom of the root zone, spatially bounded by the edges of the bund, during a crop season.

S. Govindarajan (✉) · N. K. Ambujam · K. Karunakaran
Centre for Water Resources, Anna University,
Chennai 600 025, Tamil Nadu, India
e-mail: sivagovindarajan@hotmail.com

In irrigated agricultural fields, inflows are by irrigation and by rain. Water is depleted from the domain by the growing plants through transpiration (T) and evaporation (E), and other outflows such as interception, percolation and surface runoff. evaporation & transpiration (E&T) is an important component of the water balance; because transpiration is directly used for the plant growth and its biomass production and then evaporation losses which is happening simultaneously from the exposed soil surface adjacent to the crops.

Measuring of actual ET in the field is difficult, and laborious methods like soil water balance and meteorological methods, such as Eddy Correlation and Bowen ratio require numerous calibrations of parameters. Moreover, the distinction between soil evaporation (E) and crop transpiration (T) is difficult to measure. Only specific measurement techniques such as micro-lysimeters for soil evaporation and sap flow measurement and porometers for crop transpiration can be used. Porometers for crop transpiration are able to make distinction between E and T. The soil evaporation (E) can be considered as a non-productive use of water in terms of food production. In Turkey, Kite and Droogers (2000) carried out a study to find the possibilities for estimation of actual ET using field methods, hydrological models and remote sensing techniques. This study reveals that hydrological models and field methods are suitable for estimation of evapotranspiration. An experimental study was conducted by Ines et al. (2001) at Irrigation Engineering and Management Experimental Station at Asian Institute of Technology (AIT), Thailand, for estimation of crop growth and soil water balance using soil-water-atmospheric-plant (SWAP) model and decision support system for agro technology transfer (DSSAT) model. This study in corn fields concluded that SWAP model is well advanced in prediction of soil water balance and crop growth.

The present study is conducted with an objective to determine the water productivity of paddy in different water saving irrigation methods. Hence, an experimental study was conducted at the field laboratory, Centre for Water Resources (CWR), Anna University, India, whether water saving irrigation can improve the crop yield and water productivity for paddy crop. Crop growth and water accounting at field scale was calculated using SWAP model (Van Dam et al. 1997 and Kroes et al. 1999).

Materials and methods

Experimental setup

Field experiments were conducted at the Field Laboratory (13°00′N, 80°14′E), Centre for Water Resources (CWR),

Anna University at Chennai, India, for paddy crop, ADT 36 cultivar was used; nursery was raised on 11 February 2003, transplanted on 11 March and harvested on 30 May 2003. The crop was cultivated in summer (dry) season; the total rainfall recorded during the experimental period was 8.10 mm on 3 rainy days. Maximum temperature of 42°C was recorded on 20 May and minimum temperature recorded was 24°C on 21 February 2003. In this experiment, the plot size of each treatment was 3 m × 3 m.

The experiment was laid out with two replicates and three water treatments were implemented. Those are (1) flooded (FL) (2) alternative wet and dry (AWD) and (3) saturated soil culture (SSC). First, the paddy field was well puddled, after that the bunds were constructed having the dimension of 75 cm width and 20 cm depth. In the FL treatment, plots were kept continuously flooded from transplanting to till 10 days before harvest. The water depth at FL treatment was maintained at 2 cm daily through irrigation. The AWD treatment plot was irrigated up to a depth of 2 cm after disappearance of water on the soil surface and SSC treatment plot was irrigated up to 1 cm after disappearance of water on plot.

In all the treatments, 28-days-old seedlings from crop bed nurseries were transplanted at three seedlings per hill at a spacing of 20 cm × 10 cm. As per the guidelines given in the Directorate of agriculture (2001) fertilizers (phosphorous 38 kg/ha and potassium 38 kg/ha) were incorporated in all paddy fields 1 day before transplanting. Fertilizer N in the form of urea was applied in four equal splits of 30 kg/ha as basal (1 day before transplanting) and at 15, 30 and 45 days after transplanting. Further, during the experimental study, it was ensured that there was no seepage of water across the bunds.

During the study period there was no pest attack; weeds were controlled manually. Hence, pesticides or herbicides were not used in this experimental study.

Model description

Understanding movement of water in the field is the basis for estimation of water productivity. It is essential to determine water balance components as a first step to determine water productivity. The first version of SWAP model was written in 1978 by Feddes et al. and from then on continuous development of the program started. The version used for this study is SWAP 2.0 and is described by Van dam et al. (1997).

Soil-water-atmospheric-plant model (SWAP)

SWAP is an agro-hydrological model (soil-water-atmosphere-plant); it was developed by Feddes et al. (1978), Van Dam et al. (1997) and Kroes et al. (1999). SWAP

calculates water and salt balances of cropped soil columns; in this study, the model was used to determine the water balance for soil column of experimental field. Using deterministic, physical laws, SWAP simulates variably saturated water flow, solute transport and heat flow in top soils in relation to crop development. SWAP offers a wide range of possibilities to address practical questions in the field of agricultural water management and environmental protection. Options exist for irrigation scheduling, drainage design, salinity management, leaching of solutes and pesticides, and crop growth.

Soil water flow Soil water movement is governed by the gradient of the hydraulic head, H (cm) which is written as:

$$H = h + z \tag{1}$$

where h is the soil water pressure head (cm) and z is the vertical coordinate (+upward). In unsaturated soils water flow is predominantly vertical. Using Darcy's law, the water flux density q (cm/d) can be expressed as (+upward):

$$q = -K(h)\left[\frac{\partial h}{\partial z} + 1\right] \tag{2}$$

where K is the saturated hydraulic conductivity (cm/d) as function of soil water pressure head. The law of mass conservation of a soil column with root water extraction S_a gives:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S_a(z) \tag{3}$$

where θ is the volumetric soil water content (cm³/cm³), t is the time (day) and S_a is the actual soil water extraction rate by plant roots (cm³/cm³ day). Combination of Eqs. 2 and 3 results in the well-known Richard's equation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S_a(z) \tag{4}$$

where $C(h) = \partial\theta/\partial h$ is differential water capacity (cm⁻¹). The SWAP model solves the Richard's equation numerically for specified boundary conditions and with known relations between the soil variables θ, h and K. The relation between θ and h (retention function) might be described with the analytical equation proposed by Van Genuchten (1980):

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{\left[1 + |\alpha h|^n\right]^{\frac{n-1}{n}}} \tag{5}$$

where θ_{res} is residual water content (cm³/cm³), θ_{sat} is saturated water content (cm³/cm³), and α (per cm) and n (−) are empirical shape factors. Equation 6 in combination with the theory of Mualem (1976) provides a versatile relation between θ and K:

$$K(\theta) = K_{sat}S_e^{\lambda}\left[1 - \left(1 - S_e^{n/n-1}\right)^{\frac{n-1}{n}}\right]^2 \tag{6}$$

where K_{sat} is the saturated hydraulic conductivity (cm/d), λ is an empirical coefficient (−) and S_e is the relative saturation $(\theta - \theta_{res})/(\theta_{sat} - \theta_{res})$. When regression techniques are used to investigate the dependency of each Mualem–van Genuchten parameter on more easily measured basic soil properties, continuous pedotransfer functions can be constructed. Continuous pedotransfer functions are available in SWAP to predict the hydraulic characteristics for a specific soil with known texture, organic matter content and bulk density.

