Simulation of Moisture Dynamics of the Soil Profile of a Maize Crop under Deficit Irrigation Scheduling

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ABSTRACT

An understanding of moisture dynamics of the soil profile of a crop under different water regimes is important in determining the optimum deficit irrigation scheduling practice for the crop in an area. Such understanding is necessary in order to know when to irrigate, what extent of deficit should be allowed, and at what growth stage of the crop should deficit irrigation be allowed. A model which can simulate the moisture dynamics of the plant root zone is a valuable tool. In this paper, the water balance unit of the crop growth cum irrigation scheduling model named Irrigation scheduling Impact Assessment Model (ISIAMod) was used to simulate the moisture dynamics of the soil profile layers of a maize crop grown under deficit irrigation scheduling in Mkoji sub-catchment in Tanzania during the 2004 irrigation season. The soil moisture contents of the different layers of a one-metre soil profile depth simulated by the model agreed fairly well with field measured data. The simulated average soil moisture contents of the effective root zone depth also agreed well with field measured data. Both the simulated and field-measured moisture contents suggest that the crop extracted moisture effectively from the 0-400 mm soil depth when the crop was irrigated at 7 days interval throughout the crop growing season. However, when irrigation event is skipped after every other irrigation, the changes in soil moisture contents suggest that crop extended its moisture extracted region beyond the 400 mm depth up to the 700 mm depth. Changes in soil moisture contents were not noticed beyond the 700 mm soil profile depth, which suggest that the effective root zone depth of the crop did not exceed 700 mm depth.

Keywords: Simulation model, deficit irrigation, maize crop, soil moisture content, effective rooting depth.

1. INTRODUCTION

A phenomenon that characterizes many river basins especially in sub-Saharan Africa is conflict over water. Irrigated agriculture, the largest water user in any watershed (Carruthers *et al*., 1997) is under pressure to maximize crop production with minimum water utilization so as to release water for other sectors that depend on the water in river basins (Sarwar and Perry, 2002). Regulated deficit irrigation scheduling practice is one way in which irrigation farmers can cope with this pressure. Deficit irrigation scheduling practice is the technique of withholding or skipping irrigation, or reducing the amount of water applied per irrigation at some stages of the crop growth with the aim of saving water, labour, and in some cases energy. This practice does lead to some degree of moisture stress on the crop and reduction in crop yield (Smith *et al*., 2002). However, when the moisture stress is not severe, the adverse effect on crop yield is minimal and there can be an appreciable increase in crop water use efficiency especially when there is reduction in water losses due to evaporation, deep percolation and runoff (Bucks *et al*., 1990; Liu *et al*., 1998, Panda *et al*., 2004).

In order to determine optimum deficit irrigation scheduling practice for a crop in an area there is a need for an understanding of the moisture dynamics of the soil profile of the crop under different water regimes. Such understanding is necessary in order to know when to irrigate, what extent of deficit should be allowed, and at what growth stage of the crop should the irrigation deficit be allowed. Monitoring the temporal and spatial movement of soil moisture within the soil profile of an irrigated crop field is tedious, time and labour demanding. However, application of computer-based simulation models to simulate moisture movement within the soil profile is a good alternative to physical monitoring of soil moisture content. It helps to reduce the drudgery of soil sampling or in-situ measurements and laboratory determination of soil moisture content, thus facilitating planning of irrigation scheduling. The application of simulation models to study the water dynamics in agricultural fields has been in practice for over three decades (Nimah and Hanks, 1973; Belmans *et al*., 1983; Droogers *et al*., 2000; Zhang *et al*., 2004). De Faria and Madramootoo (1996) developed and applied a soil moisture model to simulate soil moisture profiles for wheat in Brazil, while Antonopoulos (1997) used a mathematical model to study moisture dynamics of irrigated cotton in semi-arid climates in Central and North Greece. Probert *et al*. (1998) used the Agricultural Production Systems Simulator's (APSIM) water and nitrogen modules to simulate the dynamics of water and nitrogen in fallow systems in Queensland; while Kang *et al*. (2001) developed and used a simulation model to study water dynamics in winter wheat field in semiarid Northwest China.

This paper presents the simulation of moisture movement in the soil profile layers of an irrigated maize crop under deficit irrigation scheduling using the soil water balance unit of a crop growth cum irrigation scheduling model named Irrigation Scheduling Impact Assessment Model (ISIAMod).

2. MATERIALS AND METHODS

2.1 The Study Area

Field experiments were conducted during the 2004 dry season at Igurusi ya Zamani Traditional Irrigation Scheme (IZTIS) in Mkoji sub-catchment of the Great Ruaha River in Tanzania. The Great Ruaha River is one of the sub-catchments of the Rufiji River Basin. The IZTIS lies at latitude 8.33° South, and longitude 33.53° East, at an altitude of 1100 m to 1120 m above sea level. The area has a unimodal type of rainfall between November and April. The mean annual rainfall in the study area is about 800 mm. Mean daily maximum temperatures range from 28°C to 32°C, while minimum temperatures range from 9.5°C to 19.5°C, respectively. The highest values are recorded in October and November while the lowest values are experienced in June and July. The mean daily net solar radiation varies from 7.5 MJ/m^2/day to 12.3 MJ/m^2/day. The average annual open pan evaporation is about 2430 mm, and the total open pan evaporation from June to October when dry season farming takes place is about 1080 mm Detailed description of the climate of the Mkoji sub-catchment has been reported by SWMRG-FAO (2003).

2.2 Field Experimentation

Three field experiments were run concurrently during the 2004 season for the purpose of generating data to parameterize, calibrate and validate ISIAMod. The details of the field experimentation have been reported in Igbadun *et al*. (2006). This paper focuses on soil moisture dynamics of one of the field experiments. Table 1 shows the soil physical properties of the field. The description of the experimental treatments is shown in Table 2. The experimental treatment variable was the frequency of irrigation. The variation in experimental treatments was created by skipping irrigation every other week at one or more growth stages of the crop. Table 3 shows the irrigation scheduling including the depth of water applied per irrigation. The treatment variation approach was similar to Pandey *et al*. (2000). The details of the agronomic practices and the method of measuring irrigation water application depths been reported by Igbadun *et al.* (2006). Planting was done on the flat in levelled basins on 24th June, 2004. Fertilizer was applied at the rate of 120 kg N/ha and 60 kg P/ha as recommended for the maize crop in the study area by the Agricultural Research Institute, Uyole, Mbeya Region. Surface irrigation method was used to deliver water to the crops. An average discharge of 4 l/s was allowed to flow into one basin at a time. With the aid of a calculator and a stopwatch, the time required to apply the desired depth of water was immediately calculated as soon as water was introduced into the plot.

2.2.1 Soil Moisture Content Measurement

Soil moisture content was monitored throughout the crop-growing season with an ML1 Theta Probe (*Delta-T Devices, Cambridge*). Soil moisture content measurements were carried out two days after irrigation and on the day of the next irrigation in the treatments. When irrigation was skipped in any treatment, soil moisture content was still measured in-between successive irrigation events at 7 and 9 days after irrigation. Soil moisture content was monitored in a one-metre profile depth. The profile was divided into four layers consisting of 0-150, 150-400, 400-700, and 700-1000 mm depths. Soil moisture content measurements were carried out by inserting the sensing head of the Theta probe into the soil, through vertically installed PVC pipes which served as access to reaching the desired soil profile depth. The depths of insertion were 80, 250, 550, and 800 mm below the soil surface and measurement made at those depths were taken to represent soil profile layers 0-150, 150-400, 400-700, and 700-1000 mm depths, respectively.

2.2.2 Computation of Average Crop Actual Evapotranspiration

The average crop actual evapotranspiration (mm/day) between two successive soil moisture content sampling was calculated using the soil moisture depletion studies method (Michael, 1978). The expression was given as:

Table 1: Soil physical properties of the experimental site

Soil profile depth (mm)	Moisture content at field capacity (m^3/m^3)	Moisture content at wilting point (m^3/m^3)	Moisture content at planting (m^3/m^3)	Soil bulk Density (g/cm^3)	Clay %	Silt %	Sand %	Soil Textural Class
0-150	0.262	0.127	0.214	1.44	19	18	64	Sand loam
150-400	0.295	0.163	0.225	1.39	31	17	52	Sand clay loam
400-700	0.305	0.226	0.252	1.45	33	22	45	Sand clay loam
700-1000	0.278	0.212	0.245	1.38	36	19	45	Sandy clay

Table 2: Description of the experimental treatments

Treatment No	Description
1 (TR_{1111*})	Irrigated weekly without skipping irrigation at any crop growth stage. (Reference treatment).
2 (TR_{1011})	Irrigation was skipped every other week at vegetative stage only. Weekly irrigation was observed at flowering and grain filling growth stages.
3 (TR_{1101})	Irrigation was skipped every other week at flowering stage only. Weekly irrigation was observed at vegetative and grain filling growth stage.
4 (TR_{1110})	Irrigation was skipped every other week at grain filling stage only. Weekly irrigation was observed at vegetative and flowering growth stages.
5 (TR_{1001})	Irrigation was skipped every other week at vegetative and flowering stages. Weekly irrigation was observed only at grain filling growth stage.
6 (TR_{1010})	Irrigation was skipped every other week at vegetative and grain filling stages. Weekly irrigation was observed only at flowering growth stage.
7 (TR_{1100})	Irrigation was skipped every other week at flowering and grain filling stages. Weekly irrigation was observed only at vegetative growth stage.
8 (TR_{1000})	Irrigation was skipped every other week at vegetative flowering and grain filling stages.

* The subscripts represent the growth stages: 1= weekly irrigation at the growth stage and 0 = irrigation was skipped every other week at the stage.

Table 3: Irrigation scheduling

Growth stage	Crop establishment			Vegetative						Flowering				Grain filling				Total No of irrigation events	Total water applied (mm)
Week of irrigation	0*	1	2**	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
Treatment label	Water application depth per irrigation (mm)																		
1	30	30	30	30	30	40	40	40	40	50	50	50	50	50	50	50	40	17	700
2	30	30	30	30	X	40	X	40	X	50	50	50	50	50	50	50	40	14	590
3	30	30	30	30	30	40	40	40	40	50	X	50	X	50	50	50	40	15	600
4	30	30	30	30	30	40	40	40	40	50	50	50	50	50	X	50	X	15	610
5	30	30	30	30	X	40	X	40	X	50	X	50	X	50	50	50	40	12	490
6	30	30	30	30	X	40	X	40	X	50	50	50	50	50	X	50	X	13	500
7	30	30	30	30	30	40	40	40	40	50	X	50	X	50	X	50	X	13	510
8	30	30	30	30	X	40	X	40	X	50	X	50	X	50	X	50	X	10	400

* Pre-planting irrigation
** The number of days between successive irrigation was 12 (the interval of irrigation was extended due to conflict of water)
X irrigation skipped

$$AET = \frac{\sum_{i=1}^{n}\left(VMC_{1i} - VMC_{2i}\right) * D_i}{t} \qquad (1)$$

Where: AET = Average daily evapotranspiration between successive soil moisture content sampling (mm/day).

VMC_{1i} = Volumetric soil moisture content (m^3/m^3) at the time of first sampling in the i^{th} soil layer.

VMC_{2i} = Volumetric soil moisture content (m^3/m^3) at the time of second sampling in the i^{th} soil layer.

D_i = Depth of i^{th} soil layer (mm).

n = Number of soil layers sampled in the root zone depth D.

t = Number of days between successive soil moisture content sampling.

The crop consumptive use for a week was therefore the product of the daily crop consumptive use from successive soil moisture content sampling and the number of days in the week. The total crop consumptive use for the entire crop-growing season (seasonal evapotranspiration) was therefore the summation of the weekly crop water use for the entire crop growing season.

2.2.3 Computation of Seasonal Deep Percolation

The seasonal deep percolation was computed from Eq.1 re-arranged as:

$$DP = (I + R) - (Rf + ET \ IntL \pm \Delta S) \quad (2)$$

There was no rainfall throughout the period of the experiment. Therefore the R and IntL components of Eq. 2 were nil. There was also no runoff (Rf) since basin irrigation was used. The basin bunds were well-built so that there was no spill over of water applied. Consequently, the seasonal deep percolation was computed as the difference between total seasonal water applied and the sum of seasonal evapotranspiration and the difference between the residual soil moisture content at the beginning and the end of the season.

2.3 The Model Development

The Irrigation Scheduling Impact Assessment Model (ISIAMod) was developed by Igbadun (2006) to simulate crop growth process, soil water balance of a cropped field, and water management response indices (WMRI).The WMRI is a set of indicators which explains the impact of water management strategy on the crop and its environment. These indicators include water accounting indices, crop water productivity indices, and seasonal relative deficits or losses. ISIAMod runs on daily time-step, from crop planting date to crop physiological maturity date. The input data required by the model are classified into: climate, soil, crop, rainfall, and irrigation scheduling decisions. The minimum weather data required are daily maximum and minimum ambient temperatures for the duration of crop growth. Other weather parameters which are optional include daily records of wind speed, maximum and minimum relative humidity, sunshine hour and net solar radiation. The soil input data include volumetric soil moisture content at field capacity and at wilting point, initial soil moisture contents, bulk density, and the percentage of sand in the soil texture. The crop input data include maximum rooting depth, maximum leaf area index, potential (non-water limited) harvest index, radiation use efficiency (RUE), radiation extinction coefficient, and peak crop water use coefficient (K_c). Others include: crop base and optimum temperatures; leaf area index shape factors; water-limited harvest index adjustment factors; crop planting, emergence, and physiological maturity dates; days from planting for the start of each of the four crop growth stages, and fraction of the crop growth duration at which leaf area index begins to decline. The model has been calibrated and validated for a maize crop (TMV1-ST) for Mkoji sub-catchment of the Great Ruaha River basin in Tanzania (Igbadun, 2006). In this paper, the detail of the soil water balance unit of the ISIAMod model used in the simulation of the soil moisture dynamics of the maize field is presented.

2.3.1 The Soil Water Balance Unit in ISIAMod

The soil water balance unit in ISIAMod is based on the principles of soil water budget, expressed as:

$$I + R = Rf + ET + IntL + DP \pm \Delta S \quad (3)$$

Where I is irrigation depth; R is rainfall depth; ET is evapotranspiration (a combination of evaporation and transpiration); Rf is seasonal runoff; IntL is precipitation intercepted by the crop canopy; DP is deep percolation depth, and ΔS is the difference between soil moisture content at the beginning and the end of the season.