Top boundary condition The top boundary condition is determined by the potential evapotranspiration, irrigation and rainfall fluxes. The potential evapotranspiration is estimated by the Penman–Monteith equation (Monteith 1965, 1981; Smith 1992; Allen et al. 1998).

In the agricultural field conditions where crops partly cover the soil, ET_p is split into potential soil evaporation E_p (cm/day) and potential transpiration T_p (cm/day). This partitioning is achieved by crop leaf area index, LAI (m²/m²), which is a function of crop development stages (Goudriaan 1977; Belmans et al. 1983):

$$E_p = ET_p e^{-k_{gr}LAI} \tag{7}$$

where K_{gr} is the extinction coefficient for global solar radiation (−). In case of wet soil, the actual soil evaporation rate E_a (cm/day) is controlled by the atmospheric demand and will be equal to E_p. Under dry soil conditions, the soil hydraulic conductivity decreases, this may reduce E_p to a lower actual evaporation rate E_a (cm/day). In SWAP the maximum evaporation rate is from top of soil E_{max} (cm/day), which can be calculated by Darcy's law as:

$$E_{max} = k_{1/2}\left(\frac{h_{atm} - h_1 - z_1}{z_1}\right) \tag{8}$$

where $k_{1/2}$ is average hydraulic conductivity (cm/day) between the soil surface and first node, h_{atm} is soil water pressure head (cm) in equilibrium with the air humidity, h_1 is the soil water pressure head (cm) of first node, and z_1 is the soil depth (cm) of the first node.

The Darcy law may over estimate the actual soil evaporation flux (Van Dam 2000). Therefore, in addition to Eq. 8, SWAP estimates the soil evaporation rate using empirical functions E_{emp}. SWAP determined actual evaporation rate by taking the minimum value of E_p, E_{max} and E_{emp}. For this study, we used the empirical function of Boesten and Stroosnijder (1986) to limit the soil evaporation rate.

The potential transpiration rate, T_p (cm/day), follows from the balance:

$$T_p = \left(1 - \frac{P_i}{ET_{p0}}\right)ET_p - E_p \qquad (9)$$

where P_i (cm/day) is the water intercepted by vegetation and ET_{p0} is the potential evapotranspiration of a wet crop (cm/day), which can be estimated by the Penman–Monteith equation assuming zero crop resistance. The ratio P_i/ET_{p0} denotes the day fraction during which interception water evaporates and transpiration is negligible.

The actual transpiration rate is controlled by the root water extraction rate of a crop, which depends on the rooting depth and its distribution and actual soil water pressure heads in the root zone. For practical reasons SWAP adopted a homogenous root distribution over the rooting depth. The maximum root water extraction rate $S_{max}(Z)$ (per day) was calculated as:

$$S_{max}(Z) = \frac{T_p}{Z_{root}} \qquad (10)$$

where z_{root} is the rooting depth (cm) and T_p is the potential transpiration (cm/day).

Under non-optimal conditions, i.e., either too dry, too wet or too saline, $S_{max}(Z)$ will be reduced to the actual root water extraction rate. For water stress, Feddes et al. (1978) proposed a water stress reduction function as depicted in Fig. 1. The critical pressure head h_3 for too dry conditions depends on potential transpiration (T_p) value. When higher atmospheric demand or potential transpiration rate is greater than 5 mm/day root water uptake will tend to reduce linearly from the soil water pressure head 0 cm (h_{3h}) to −10,000 cm (h_4), if the atmospheric demand is low or potential transpiration is lesser or equal to 5 mm/day, root water uptake will tend to reduce linearly from the soil water pressure −200 cm (h_{3l}) to −10,000 cm (h_4). The above soil water pressure head values h_{3h} and h_{3l} for paddy during low and high atmospheric demand is given in Belder (2005) and Singh et al. (2003). Effect of salinity stress in the crop yield was not considered in this study because, no salinity problem in the soil and water.

In case of water stress, the actual root water extraction rate $S_a(z)$ is calculated as the product of the reduction coefficients (Cardon and Letey 1992):

$$S_a(Z) = \alpha_{rw}\alpha_{rs}S_{max}(Z) \qquad (11)$$

where α_{rw} is the reduction co-efficient for water stress [−], and α_{rs} for salt stress [−]. Finally the actual transpiration rate T_a (cm/day) follows from the integration of $S_a(Z)$ over the rooting depth.

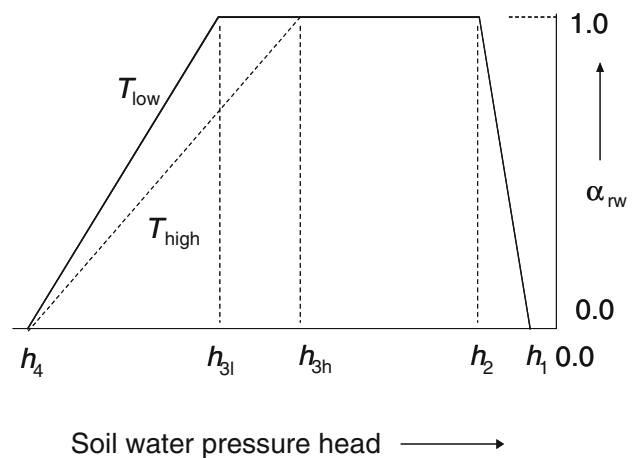*Crop growth* SWAP includes both a simple and detailed crop growth module. In the simple crop module, crop

Fig 1 Reduction coefficient α_{rw} as function of soil water pressure head h and potential transpiration rate T_p (Feddes et al. 1978)

growth is described by the measured leaf area index, crop height and rooting depth as a function of crop development stage. The detailed crop growth module is based on the world food studies (WOFOST) model (Spitters et al. 1989; Supit et al. 1994), which simulates the crop growth and its production based on the incoming photosynthetically active radiation (PAR) absorbed by the crop canopy and the photosynthetic characteristics of leaf, and accounts for water and salt stress of the crop. In addition to the water and salt stress, nutrient deficiency, weeds, pests and diseases may affect the crop production in actual field conditions. This reduces the water and salt limited production further to the actual production (Fig. 2).

The effects of nutrient deficiency, pests, weeds, and diseases on crop growth and its production are not implemented in the present version of WOFOST. However, this detailed crop growth module has the advantage of giving a feedback between crop growth and different water and salt stress conditions. The details of the light interception and CO_2 assimilation as growth driving processes and the crop phenological development as growth controlling process are included. To distinguish the simulations in this study, SWAP 2.07 when used with the simple crop growth module is called SWAP hereafter, and when used with the detailed crop growth module is called SWAP–WOFOST. The detailed crop module, SWAP–WOFOST, simulates the potential and water and salt limited crop yields, which cannot be simulated by the simple crop model SWAP. In this study, salt interaction is switched off.