ISIAMod assumed irrigation and rainfall as the only sources of water input to the cropped field. Through the process of evaporation, water is removed from the uppermost soil layer of the cropped field. The depth of soil from which evaporation takes place does not exceed 100 mm. Through the process of transpiration water is removed from the crop root zone depth which increases with rooting depth. Soil water is usually held in an unsaturated state within the crop root zone for crop use. Soil moisture beyond the potential at which water can be held in the plant root zone is drained out of the zone via the process of deep percolation. The model assumes a one-dimension vertical movement of water in the soil profile. It assumes that the soil has a high hydraulic conductivity, with no drainage impediment. Therefore, there is no temporary storage of water in excess of field capacity beyond two days. It also assumes a soil with a deep water table, and consequently no significant contribution from groundwater to the plant root zone.

The atmospheric evaporative demand is assumed to be the driving force of the soil water balance. In response to the evaporative demand, plant root remove water from the soil and this water is translocated through the plant tissues and escapes through the leaves of the plants. So the water balance program of ISIAMod starts with the quantification of the evaporative demand exerted upon the crop. It partitions the potential evaporative demand (referred to as potential or maximum evapotranspiration) into potential evaporation and transpiration. If the root zone layers have sufficient moisture to meet the potential evaporative demand, water is removed from the layers at a rate which equals the potential demand. Otherwise, water is removed at a rate that is a function of the available water in the soil, and at such instance the potential evaporative demand will not be met and the crop could be subjected to moisture stress.

2.3.2 Potential Evapotranspiration Partitioning

The reference evapotranspiration (ET_o) is first computed based on FAO-Penman-Monteith (Allen et al., 1998) by the model using the weather input data. Then the ET_o is converted to crop maximum evapotranspiration (ET_c) using a factor (K_c), expressed as (Stockle and Nelson, 1996):

$$ET_c = K_c * ET_o \quad (4)$$

K_c factor is defined as (Stockle and Nelson, 1996):

$$K_c = 1 + (Kc' - 1) * \frac{LAI}{3} \qquad if \; Kc' > 1 \; and \; LAI < 3 \quad (5)$$

$$K_c = Kc' \qquad \text{Otherwise} \quad (6)$$

$$if = Kc' < 1 \; then \; K_c = Kc'$$

Where Kc' is peak crop coefficient, which is a crop input parameter; LAI is leaf area index with a maximum value of three for the reference crop (Stockle and Nelson, 1996).

The maximum evapotranspiration is partitioned to potential evaporation and potential transpiration using the fractional solar radiation interception factor. The partitions are expressed as:

$$E_p = (1 - FI) * ET_c \quad (7)$$

$$T_p = ET_c - E_p \quad (8)$$

Where E_p is potential evaporation from the cropped soil surface; T_p is potential transpiration; FI is fractional solar radiation interception factor, and ET_c is the crop maximum evapotranspiration.

De Faria and Madramootoo (1996) (citing Tanner (1957) and Hanks *et al.* (1971)) reported that when the soil surface layers of a cropped field become dry and the potential soil evaporation cannot be met, sensible heat originate from between crop rows and is partially or totally transferred to the crop canopy, which increases the potential transpiration. The sensible energy (H) transfer is expressed as (de Faria and Madramootoo, 1996):

$$H = (ET_c - E_p) * St \quad (9)$$

Where:

$$St = 1 \; for \; LAI \geq 1.5 \quad (10)$$

$$St = 0.67 * LAI \; for \; LAI < 1.5 \quad (11)$$

Therefore, the potential transpiration expression (Eq.8) can be modified and expressed as (de Faria and Madramootoo, 1996):

$$T_p = ET_c - E_p + H \quad (12)$$

2.3.3 Solar Radiation Interception Factor

The fractional radiation interception factor was expressed as (Yang *et al.*, 2004):

$$FI = [1 - EXP(-REXF * LAI)] \quad (13)$$

Where FI is fractional radiation interception coefficient by the crop canopy; REXF is radiation extinction coefficient, and LAI is leaf area index. REXF was taken as 0.55 for the maize crop (Yang *et al.*, 2004).

2.3.4 Actual Evaporation

The actual evaporation from the soil surface of a cropped area was assumed to occur in two phases. The first phase occurs when the soil is wetted by irrigation or rainfall. Evaporation occurs first at potential rate, and subsequently as a function of the soil moisture content. ISIAMod expressed the rate of evaporation as:

$$E_a = E_p \qquad \text{if } \theta \geq \theta_{fc} \qquad (14)$$

$$E_a = E_p * \frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}} \qquad \text{Otherwise} \qquad (15)$$

The second phase of evaporation sets in when the soil moisture content of the evaporation layer reaches the wilting point. The second phase of evaporation is expressed as (Campbell and Daiz, 1988):

$$E_a = E_p * \left[\frac{\theta - \theta_{adwc}}{\theta_{pwp} - \theta_{adwc}} \right]^2 \qquad (16)$$

Where E_a is actual evaporation from the cropped soil surface; E_p is potential evaporation from the cropped surface; θ is moisture content of the soil; θ_{fc} is moisture content of the soil at field capacity, θ_{pwp} is moisture content of the soil at wilting point, and θ_{adwc} is air-dry soil moisture content, given as one-third of moisture content wilting point (Stockle and Nelson, 1996).

2.3.5 Crop Actual Transpiration

The actual transpiration (root water uptake) module of ISIAMod was based on Plauborg *et al.* (1996) transpiration function given as:

$$T_a = T_p \qquad \text{if } \theta \geq \theta_{fc} \qquad (17)$$

$$T_a = 0.0 \qquad \text{if } \theta \leq \theta_{pwp} \qquad (18)$$

$$T_a = T_p * \left[1 - \left(\frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}} \right)^{\frac{CT}{T_p}} \right] \qquad \text{Otherwise} \qquad (19)$$

Where Ta is actual transpiration; T_p is potential transpiration, and CT is an empirical soil dependent constant of a range of 10 to 12 mm/day (Plauborg *et al*., 1996). The other terms are as previously defined.

2.3.6 Leaf Area Index

The potential (non water-limited) leaf area index function from crop emergence to start of leaf area index decline was expressed as (Igbadun, 2006):

$$PLAI_i = \frac{LAI_{\max}}{\{1 + a * EXP(-b * D_i)\}} \tag{20}$$

Where $PLAI_i$ is potential leaf area index on day i; LAI_{max} is maximum leaf area index, which is a crop parameter, 'a' and 'b' are crop coefficients, and D_i is fraction of the crop growth duration $[0 \leq D_i \leq 1]$.

The fraction of the crop growth duration is given as:

$$D_i = \frac{i - i_{pld}}{i_{mtd} - i_{pld}} \tag{21}$$

Where 'i' is day of the year from planting; i_{pld} is the day of the year of planting, and i_{mtd} is the day of the year of crop maturity.

Equation 20 is a growth function, and was assumed to hold under non water-limiting condition. Therefore, the daily increment in leaf area index was adjusted to actual by multiplying the potential daily increment by the water stress factor (WSF_{GLF}). The actual daily increment in leaf area index is given as:

$$\Delta LAI_i = (PLAI_i - PLAI_{i-1}) * (WSF_{GLF})^{0.5} \tag{22}$$

Therefore, actual leaf area index on day 'i' is given as:

$$LAI_i = LAI_{i-1} + \Delta LAI_i \tag{23}$$

The leaf area index from the start of decline to end of the crop growing season under non-water limiting condition was expressed as (Igbadun, 2006):

$$DPLAI_i = LAI_o * \left\{\frac{(1.01 - D_i)}{(1.01 - D_0)}\right\}^{\beta} \tag{24}$$

Where $DPLAI_i$ is declining leaf area index on day 'i' not affected by moisture stress; LAI_o is leaf area index on the day leaf area index decline started, D_o is fraction of growth duration at which leaf area index decline started, and D_i is as previously defined.

Leaf area index decline was assumed to be accelerated by soil moisture stress. Therefore, the actual leaf area index on day 'i' during the decline stage was expressed as:

$$LAI_i = DPLAI_i * (WSF_{GLF})^{0.5} \quad (25)$$

2.3.7 Water Stress Factor

The water stress growth-limiting factor (WSF_{GLF}) is expressed as the ratio of actual transpiration (T_a) to the potential transpiration (T_p):

$$WSF_{GLF} = \frac{T_a}{T_p} \quad (26)$$

2.3.8 Root Depth

The potential (unrestricted and non water-limited) root depth is given as (Campbell and Daiz, 1988):

$$PRD_i = \frac{RD_{max}}{1 + 442 * EXP(-8.5 * D_i)} \quad (27)$$

Where PRD_i is potential rooting depth on day i; RD_{max} is crop parameter maximum rooting depth.

Since root development us inhibited by factors such as high bulk density, water stress, high water table, low fertility, soil temperature (Sharpely and Williams, 1990), the potential rooting depth was adjusted to actual rooting depth considering two limiting factors: a soil strength factor (SS_{GLF}) (as described by Sharpley and Williams, 1990), and the water stress factor, WSF_{GLF} which is a function of the available soil moisture content. Any of the two factors dominant at any time was assumed to limit rooting depth.

The daily increment in rooting depth as influenced by the root-growth limiting factor is expressed in ISIAMod as:

$$\Delta RD_i = (PRD_i - PRD_{i-1}) * (RD_{GLF})^{0.5} \quad (28)$$

Therefore, $$RD_i = RD_{i-1} + \Delta RD_i \quad (29)$$

Where ΔRD_i is daily increase in rooting depth; RD_{GLF} is dominant factor which limits rooting depth on a given day (either WSF_{GLF} or SS_{GLF}), and RD_i is rooting depth on day i.

2.3.9 Root Density

The root density module of ISIAMod was based on (Campbell and Daiz, 1988) function. It assumes that crop root decreases linearly with depth, with a maximum at the top of the soil and a value of zero at the tip of the current rooting depth**.** Therefore the root density is determined as a root length fraction.

If Z_l is the soil profile depth to the bottom of soil layer *l*:

$$FR_l = \Delta Z_l * \frac{2 * (RD - Z_l) + \Delta Z_l}{RD^2} \qquad if \; Z_l \le RD \qquad (30)$$

$$FR_l = \left[\frac{RD - (Z_l + \Delta Z_l)}{RD} \right]^2 \qquad if \; Z_l - \Delta Z_l < RD < Z_l \qquad (31)$$

Where FR_l is fractional root density in layer *l*; RD is rooting depth, and ΔZ_l is incremental depth in the soil profile**.**

The depth of water removed from a soil layer by transpiration is a function of the fractional root density in the layer *l* expressed as (Campbell and Daiz, 1988):

$$T_{al} * T_a * FR_l \qquad (32)$$

Where T_a is total amount of water removed by transpiration, T_{al} is amount removed from soil layer *l*.

2.3.10 Soil Water Distribution within the Soil Layers and Deep Percolation Estimation

The infiltration/distribution of water applied to the cropped field and deep percolation in ISIAMod was based on the "tipping bucket" method (Zhang *et al.,* 2004). CropSyst called it the cascading method (Stockle and Nelson, 1996). The entire soil profile is assumed to be made up of stratified layers which may differ in properties. Therefore the model requires that the soil profile be divided into a number of layers and the each layer into compartments. The minimum number of layers allowed for by the model is 4 while the maximum number is 10. The number of layers considered in a simulation is to be specified by the user as part of the soil input data. Each layer, with the exception of the first topmost layer, can be subdivided into any number of compartments, but the total compartments in the entire soil profile cannot exceed 60. Each compartment in a layer assumes the soil properties of the layers. The depth of the topmost profile layer is restricted to 20 cm thick, and the layer can only be divided into two compartments. The top of the two compartments of the first layer constitutes the evaporation zone. The active root zone starts from the second compartment of the first layer. Each compartment is assumed to be filled with water to field capacity after irrigation or heavy rainfall, and then passes on any remaining water to the compartment below. Any water which passes beyond the bottom layer of the profile depth is assumed lost to deep percolation. No upward movement of water in the profile is allowed.

2.4 Model Performance Evaluation Procedure

The soil water balance unit in ISIAMod is an integral part of the entire model. In order to use the soil water balance unit of the model to simulate soil water dynamics for a given crop, the weather, soil, and crop input data are required. To simulate the soil water dynamics of a crop grown under irrigation, the irrigation input data is also required.

The weather input data used in simulating the soil water dynamics of the maize crop reported herein include daily maximum and minimum air temperature, and wind speed. These data were used by the model to compute daily reference evapotranspiration based on the FAO-Penman-Monteith model (Allen *et al*., 1998). The soil input data include volumetric soil moisture content at field capacity and at wilting point, initial soil moisture contents, bulk density, and the percentage of sand in the soil texture. These data are required for each soil profile layer. The soil input data used in the simulation were those of Table 1, while the irrigation scheduling input data were those of Table 3. The crop input data used in the simulation are presented in Table 4.

Table 4: Crop input data used in model simulation

Input data	Calibrated values	Source of initial values	Remark*
Maximum rooting depth (RD_{max})	1.2 m		C
Radiation extinction coefficient (REXF)	0.55	Yang *et al*. (2004)	C
Maximum leaf area index (LAI_{max})	0.35 m^2/m^2	Idinoba *et al.* (2002)	C
Peak crop coefficient (Kc')	1.2	Allen *et al*. (1998)	
Planting date	24/06/2004		
Emergence date	02/07/2004		
Maturity date	28/10/2004		
Days after planting at which establishment growth stage starts	0	Field experiment	
Days after planting at which vegetative growth stage starts	23	Field experiment	
Days after planting at which flowering growth stage starts	64	Field experiment	
Days after planting at which maturity growth stage starts	93	Field experiment	
Fraction of the growth duration at which leaf area index started to decline (D_o)	0.75	Field experiment	
Soil dependent transpiration constant (CT)	0.018 m/day	Plauborg *et al.* (1996)	C

***** C= initial values either taken from literature or computed from field data and confirmed through calibration

Qualitative and quantitative methods were used to compare the model-simulated and field-measured soil moisture content data. The qualitative comparison was by plotting the volumetric soil moisture content-time (crop age from date of planting) graphs of the model simulated and field measured data for each of the soil profile layers. The quantitative comparison of the simulated and measured data was by using the following statistical tests given by Mahdian and Gallichard (1995) and Panda *et al*. (2004):

$$Average\ Error\ of\ Bias\ (AE) = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \qquad (33)$$

$$Coefficient\ of\ Variation\ (CV) = 100 * \frac{\left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5}}{O_m} \qquad (34)$$

$$Root\ Mean\ Square\ Error\ (RMSE) = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5} \qquad (35)$$

$$Modelling\ Efficiency\ (EF) = \frac{\left[\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}(P_i - O_i)^2\right]}{\sum_{i=1}^{n}(P_i - O_i)^2} \qquad (36)$$

$$Coefficient\ of\ Residual\ Mass\ (CRM) = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i} \qquad (37)$$

Where P_i is simulated values; O_i is measured values; O_m is mean of measured values, and n is number of observations.