Bottom boundary condition The SWAP model offers various bottom boundary conditions to be selected by the user. These can be generalized in to three types: flux specified, pressure specified and flux–groundwater level relationships. In the field lab, depth of ground water level

Fig. 2 Production hierarchy in the crop production system (Adapted from Lovenstein et al., 1995)
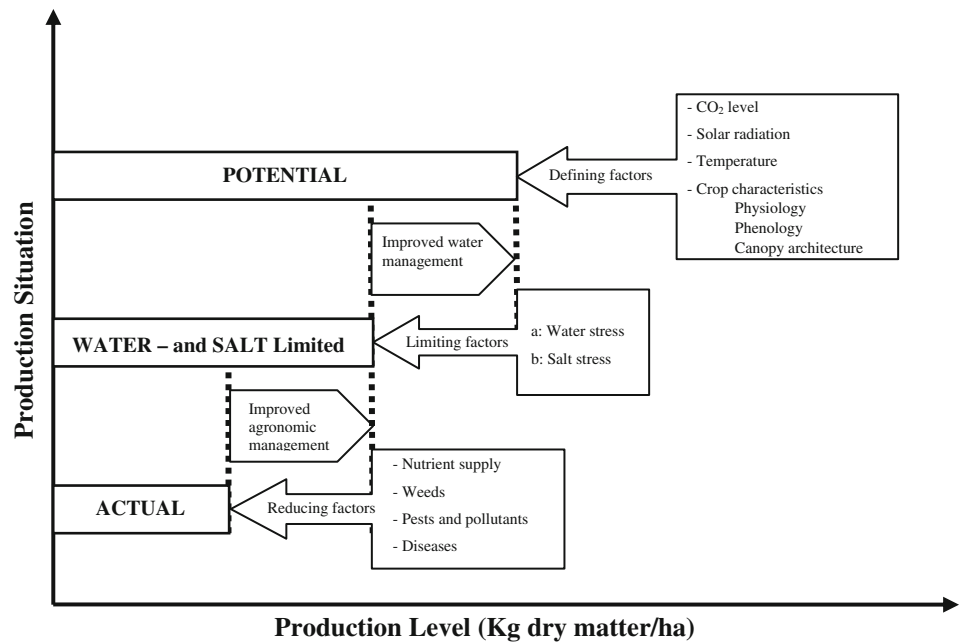
were observed at bore well and it was used as input for the model as bottom boundary conditions. Groundwater level was measured randomly throughout the crop period (Fig. 3).

In this study, SWAP model was used to determine the water balance under different water management conditions; simulation of solute and heat transport was not considered.

Water productivity indicators

Water productivity means quantum of production per unit water used (Molden 1997, Molden et al. 2001). The denominator unit water used or committed is varies significantly with respect to scale (Molden et al. 2001, Kijne et al. 2003). This paper deals with the water productivity at field scale.

The actual transpiration represents the lower limit of water used by the crop. In this case, water productivity

Fig. 3 Ground water table depth at field lab during crop season

expressed in terms of grain or dry matter production Y (kg/m^2) per unit water transpired (T).

$$WP_T = \frac{Y\left(kg/m^2\right)}{T(m^3/m^2)} = \frac{Y}{T}\left(Kg/m^3\right) \tag{12}$$

Water productivity of transpiration depends on crop types and varieties. The dry matter production and transpiration rate of crop are related to the diffusion rates of CO_2 and H_2O molecules at stomatal aperture of leaves. Under a fixed set of environmental conditions, the diffusion rates of CO_2 and H_2O molecules vary proportionally to the size of stomatal aperture of a certain crop, the ratio of these rates remains constant. For such conditions, WP_T for a certain crop is expected to remain constant (Leffelaar et al. 2003). However, continuously changing environmental conditions in terms of the CO_2 concentration in air, radiation, temperature and vapor pressure result in varying evaporative demands, and subsequently the transpiration rate vary at a given stomatal aperture. As a result, WP_T for a certain crop shows a considerable variation depending on the ecohydrological conditions of a region.

The unavoidable loss of water due to soil evaporation E decreases the water productivity from WP_T to WP_{ET}, which is expressed in terms of Y per unit amount of evpotranspiration (ET).

$$WP_{ET} = \frac{Y}{E + T} = \frac{Y}{ET}\,(kg/m^3) \tag{13}$$

The ET represents the actual amount of water used in crop production or depletion of water under the process of agriculture production, and must be used as productive as possible. Relative low value of WP_{ET} as compared to WP_T
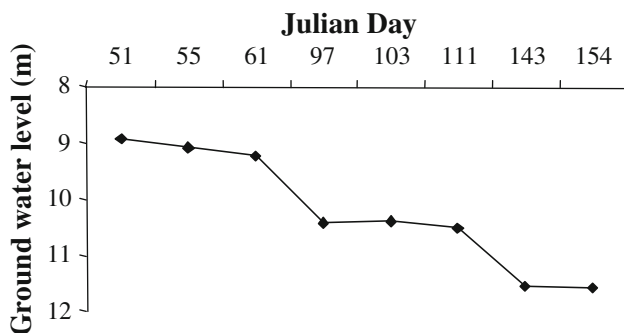
indicates the need to reduce soil evaporation by agronomic measures such as soil mulching and conservation tillage.

Similarly, including percolation Q_{bot} from field irrigation enlarges the denominator in expression of water productivity, and hence decreases it from WP_{ET} to WP_{ETQ}.

$$WP_{ETQ} = \frac{Y}{ET + Q_{bot}} = \frac{Y}{ETQ} (kg/m^3) \qquad (14)$$

Apparently it seems that both percolation and seepage losses reduce the WP_{ETQ}, but it depends on the groundwater quality of that region. For instance, percolation from field irrigation and seepage from conveyance system recharge to groundwater, which is recycled through groundwater pumping in good quality groundwater regions. If groundwater is poor, recycling of this water may not be possible, and any percolation and seepage should be considered as loss of water.

The irrigation and rainfall is the total water applied to the field. In this case, the water productivity expressed in terms of Y per unit water available in the field through irrigation I and effective rainfall ER. In this case, the effective rainfall is equal to rainfall minus quantity of intercepted rainfall due to plant leaf area.

$$WP_{I+ER} = \frac{Y}{I + ER} (kg/m^3) \qquad (15)$$

WP_{I+ER} depends on method of irrigation and water stress tolerance of a crop; for example, paddy is a water loving crop; small stress also significantly affects the plant growth.

Data collection

To run the simulation model, data were collected relating to soil, depth of irrigation, and climate and plant growth details from February to May 2003.