The AE is a measure of bias between the simulated and measured data. The CV is a measure of variability while the RMSE is a measure of precision. The modelling efficiency (EF) which is also referred to as the coefficient of Nash-Sutcliffe (Mahdian and Gallichard, 1995) is a measure of the degree of fit between simulated and measured data. It is similar to the coefficient of determination (r^2). EF varies from $-\infty$ for total lack of fit to 1 for an exact fitting (Mahdian and Gallichard, 1995). CRM is an indicator of the tendency of the model to either over- or under-predict measured values. A positive value of CRM indicates a tendency of underestimation, while a negative value indicates a tendency of overestimation (Antonopoulos, 1997).

3. RESULTS AND DISCUSSION

3.1 Reference Evapotranspiration

Figure 1 shows the daily reference evapotranspiration (ETo) (mm/day) for the 2004 season, from the day of year of planting to crop maturity. The daily ETo for the cropping season ranged between 3.57 and 6.06 mm/day. The average daily ETo was less than 5 mm/day between end of June (DOY 173) when the crop was planted and about end of August (DOY 240). Temperatures during this period of the year are usually low, with average maximum and minimum temperatures of 27 ^{o}C and 11 ^{o}C, respectively.

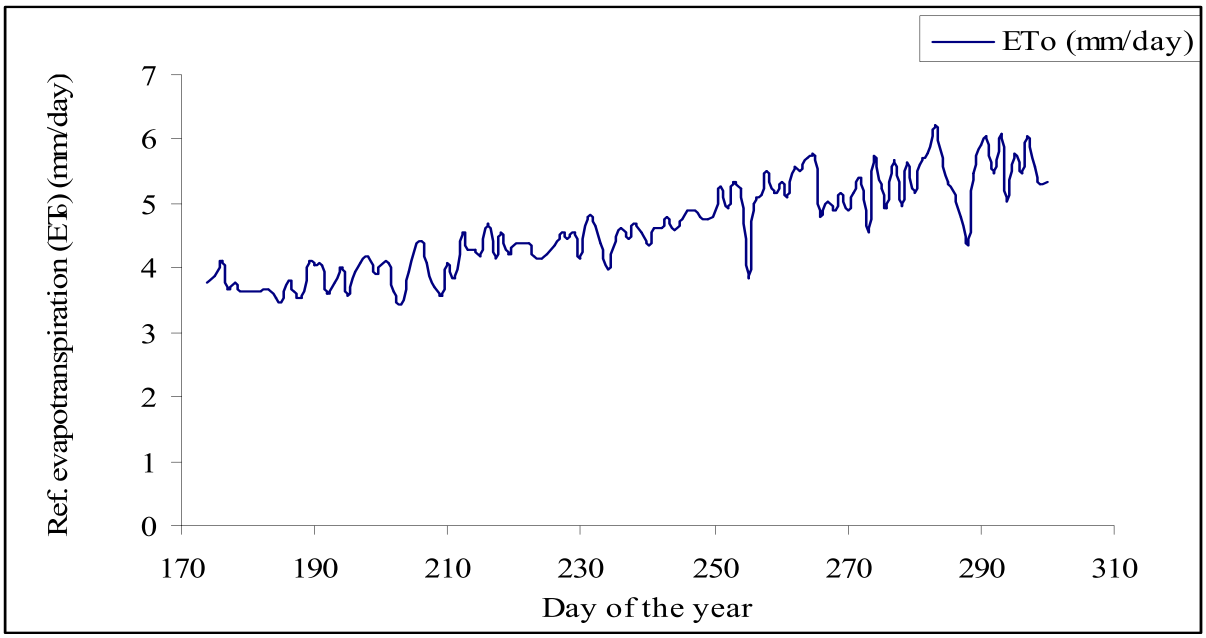

Figure 1: Daily reference evapotranspiration (ETo) (mm/day) for the study area in the 2004 season

3.2 Comparison of Model-simulated and Field-measured Soil Moisture Contents

The graphical comparisons of the simulated and measured soil moisture contents for the four profile layers of each of the 8 treatments are shown in Figures A1.1 (a-d) to A1.8 (a-d) in Appendix 1. The trends of the graphs show that there was generally a close agreement between the simulated and measured volumetric soil moisture contents in the profile layers. The amplitudes of the first two profile layers were noticed to be higher than for the lower layers in all the treatments. This implies that between the times of successive irrigations, there was more moisture extraction within the two upper layers compared to the lower layers. The reasons for this are not far-fetched. Firstly, water was being removed from the uppermost layer at a faster rate because of evaporation from soil surface and transpiration from the growing plants. Secondly, it is a common characteristic of plant root distribution to have a higher percentage concentrated at the upper portion of the soil profile (Ley *et al*., 1994). According to Ley *et al*. (1994), 70-80 % of a crop water uptake will be from the top half of the rooting depth if the crop is under high frequency irrigation such as with centre pivot sprinkler irrigation.

In Treatment 1 (TR_{1111}) where the crop was irrigated weekly, moisture extraction appeared to have taken place effectively within the 0-400 mm depth throughout the crop growing season. This is shown by the difference in soil moisture content between successive irrigation events. There was little or on changes in soil moisture contents from the soil layers below the 400 mm before the next irrigation which implied that there was little or no moisture extraction in the layers. The reason for this may be that since the treatment was regularly irrigated, the crop moisture uptake requirement was being satisfied within the 400 mm depth. Therefore a greater percentage of the root density may have been concentrated within the profile depth, and hence moisture extraction below this depth was minimal. This finding agrees with Panda *et al*. (2004) who observed that irrigated maize plants extracted most of the soil moisture from the 0-450 mm soil layer in an experiment they conducted in Kharagpur, India. They recommended that only the 0-450 mm soil layer be considered for scheduling of irrigation in case of maize grown in sandy loam soil in the sub-tropical regions.

In Treatments 2 to 8 where weekly irrigations were being skipped after every other week in one or more growth stages, there was moisture depletion from the profile layer below the 400 mm depth during the growth stages when irrigation events were being skipped. This suggests that the crop extended its rooting density into the lower profile depth to be able to extract water to meet uptake demand. It was however noticed that water applied during irrigation in those treatments was only sufficient to raise the soil moisture contents of the upper soil layers to field capacity. The soil moisture of the lower layers was not replenished. As a result a downward trend in the soil moisture content was notice in those treatments at such growth stages until weekly irrigation event resumed. However, even for the treatments where irrigations were skipped, there was little or no moisture extraction from the soil below the 700 mm depth. This implies that the effective rooting depth of the crop did not exceed the 700 mm depth. This result also agrees with different studies which reported that rooting activity of maize under irrigation is usually concentrated in the top 600 mm depth of the soil (Dardenelli *et al*., 1997; Otegui *et al*., 1995) with little water depleted below 1000 mm (Gordon *et al*., 1995).

3.3 Average Soil Moisture Content of the Effective Root Zone Depth

In practical irrigation scheduling, information on the soil moisture content of the effective rooting depth of the crop is more important than that of the individual layers the soil profile has been divided into. Therefore, the model was used to simulate the average soil moisture content of the seasonal effective root zone depth of the crop. The seasonal effective root zone depth was considered as the soil profile layers that appeared to have significantly contributed to the crop consumptive use for the season (i.e., layers where there was appreciable change in soil moisture content between successive irrigations throughout the crop growing season). Table 5 shows the average simulated and field-measured soil moisture content of the effective root zone depth for the eight treatments for some selected days in the crop growing season.

Table 5: Volumetric soil moisture content of the effective root zone depth (m^3/m^3)

	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
DAP	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
14	0.286	0.286	0.286	0.274	0.286	0.286	0.286	0.289
44	0.257	0.252	0.258	0.257	0.257	0.257	0.257	0.255
51	0.245	0.248	0.226	0.212	0.245	0.247	0.245	0.247
72	0.233	0.238	0.230	0.210	0.233	0.243	0.233	0.237
86	0.229	0.229	0.228	0.227	0.216	0.221	0.229	0.233
114	0.232	0.242	0.229	0.227	0.228	0.243	0.209	0.219

Table 5 continues: Volumetric soil moisture content of the effective root zone depth (m^3/m^3)

	Treatment 5		Treatment 6		Treatment 7		Treatment 8	
DAP	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
14	0.286	0.286	0.286	0.283	0.286	0.282	0.286	0.282
44	0.258	0.260	0.258	0.257	0.257	0.255	0.258	0.262
51	0.226	0.215	0.226	0.214	0.245	0.250	0.226	0.220
72	0.230	0.208	0.230	0.216	0.233	0.244	0.230	0.207
86	0.215	0.202	0.228	0.230	0.216	0.220	0.215	0.200
114	0.230	0.231	0.209	0.226	0.206	0.194	0.207	0.185

Table 6 shows the statistics of the comparison between the measured and simulated average volumetric soil moisture contents of the effective root zone depth. The average error of bias (AE) between simulated and measured data was ± 0.01 m^3/m^3. The RMSE was between 0.01 and 0.02 m^3/m^3. The modelling efficiency (EF) was good (>0.80) in most of the treatments. The average errors value obtained were very much comparable with values obtained by Clemente *et al.* (1994) when they tested the performance of three soil water flow models: SWATRE (Belmans *et al.*, 1983), LEACHW (Wagenet and Hutson, 1989, as cited by Clemente *et al.*, 1994) and SWASIM (Hayhoe and de Jong, 1982, as cited by Clemente *et al.*, 1994). They reported an average error of bias between simulated and measured field data which ranged from -0.03 to 0.04 m^3/m^3 and an RMSE ranging from 0.0083 to 0.0475 m^3/m^3 for the models. The results from this study also compare favourably with Antonopoulos (1997) who compared the performance of his one-dimensional soil moisture model based on the Galerkin finite element method in simulating soil moisture dynamics of irrigated cotton in Greece. Antonopoulos (1997) reported RMSE ranging from 9.12 to 13.03 % (0.0912 - 0.13 m^3/m^3). The modelling efficiencies ranged from 0.42 to 0.67, and CRM ranged from -0.05 to 0.02.

Table 6: Statistics of the comparison between simulated and field measured volumetric soil moisture content of the effective root zone depth

Performance indicators	Treatment							
	1	2	3	4	5	6	7	8
AE (m^3/m^3)	-0.01	0	-0.01	-0.01	0.01	0	0	0.02
RMSE (m^3/m^3)	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
CV (%)	3.51	4.71	4.49	4.23	6.12	6.23	5.30	8.23
EF	0.89	0.82	0.92	0.93	0.84	0.79	1.00	0.82
CRM	0.03	0.01	0.02	0.04	-0.05	-0.01	-0.01	-0.07

3.4 Seasonal Evapotranspiration and Deep Percolation

Table 7 shows the simulated and field-measured seasonal evapotranspiration and deep percolation. Table 8 shows the statistics of the comparison of simulated and measured evapotranspiration, and deep percolation. There was a tendency of over prediction (CRM values) of the seasonal evapotranspiration by 1%. However, the performance of the model in simulating seasonal evapotranspiration compares favourably with several models reported in literature. For example, Cavero *et al*. (2000) compared the performance of EPICphase, Modified EPICphase and CROPWAT models under maize crop and reported values of 1.51, -1.05, and 37 mm as average error of bias (AE) between simulated and measured seasonal evapotranspiration for the three models, respectively. They also obtained RMSE of 39.8, 38.6 and 69.6 mm for EPICphase, Modified EPICphase and CROPWAT, respectively. Arora and Gajri (1996) also compared the performance of three simplified water balance models under maize in a semiarid subtropical environment and reported RMSE of 30, 40, and 30 mm for the Soil-Plant-Atmosphere-Water (SPAW) model (Saxton, 1989), Water Balance Model (WBM) (Arora *et al*., 1987), and the modified WBM, respectively. The RMSE for ISIAMod for the two seasons was 9.76 mm. ISIAMod was therefore considered to have performed well in simulating seasonal evapotranspiration.

Table 7: Simulated and measured seasonal evapotranspiration and deep percolation

Treatment	Seasonal evapotranspiration (mm)		Seasonal deep percolation (mm)	
	Simulated	Measured	Simulated	Measured
1	545.7	541.12	138.6	154.6
2	501.1	486.95	65.0	97.6
3	496.4	502.56	90.0	94.4
4	501.9	504.58	126.5	97.4
5	449.8	443.72	16.5	38.5
6	460.6	446.95	51.8	55.3
7	437.6	451.58	90.0	52.1
8	394.3	385.48	16.5	15.4

Table 8: Statistics of the comparison between simulated and field measured seasonal evapotranspiration (SET) and deep percolation (DP)

Performance indicators	SET	DP
AE (mm)	3.06	-5.27
RMSE (mm)	9.76	23.04
CV (%)	2.08	28.94
EF	0.95	0.70
CRM	-0.01	0.07

Table 8 also shows that the model under-simulated deep percolation for about 7%. The modelling efficiency was about 70 %, while the coefficient of variability was about 29%. The presence of mudstones and gravels in the underlying soil profile layer below the one metre depth could have affected the flux of water below the profile depth. Hence the wide disparity between the field observed and model-simulated deep percolation. This disparity not withstanding, the model was considered to have performed fairly well in simulating deep percolation within the crop root zone.

4. CONCLUSION

The soil water balance unit of the Irrigation scheduling Impact Assessment Model (ISIAMod) was used to simulate the moisture dynamics of the soil profile layers of a maize crop grown under deficit irrigation scheduling. The model-simulated soil moisture contents for the different layers of a one-metre soil profile depth agreed fairly well with field measured data. The simulated average soil moisture contents of the effective root zone depth also agreed well with field measured data. Both the simulated and field-measured soil moisture contents suggest that the crop extracted moisture effectively from the 0-400 mm soil depth when the crop received a regular irrigation at 7 days interval. However, when the regular 7 days irrigation interval was skipped once after every other irrigation, the crop extended its moisture extracted region beyond the 400 mm depth up to 700 mm depth. The effective root zone depth of the maize crop did not exceed 750 mm depth. The assumptions made in the cause of the development of the model restricted the use of the model and the results obtained in this study to well-drained light to medium soils. The performance of this model and the soil moisture dynamics in heavy soils (clay soils) or soils with high or perched water table where water movement by capillary action is rampant need to be evaluated.