Meteorological data

The required climate data to run the simulation model was collected from the meteorological station which is situated within the field lab. Average daily temperature was calculated using maximum and minimum daily temperature.

Daily relative humidity was measured using wet and dry bulb. Wind velocity was measured using anemometer. Simon's rain gauge was used for measurement of daily rainfall. Daily radiation (R_s) was calculated using the adjusted and validated Hargreaves radiation formula given by Allen et al. (1998).

$$R_s = K_{RS} \sqrt{(T_{max} - T_{min})R_a} \qquad (16)$$

where R_a is extraterrestrial radiation (MJ/m^2 day), T_{max} is the maximum air temperature (°C), T_{min} is the minimum air temperature (°C) and K_{RS} adjustment co-efficient (0.16…0.19) (per °C). In this study, a K_{RS} value of 0.16 was used. The meteorological data were used to determine the daily potential water demand of the crop.

Soil data

To solve the Richard's equation, the soil physical characteristics, soil retention and hydraulic conductivity curves should be known. Determination of these soil characteristics requires specialized laboratory technique and is time consuming. A promising technique to derive these properties is to relate them to easily obtainable data like texture and organic matter using the so called pedotransfer functions (Tietje and Tapkenhinrichs 1993). Representative soil samples were collected before sowing and after harvesting. Sampling was done at every 15 cm interval upto 60 cm depth of soil. Soil textural composition was determined for each layer. Bulk density was measured by sand replacement method and percentage organic carbon was estimated using the wet digestion method of Walkley and Black as described in Jackson (1973). The measured soil characteristics and derived soil hydraulic functions using pedotransfer function is given in Table 1.

Crop growth data

The phonological stages of paddy crop were recorded. In addition to that, plant density, crop height, leaf area index (LAI) and dry matter in different plant organs were recorded during the crop season at different stages. The plant density in the field was 50 plants/m^2. The plant height

Table 1 Soil characteristics and derived soil hydraulic functions

Layer (cm)	Clay (%)	Silt (%)	Sand (%)	O.M (%)	B.D (g/cm^3)	θ_{res} (cm^3/cm^3)	θ_{sat} (cm^3/cm^3)	α	n	K_{sat} (cm/d)	λ
0–15	14	22	64	2.4	1.83	0.01	0.29	0.02	1.18	12.80	−3.12
15–30	13	24	63	1.9	1.94	0.01	0.27	0.01	1.14	5.16	−2.95
30–45	12	26	62	1.5	1.98	0.01	0.25	0.01	1.13	5.04	−2.63
45–60	12	27	61	1.0	2.05	0.01	0.24	0.009	1.11	4.29	−2.48

O.M Organic matter, *B.D* Bulk Density, θ_{res} Residual water content, θ_{sat} Saturated water content, K_{sat} Saturated hydraulic conductivity, α (1/cm), n, and λ are empirical shape factors

Table 2 Maximum values of crop parameters observed experimental plots

Crops	Start growing season	End growing season	Maximum rooting depth (cm)	Maximum crop height (cm)	Max LAI (m²/m²)
Paddy					
FL	11.03.2003	30.05.2003	60.95	96.50	8.45
AWD	11.03.2003	30.05.2003	40.60	80.60	7.16
SSC	11.03.2003	30.05.2003	21.15	70.00	5.11

was measured from the soil surface to the top of the straightened shoot/leaf. Above the soil surface, plant parts were cut and were divided in to leaves (living and dead leaf), stems and storage organ. Collected samples were kept at oven drying at 65°C until there is no difference in weight with successive readings. Leaf area was measured for two plant hills in each plot; based on plant density, LAI was calculated. Root depth was measured in different stages of the crop season. At the time of harvest, crop cutting experiment was conducted for the centre 1 m² of the plot. After manual threshing, the grain and straw were separated, and then measured; it is recorded in kg/ha. Table 2 gives the maximum value of crop parameters observed in the experiment.

The quantity of irrigation water applied was measured using a calibrated water meter. Ground water level during this season was 8 m below ground level. It was observed using water level indicator at a bore well located within 50 m distance from the experimental plots. This data was used as input for the model to specify the bottom boundary conditions. Groundwater level was measured randomly throughout the growing period.

Result and analysis

Experiment

The total rainfall recorded during the experiment (11/3/2005 to 12/5/2005) was 8.10 mm in 3 days. The average depth of water irrigated in each treatment was 132.5 cm for FL, 120.3 cm for AWD and 107.6 for SSC but number of irrigation was 67, 24 and 37 in FL, AWD and SSC treatments, respectively.

The measured leaf area index is given in Fig. 4 for all the paddy treatment fields. In the FL, the values reached a maximum of about 8–8.5; in the AWD 6–7.5, and in the SSC 4.5–5.5. The LAI in the SSC was considerably lower than the FL.

The biomass production is given in Fig. 5; the same trend as in the LAI development was observed. In the FL biomass accumulation of 12,000 kg/ha is reached while under SSC it reached only 9,500 kg/ha. The crop cutting experiment was conducted in all treatments to measure the
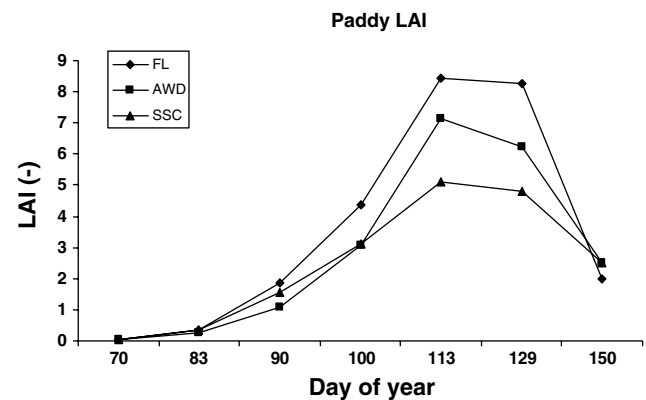
Fig. 4 Leaf area index of the paddy experiment
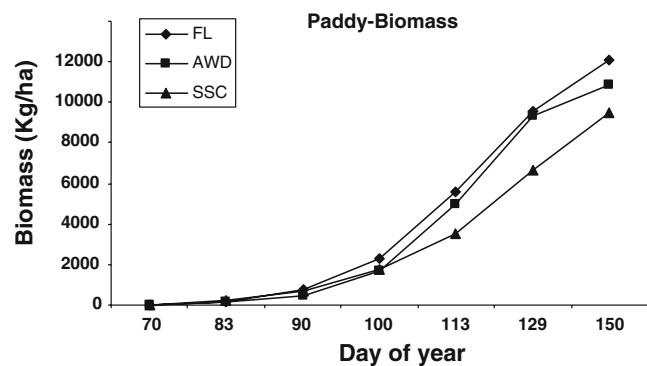
Fig. 5 Dry biomass in the paddy experiment

yield. The measured yield in FL treatment was 6,770 kg/ha. In the AWD and SSC treatments, measured yield were 5,460 and 5,200 kg/ha, respectively. The moisture content in the yield was 12%.