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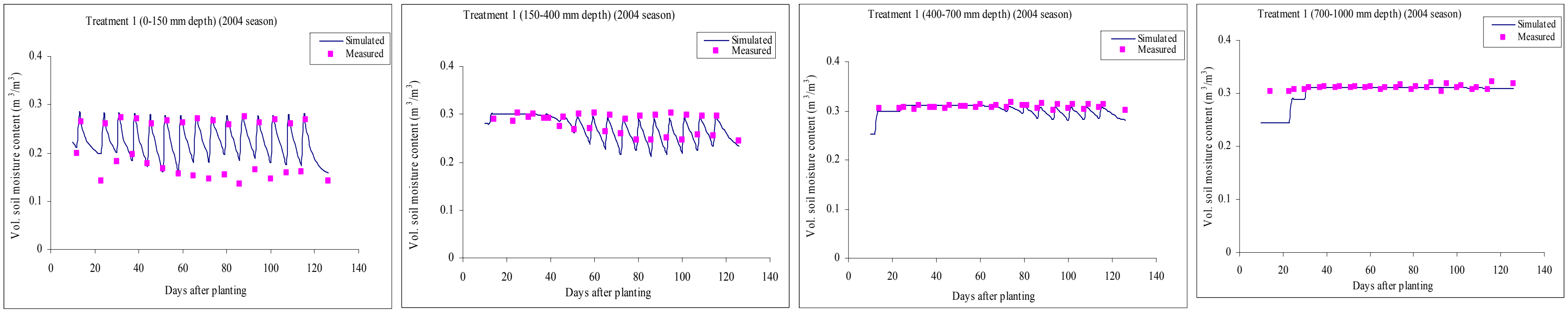
Appendix 1: Comparisons of simulated and measured soil moisture contents



a b c d

Figure A1. 1 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 1 (2004 season)

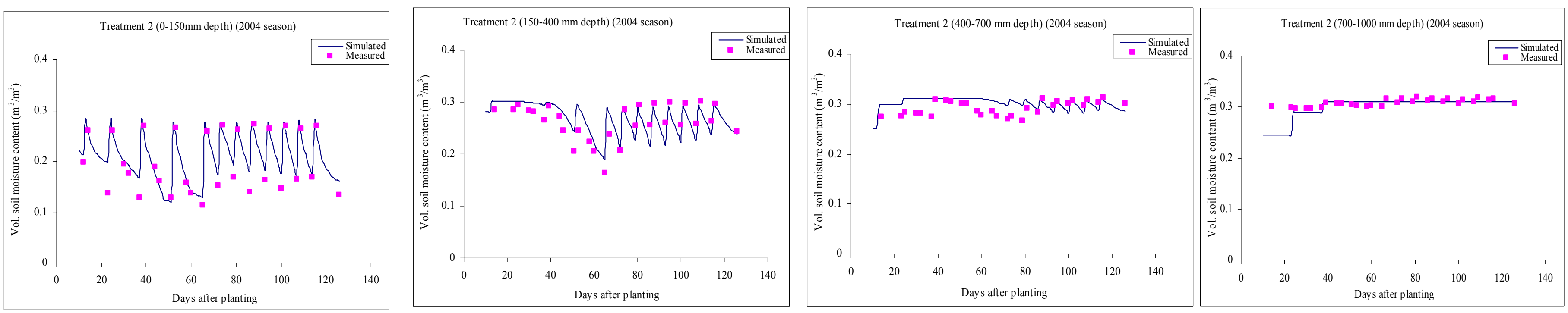


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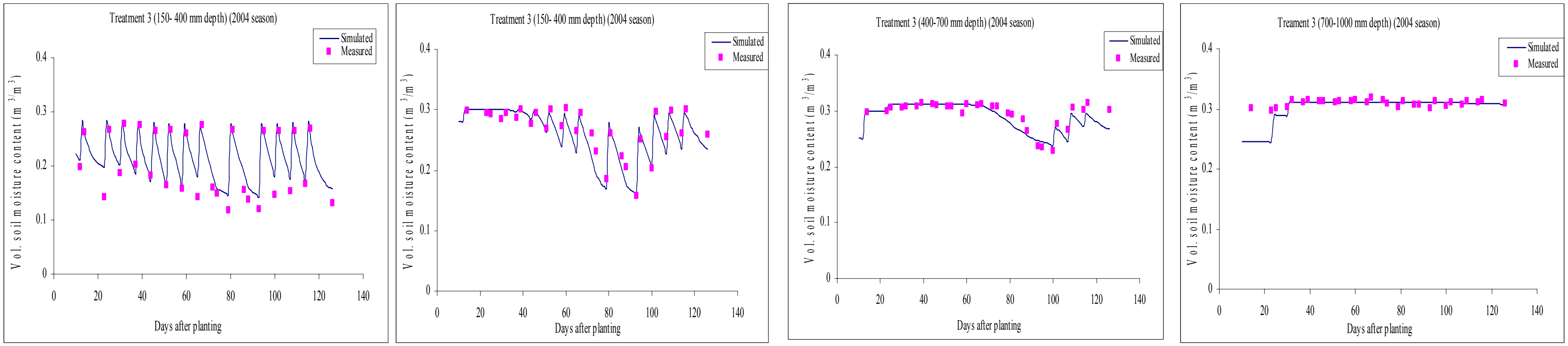
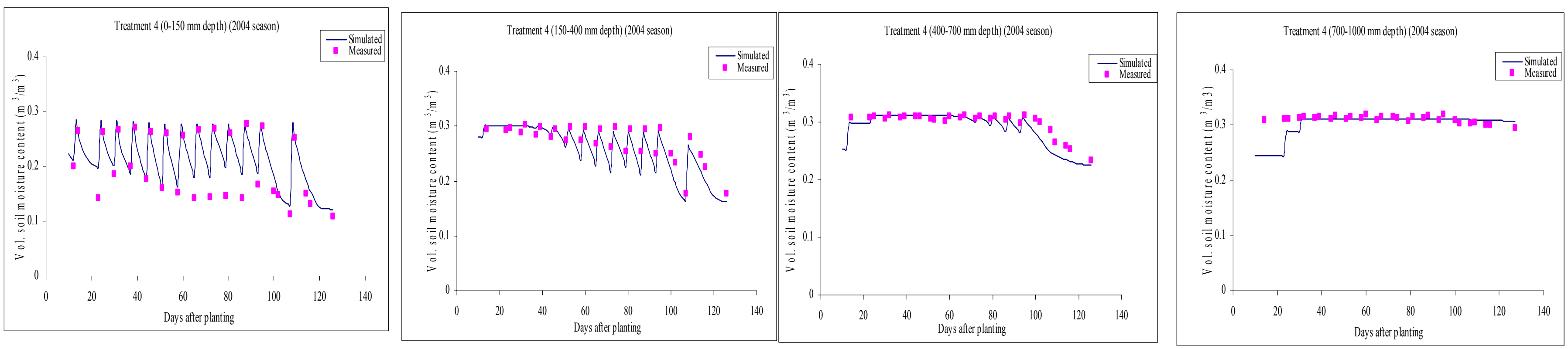
Figure A1. 2 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 2 (2004 season)