SWAP model

The potential and actual evaporation (E) and transpiration (T) and all the water balance components were determined using SWAP with simple crop growth model, called SWAP. In simple crop growth model, plant growth details such as LAI, crop height, root depth and yield response were given as input to model as function of development stages. So based on the actual plant growth, water balance

components were simulated, and the results are showed in Table 3.

SWAP–WOFOST model

The water balance components were determined using SWAP with detailed crop growth model, called SWAP–WOFOST. In this analysis, water balance and plant growth were simulated. To run the SWAP–WOFOST, calibration is required for detailed crop growth model; for this purpose, sensitive parameters were identified by using the method suggested by Van dam and Malik (2003). The identified sensitive parameters for analysis are given in Table 4. Based on the experimental data and literature, realistic values of the parameters are determined. During calibration, the remaining sensitive parameters were adjusted. Observed data, namely the leaf dry matter, storage organs, total dry matter above ground and leaf area index were used. Based on small adjustment of the sensitive parameters, the LAI, dry matter and yield were calibrated. During the calibration process, high priority was given to the calibration of LAI.

Calibration

For calibration, data from the paddy experiment was used. Figure 6 shows comparison of measured and simulated values of LAI, total dry matter production (TDM) and storage organ (SO) in the treatments of FL, AWD and SSC. Paddy growth is simulated from transplanting to harvest. Simulated LAI is underestimated during the initial stages,

Table 4 Overview of crop parameters that were based on measurements and those adjusted, within realistic values, during calibration

Parameters based on measurement	Parameter adjusted during calibration
Initial dry matter, Leaf Area Index and growth rate of LAI	Initial dry matter and growth rate LAI
Specific leaf area	Life span of leaves
Life span of leaves	Specific leaf area
Dry matter partitioning	Dry matter partitioning
Conversion co-efficient	Extinction co-efficient of diffuse light
Rooting depth increase	Initial light use efficiency
Maximum rooting depth	Maximum assimilation rate
Crop height	Death rate of leaves due to water stress
Length growing phases	Critical pressure heads for water uptake

Parameters not mentioned in the table were based on literature

and fitted well during later stages under flooded conditions. In the treatment of AWD, LAI measured and simulated fitted well throughout the season (Figs. 7, 8).

The total dry matter production is somewhat underestimated throughout the season in all the treatments. Regarding the storage organ, best fit is arrived in the treatment FL and SSC; underestimation of storage organ is prevailing in the treatment of AWD. The water balance results of the SWAP–WOFOST model are shown in Table 5.

Water productivity

The water productivity values were calculated using the water balance components T_{act}, ET_{act} and percolation simulated by SWAP and SWAP–WOFOST and using actual grain yields Y_g measured at the experimental fields.
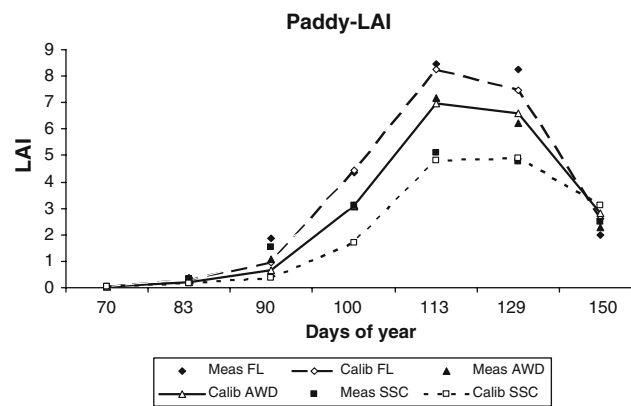
Table 3 Water balance components estimated by SWAP

Water balance components	FL	AWD	SSC
Inflows			
Rainfall	0.81	0.81	0.81
Irrigation	132.57	120.34	107.60
Outflows			
Interception	0.18	0.15	0.13
Runoff	0.00	0.00	0.00
T_{act}	29.93	29.90	29.30
E_{act}	8.74	8.01	9.78
ET_{act}	38.67	37.91	39.08
Percolation	93.80	81.42	66.03
Storage change	1.23	1.68	3.17
Potential			
T_{pot}	34.17	32.39	30.60
E_{pot}	9.73	10.42	11.24
ET_{pot}	43.90	42.81	41.84

Units are in cm

Fig. 6 Measured and simulated leaf area index versus days of year

Fig. 7 Measured and simulated total dry matter versus days of year
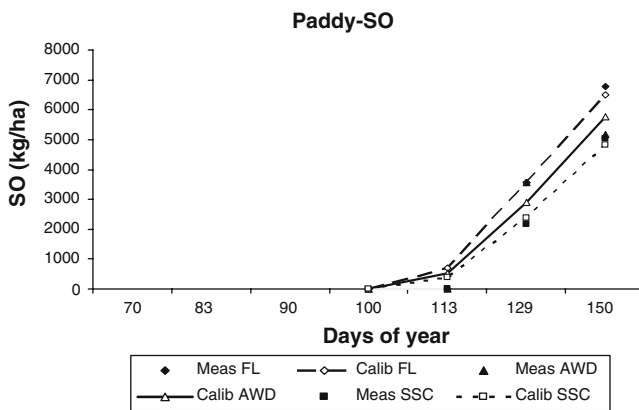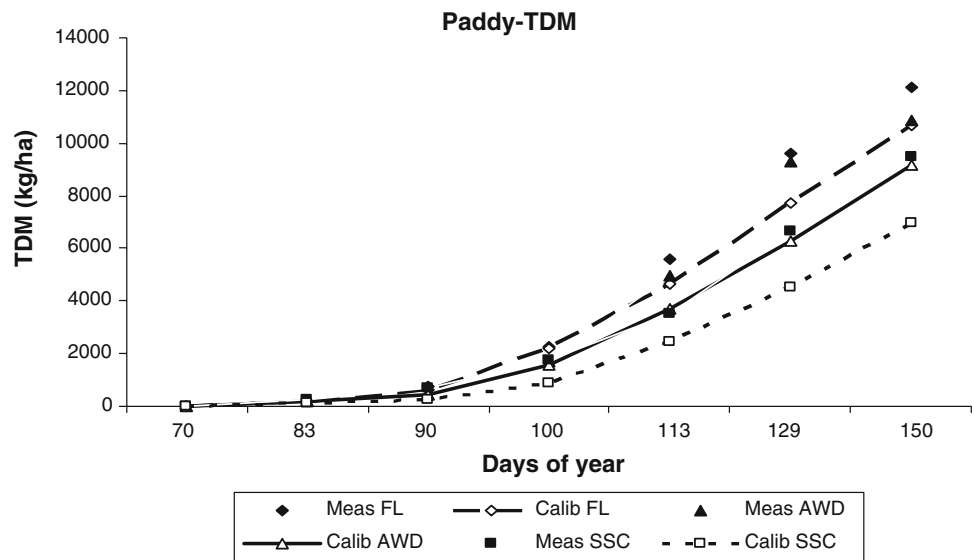

Fig. 8 Measured and simulated storage organ versus days of year

The results of the water productivity computed are given in Table 6.

The potential evaporation (E) and transpiration (T) and all the water balance components were determined using SWAP with simple crop growth model, called SWAP. To simulate the interaction between crop growth and water stress a detailed crop growth model, called SWAP–WOFOST was used. The SWAP and SWAP–WOFOST is used to analyze the movement of water and its interaction on crop growth. Under field laboratory condition, we used both SWAP and SWAP–WOFOST for comparison purposes. One may ask the question as to which one is superior; each one has its own strength and weakness. While SWAP is simple to use, it needs considerable amount of crop growth data to be collected at the field while SWAP–WOFOST calibrates the movement of water and its interaction on crop growth at a particular location and determines the parameters which can then be adopted in areas where the same crop and climatic conditions are prevalent.

Table 5 Water balance components estimated by SWAP-WOFOST

Water balance components	FL	AWD	SSC
Inflows			
Rainfall (cm)	0.81	0.81	0.81
Irrigation (cm)	132.57	120.34	107.60
Outflows			
Interception (cm)	0.18	0.17	0.14
Runoff (cm)	0.00	0.00	0.00
T_{act} (cm)	30.60	30.72	29.08
E_{act} (cm)	7.69	7.19	9.98
ET_{act} (cm)	38.29	37.91	39.06
Percolation (cm)	93.38	81.59	66.19
Storage change (cm)	1.53	1.48	3.01
Potential			
T_{pot} (cm)	35.69	33.60	30.62
E_{pot} (cm)	8.24	9.20	11.23
ET_{pot} (cm)	43.93	42.80	41.85

Units are in cm

Discussion

In the present experiment, the highest yield of 8.95 t/ha for 133 cm depth of irrigation was obtained from flooded treatment. In the AWD, the yield was reduced by 21% of flooded treatment against 9% reduction in depth of water supplied in flooded treatment irrigation. Forty percentage of yield was reduced in the SSC, with 19% reduced depth of irrigation compared to FL. When compared to AWD, the reduction in yield in SSC was 24% along with 10% reduction in the depth of irrigation. Contrary to results obtained in this study (Table 6), many studies reveal that alternate wet/dry irrigation and saturated soil culture give higher water productivity. The deep groundwater table and higher

Table 6 Results of water productivity for paddy crop at experimental fields

Water productivity	SWAP				SWAP-WOFOST			
	FL	AWD	SSC	Average	FL	AWD	SSC	Average
WP_T (kg/m³)	2.26	1.73	1.71	1.90	2.12	1.88	1.66	1.88
WP_{ET} (kg/m³)	1.75	1.36	1.29	1.47	1.69	1.52	1.23	1.48
WP_{ET+Q} (kg/m³)	0.51	0.43	0.48	0.47	0.49	0.48	0.46	0.48
WP_{I+ER} (kg/m³)	0.51	0.43	0.46	0.47	0.49	0.48	0.45	0.47

evaporative demand during the study affected the yield in the AWD and SSC treatments, more than that the water saved by these treatments, and consequently lower water productivities resulted in these treatments compared to FL.

In water saving treatments, one needs to ensure hydraulic separation of the experimental plots from the surrounding to prevent surface and subsurface flow, but subsurface flow could not be fully prevented when the groundwater table was deep or greater than 2 m. When the depth of the groundwater table is shallow, it is the determining factor in reducing the percolation loss; it causes reduction in inflow to groundwater and avoids yield loss during the water stress periods. Also the plant can get its water for transpiration from the groundwater or capillary pores. Naturally the paddy cultivable soil having tiny soil pore space could accelerate the capillary rise to maximum extent. Most of the water saving experimental studies was conducted at farmer fields where the water table was less than 2 m. This study was conducted with groundwater level around 11 m below ground level, because of this reason higher WP was obtained in the FL treatment, where water supplied by irrigation and rainfall was sufficient to give higher yield. In AWD and SSC treatments where capillary water could not be used due to deeper ground water table and hence their yields were low compared to FL treatment.

It is reported by Tuong and Bouman (2003) that in most cases of AWD and SSC treatments yield decrease occurs. The level of yield decrease depends largely on the ground-water table depth and the evaporative demand; because of this, lower WP obtained in AWD and SSC. During the study period, observed groundwater level was 11 m below ground level and higher atmospheric demand during summer season accelerated the higher evaporative demand, thereby reducing the yield significantly in AWD and SSC.

The daily potential transpiration and evaporation and actual transpiration and evaporation of the FL treatment experiment are given in Fig. 9a and b.

From Fig. 9a and b, it could be seen that in the early stage of the crop, potential T was low and potential E was high. Also at the end of growing season, the effect of dying
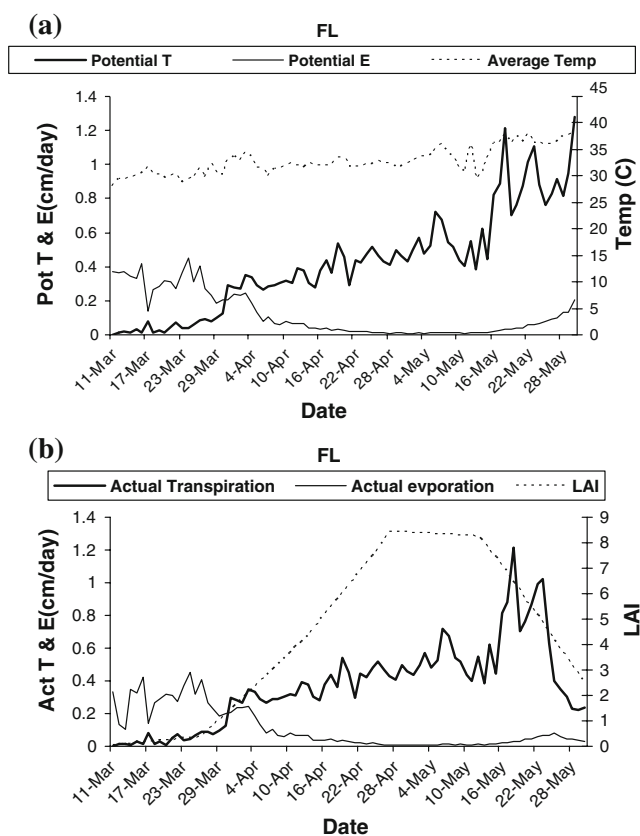

Fig. 9 a Potential transpiration, potential evaporation and average temperature versus date in the FL treatment. **b** Actual transpiration, actual evaporation and leaf area index versus date in the FL treatment

leaves decreased the potential T and a little rise in potential E. The LAI tends to decline after 13 May because of aging of leaves, but the T_{pot} value was in an increasing trend for couple of days, because of higher temperature. (Refer to Fig. 9a).