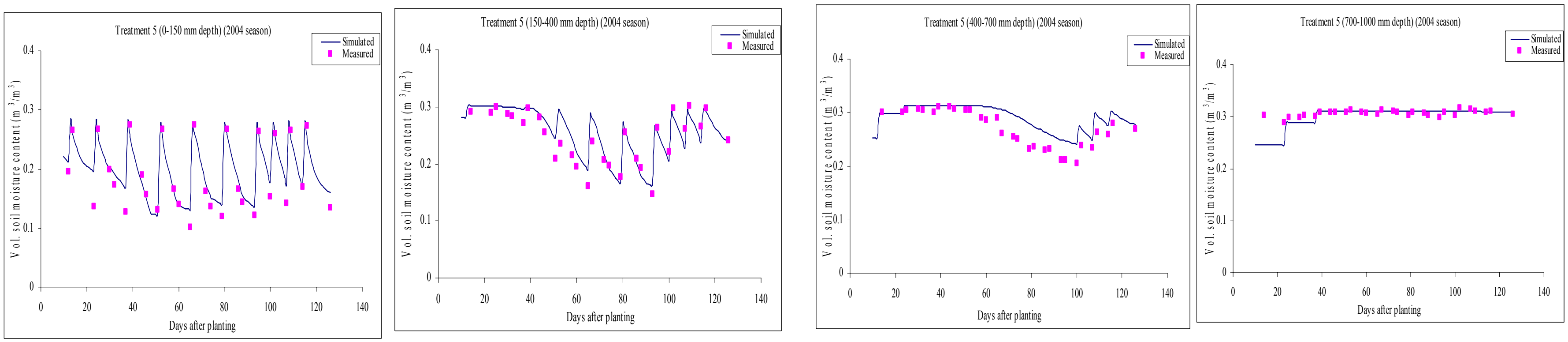
a b c d

Figure A1. 3 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 3 (2004 season)



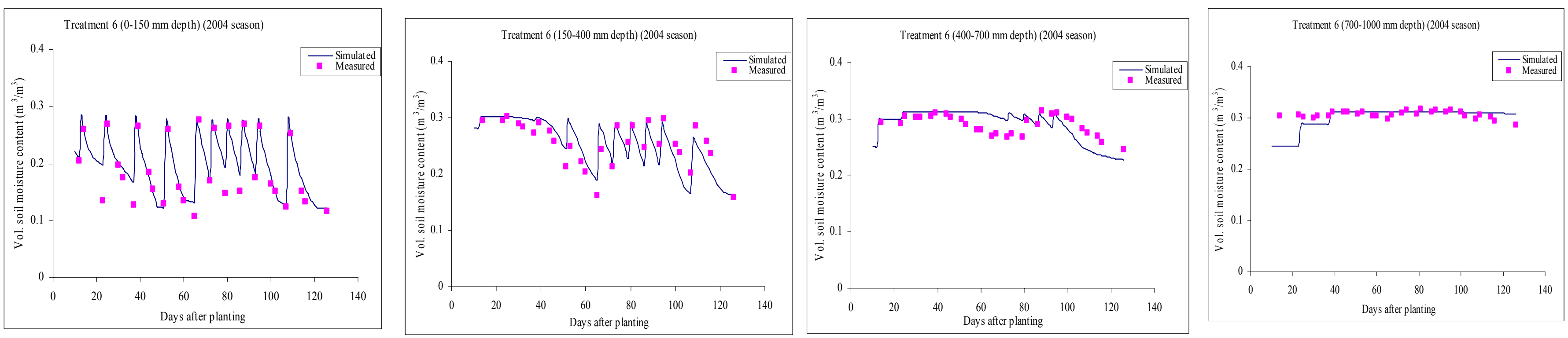
a b c d

Figure A1. 4 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 4 (2004 season)



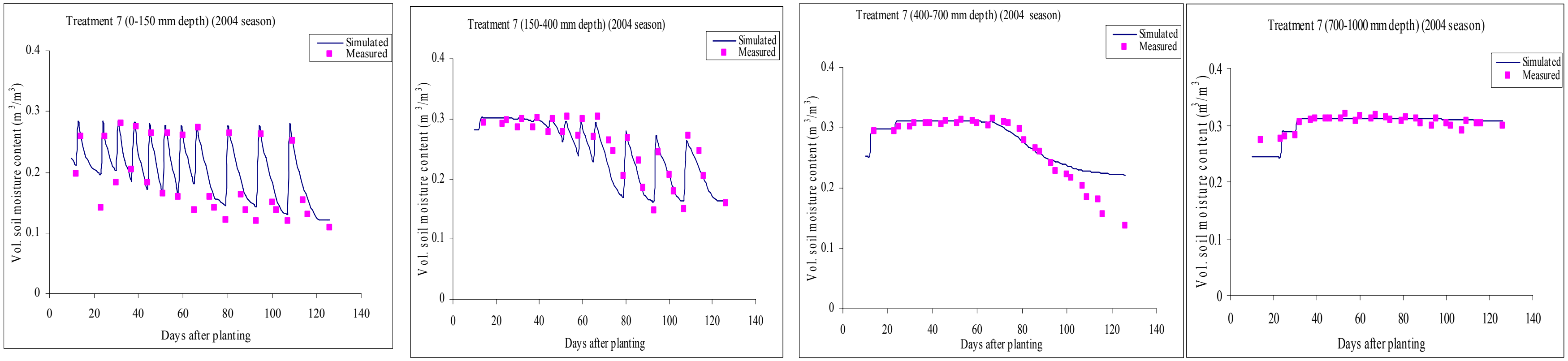
a b c d

Figure A1. 5 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 5 (2004 season)



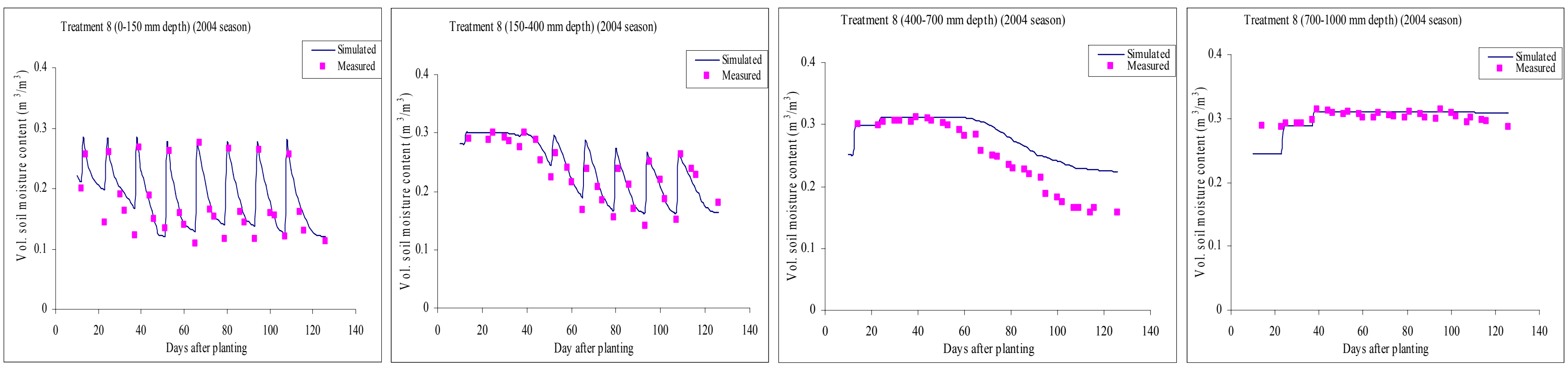
a b c d

Figure A1. 6 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 6 (2004 season)



a b c d

Figure A1. 7 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment7 (2004 season)



a b c d

Figure A1. 8 (a-d): Comparison of simulated and measured soil moisture content of the profile layers for Treatment 8 (2004 season)