Figure 10a shows that there is no significant difference between potential and actual transpiration in early and middle stages of the crop growth in AWD treatment; At the end of the season water was stopped for a week for harvest, because of that the actual transpiration deviated from potential values. In soil evaporation, there is water stress in the initial and at the end stage of crop growth (Fig. 10b).

From the profile of actual crop transpiration and soil evaporation shown in Fig. 9b, crop transpiration is directly proportional to LAI and soil evaporation is inversely proportional to LAI.

The percentage irrigated water augmented to groundwater table was determined using SWAP as 93.30 cm, i.e, 70% of inflow water goes into the groundwater in the FL. In AWD treatment, 67% of inflow water reaches to groundwater. SSC treatment percolates 61% of inflow into groundwater. These percentage figures indicate that method of irrigation causes very little difference in recharging of groundwater.
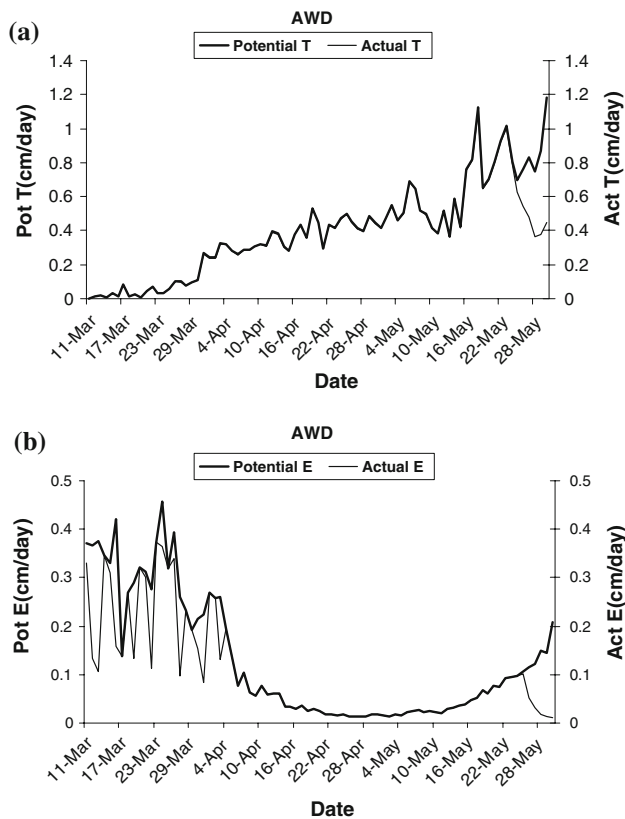
(a)

(b)

Fig. 10 **a** Potential and actual crop transpiration in AWD treatment, **b** potential and actual crop evaporation in the AWD treatment

During the calibration of SWAP–WOFOST model, it was observed that water stress in plants created delay to complete crop growth stages; hence, the partitioning of the carbohydrates in different plant organ were severely affected. Due to this reason, when using the calibrated SWAP–WOFOST in different condition one needs few measurements of crop growth.

The water productivity of paddy was determined using four denominators: transpiration, evapotranspiration, total depletion which includes evapotranspiration plus percolation, and inflows that is irrigation plus effective rainfall. In rice experiment, water productivity of transpiration WP_T is 2.262 kg/m^3 in FL, 1.726 and 1.713 kg/m^3 in SSC and AWD treatments, respectively. The average value for this experiment is 1.90 kg/m^3.

Zwart and Bastiaanssen (2004) found global average value of WP_{ET} for rice crop as 1.09 kg/m^3 and further they stated that in many of the alternative wetting and drying and continuous flooding experiments, there was no significant difference in crop water productivity. Analysis of traditional and AWD method of irrigation in China by Dong et al. (2001) found similar result and concluded that there was no significant difference between FL and AWD

experiments; since 10-year average WP_{ET} was 1.49 and 1.58 kg/m^3 for continuous flooding and intermittent irrigation experiments, respectively.

In this study, the average value of WP_{ET} is 1.48 kg/m^3 and 27% lesser than WP_T. It is reported by Tuong and Bouman (2003) and Bouman and Tuong (2001) that the water productivity of rice, WP_{ET} values under typical low land condition range from 0.4–1.6 kg/m^3. To improve the water productivity of evapotranspiration, WP_{ET}, the fraction of evaporation E in ET is important. The high evaporative demand and continuously surface ponding result in high soil evaporation during the rice growing season.

The average WP_{ETQ} was 0.474 kg/m^3. The percolation Q reduces the WP_{ET} to WP_{ETQ} at field scale. Note the high reduction from WP_{ET} to WP_{ETQ} at paddy fields; in percentage it was 68. Usually in irrigated areas Q contributes to the groundwater recharge, which is recycled through groundwater pumping in good quality groundwater areas. Therefore, the reduction of Q will be beneficial for improving the low WP_{ETQ} values in the poor quality groundwater areas. The average water productivity of irrigation plus effective rainfall is 0.466 kg/m^3. Flooded treatment got highest WP_{I+ER} equal to 0.508 kg/m^3. It is reported by Tuong and Bouman (2003) and Bouman and Tuong (2001) that the water productivity of irrigated rice is ranges from 0.20 to 1.1.kg/m^3.

In the WP_{ET}, E&T is important which depends on LAI. T is directly proportional to LAI, but E is indirectly proportional to LAI. Since paddy is sensitive crop on water stress, small stress will affects the LAI; due to that evaporation loss will increase since most of the paddy fields are kept under saturated condition during the growing season; this will make potential and actual E more or less equal. The reduction of LAI reduces the transpiration while it increases the evaporation. Thus, in this study the ET value has not varied significantly among the paddy treatments.

There is wide difference between the WP values obtained in this research, because of the change in E values due to different treatments most of the WP values obtained are lying within the ranges prescribed by the different researchers.

Conclusions

This study concludes that water saving irrigation alone cannot improve the water productivity of paddy crop at field scale. The improvement of water productivity in water saving irrigation depends on groundwater level and evaporative demand. This study demonstrates that for estimation of actual plant transpiration and soil evaporation, SWAP model is useful at field scale.

The potential plant T is directly proportional to depth of irrigation supply, while potential soil E is indirectly proportional to depth of irrigation supply; due to changes in leaf area affected by water stress. The availability of moisture content in root zone increases the leaf area index value which in turn increases the T_{act} value, but the actual E value is decreasing due to increasing shaded area. In all the treatments, the potential transpiration value has been 10 mm/day during the study season. In reality, crops close their stomata with high atmospheric demand, resulting in lower values of T_{act}. Further study is desirable to explore these processes. The study has also shown that to estimate the soil physical properties, pseudo-transfer functions are useful. In this experimental study, irrigation water productivity for paddy varies from 0.52 to 0.47 kg/m^3 and water productivity of evapotranspiration varies from 1.75 to 1.28 kg/m^3. In this case, higher water productivity is obtained from the flooded irrigation field. This is mainly because of reduction in crop yield in AWD and SSC treatment. The low yield is due to deeper groundwater level. Further intensive work is required to study the interaction between the surface water and groundwater level in paddy fields. This study reveals that in paddy fields 66% inflow water is recharging the groundwater.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration, guidelines for computing crop water requirements. Irrigation and drainage paper 56, FAO, Rome, Italy, pp 300

Belder P (2005) Water saving in lowland rice production: an experimental and modeling study. Dissertation, Wagenigen University, Wagenigen, The Netherlands.

Belmans C, Wesseling JG, Feddes RA (1983) Simulation of the water balance of cropped soil: SWATRE. J Hydrol 63:271–286

Boesten JJTI, Stroosnijder L (1986) Simple model for daily evaporation from fallow tilled soil under spring conditions in temperate climate. Netherland J Agric Sci 34:75–90

Bouman BAM, Tuong TP (2001) Field water management to save water and increase its productivity in irrigated lowland rice. Agric Water Manage 49:11–30

Cardon GE, Letey J (1992) Plant water uptake terms evaluated for soil water and solute movement models. Soil Sci Soc Am J 32:1876–1880

Directorate of agriculture (2001) Crop production guide. Chepauk, Chennai, Tamil Nadu, India

Dong B, Loeve R, Li Y, Chen CD, Deng L, Molden D (2001) Water productivity in the Zhanghe irrigation system: issues of scale. In: Barker R, Loeve R, Li Y, Tuong TP (eds) Proceedings of an international workshop in water-saving irrigation for rice. Wuhan, China, March 23–25, pp 97–115

Feddes RA, Kowalik PJ, Zaradny H (1978) Simulation of field water use and crop yield. Simulation monographs, Pudoc, Wageningen, The Netherlands, pp 189

Goudriaan J (1977) Crop meteorology: a simulation study. Simulation monographs, Pudoc, Wageningen, the Netherlands

Ines AVM, Droogers P, Makin I, Das Gupta A (2001) Crop growth and soil water balance modeling to explore water management options. IWMI Working Paper 22. International Water Management Institute, Colombo, Sri Lanka

Jackson ML (1973) Soil chemical analysis. Prentice-Hall, New Delhi

Kijne J, Barker R, Molden D (2003) Water productivity in agriculture: limits and opportunities for improvement. Comprehensive assessment of water management in agriculture, vol Series No. 1. CABI press, Wallingford, pp 352

Kite GW, Droogers P (2000) Comparing evapotranspiration estimates from satellites, hydrological models and field data. J Hydrol 229:3–18

Kroes JG, Van Dam JC, Huygen J, Vervoort RW (1999) User's Guide of SWAP version 2.0 Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Technical Document 48, Alterra Green World Research, Wageningen, Report 81, Department of Water Resources, Wageningen University, pp 127

Leffelaar PA, Van Dam JC, Bessembinder JJE, Ponsioen T (2003) Integration of remote sensing and simulation of crop growth, soil water and solute transport at regional scale. In: Van Dam JC, Malik RS (ed) Water productivity of irrigated crops in Sirsa district, India. Integration of remote sensing, crop and soil models and geographical information systems. WATPRO final report, including CD-ROM. ISBN 90–6464–864–6, pp 121–134

Lovenstein HM, Lantinga R, Rabbinge R, Van Keulen H (1995) Principles of production ecology: text of course F 300–001, pp 8. Fig. 8. Department of theoretical production ecology, Wageningen university and research centre, Wageningen, The Netherlands, pp 121 Open University, Heerlen. ISBN 90–358–1111–1, pp 247

Molden D (1997) Accounting for water use and productivity. SWIM Paper 1, International Irrigation Management Institute, Colombo, Sri Lanka

Molden D, Sakthivadivel R (1999) Water accounting to assesses and productivity of water. J Water Resour Dev 15:55–72

Molden D, Murray-Rust H, Sakthivadivel R, Makin I (2001) A water productivity framework for understanding and action. Workshop on water productivity. Wadduwa, Sri Lanka, November 12 and 13, 2001

Molden D, Murray-Rust H, Sakthivadivel R, Makin I (2003) A water productivity framework for understanding and action. In: Kijne J, Barker R, Molden D (eds.) Water productivity in agriculture: limits and opportunities for improvement. CABI publishing and International Water Management Institute

Monteith JL (1965) Evaporation and the environment. In: Fogg GE (ed) The state and movement of water in living organisms, Cambridge university press, pp 205–234

Monteith JL (1981) Evaporation and surface temperature. Quart J Royal Soc 107:1–27

Mualem Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour Res 12:513–522

Singh R, Van dam JC, Jhorar RK (2003) Water and salt balances at farmer fields. In: Van Dam JC, Malik RS (eds.) Water productivity of irrigated crops in Sirsa district, India. Integration of remote sensing, crop and soil models and geographical information systems. WATPRO final report, including CD-ROM. ISBN 90–6464–864–6, pp 41–58

Smith M (1992) CROPWAT, a computer programe for irrigation planning and management. Irrigation and drainage paper 46, FAO, Rome, Italy

Spitters CJT, Van Keulen H, Van kraalingen DWG (1989) A simple and universal crop growth simulator: SUCROS87. In: Rabbinge R, Ward SA, Van laar HH (eds) Simulation and systems management in crop protection. Simulation monographs, Pudoc, Wageningen, the Netherlands, pp 147–181

Supit I, Hooyer AA, Van deepen CA (1994) System description of the WOFOST 6.0 crop simulation model implemented in CGMS. Vol 1: theory and algorithms. EUR publication 15956, Agriculture series, Luxembourg, pp 146

Tietje O, Tapkenhinrichs M (1993) Evaluation of pseudo-transfer functions. Soil Sci Soc Am J 57:1088–1095

Tuong TP, Bouman BAM (2003) Rice production in water-scarce environments. In Kijne J, Barker R, Molden D (2003) Water productivity in agriculture: Limits and opportunities for improvement. Comprehensive assessment of water management of agriculture, series number 1, International Water Management Institute and CABI publication, UK, pp 352

Van Dam JC (2000) Field-scale water flow and solute transport. SWAP model concepts, parameter estimation, and case studies. Dissertation, Wageningen University, Wageningen, The Netherlands

Van Dam JC, Malik RS (2003) Water productivity of irrigated crops in Sirsa district, India. Integration of remote sensing, crop and soil models and geographical information systems. WATPRO final report, including CD-ROM. ISBN 90–6464–864–6

Van Dam JC, Huygen J, Wesseling JG, Feddes RA, Kabat P, Van Walsum PEV, Groenendijk P, Van Diepen CA (1997) Technical Document 45. Theory of SWAP version 2.0. Wageningen Agriculture University and DLO Winand Staring Centre, The Netherlands

Van Genuchten MTh (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898

Zwart J, Bastiaanssen WGM (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric Water Manag 69:115–133