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Irrigation Scheduling Impact Assessment MODel (ISIAMOD): A decision tool for irrigation scheduling

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Abstract

This paper presents a process-based simulation known as Irrigation Scheduling Impact Assessment MODel (ISIAMOD). It was developed to simulate crop growth & yield, soil water balance and water management response indices to define the impact of irrigation scheduling decisions. ISIAMOD was calibrated and validated using data from field experiments on the irrigated maize crop conducted in an irrigation scheme located in south western Tanzania. The model adequately simulates crop biomass yield, grain yield, seasonal evapotranspiration and average soil moisture content in the crop effective rooting depth. Some unique features of this model make it a major improvement over the existing crop-soil simulation models.

Keywords: Simulation model, Irrigation scheduling, Water management, Crop water productivity, ISIAMOD

Introduction

Application of computer-based simulation models as tools for providing support for decision-making in agricultural research has increased tremendously in the last three decades. In the field of irrigation, dynamic process-oriented simulation models are being used to evaluate irrigation-scheduling practices in different parts of the developed and developing countries. Some of the fairly popular models include, IRSIS (Raes *et al*., 1986), SWATRE (Belman *et al*., 1983) CROPWAT (Smith, 1992), CERES-Maize (Jones & Kiniry, 1986), EPIC (Williams *et al*., 1989), CropSyst (Stockle & Nelson, 1996), SWAP (van Dam *et al*., 1997), and APSIM (McCown *et al*., 1996).

Despite the fact that quite a number of crop-soil-irrigation simulation models already exist, there are always reasons to modify existing models or develop new ones to perform the desired task. One primary reason is that the choice of model to solve a problem largely depends on the nature and location of the problem as well as the desired results. Unfortunately, no single model can claim universal applicability. Moreover, readily available models may not possess the features or capability to give a desired output or solving a problem in a desired way. Therefore, the need to modify an existing model or develop a new one to address the task at hand becomes necessary.

This objective of this paper is to present a process-based crop growth cum irrigation scheduling model developed to generate Water Management Response Indices (WMRI) which is used to assess the level of impact of irrigation scheduling decisions on crops and its environment. The paper specifically presents the features of this model, its calibration and validation for irrigated maize crop.

Materials and methods

Model description

The Irrigation Scheduling Impact Assessment Model (ISIAMOD) is a process-based model created to simulate crop growth process, soil water balance of a cropped field, and water management response indices (WMRI). ISIAMOD runs on daily time-step, from crop planting date to crop physiological maturity date. The input data required in the model include weather, soil, crop, 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 wind speed, maximum and minimum relative humidity, sunshine hour or 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 soil profile is to be divided into a minimum of four and a maximum of ten layers, and each layer is divided into a number of compartments, such that the total number of compartments of the entire soil profile can be up to sixty. The division of the soil profile into layers and compartments is to facilitate numerical computation of the soil water flux.

The infiltration and distribution of water within the soil profile is based on the “tipping bucket” method (Campbell & Daiz, 1988; Zhang *et al.,* 2004). Each compartment is assumed to be filled with water to field capacity after irrigation or heavy rainfall, and then passes on excess 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.

ISIAMOD assumes 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. Through the process of transpiration water is removed from the crop root zone depth which increases down the soil profile as the crop rooting depth. Soil water is assumed 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 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 started to decline. The model divides the crop growth stages into four: crop establishment, vegetative, flowering and maturity (which include seed formation through to maturity).

A unique feature of the model which makes it an improvement on existing model is water management response indices (WMRI) module which generates the water accounting indices, crop productivity indices and the seasonal relative deficit/losses indices used to define the level of impact of an irrigation scheduling decision on the crop and the environment. In addition, the reference evapotranspiration module has eight options of weather data combination for calculating reference evapotranspiration (ETo) based on the Penman-Monteith and Hargreaves methods as detailed by Allen *et al.* (1998). This makes the model versatile and flexible to accommodate limited weather input data. The options include: (1) Maximum and minimum temperature, wind speed, maximum and minimum relative humidity, and solar radiation; (2) Maximum and minimum temperature, wind speed, maximum and minimum relative humidity, and sunshine hours; (3) Maximum and minimum temperature, wind speed, maximum relative humidity, and solar radiation; (4) Maximum and minimum temperature, wind speed, maximum relative humidity, and sunshine hours; (5) Maximum and minimum temperature, wind speed, and solar radiation; (6) Maximum and minimum temperature, wind speed, and sunshine hours; (7) Maximum and minimum temperature, and wind speed; and (8) Maximum and minimum temperature only. When the only weather parameters available are maximum and minimum temperature, reference evapotranspiration will be calculated using the Hargreaves' method (Hargreaves & Samani, 1985).

The irrigation scheduling module is also equipped with five options of irrigation timing criteria and three options of water application depth (WAD) from which the user can select. The irrigation timing criteria include: (1) User's specified dates of irrigation and depths of water to be applied; (2) Fixed irrigation interval throughout the crop growing season; (3) Fixed irrigation interval per growth stage; (4) Fixed maximum allowable depletion (MAD) throughout the crop growing season; (5) Fixed MAD per growth stage. The water application option include: (1) Depth of water equals the amount of water used by the crop at user's defined water application efficiency; (2) Fixed depth of water throughout the crop growing season; (3) Fixed water application depth per growth stage. ISIAMOD allows a combination of any of the timing criteria with any water application depth options. However, this rule does not apply when the user chooses to use the first option of irrigation timing criteria in which the user specifies the dates and depth of water to be applied.

The model simulation output include crop growth response like leaf area index, crop rooting depth, crop biomass, final harvest index and grain yield; soil water balance components such as daily soil moisture content, evaporation, transpiration, runoff, deep percolation, and rainfall interception. The crop yields and water balance components outputs are further processed by the model to generate the water management response indices which include the water accounting, crop water productivity, and seasonal relative deficit/losses indices. It is these indices that are used to assess the impact of the irrigation schedule. ISIAMOD program was written in FORTRAN language and compiled using Microsoft FORTRAN PowerStation version 1.0F. The executable file runs on command prompt of Windows XP. Fig. 1 shows the schematic diagram of the model.

The modules of ISIAMOD

The modules of ISIAMOD consist of the following:

Biomass yield module

The biomass yield module of ISIAMOD is given as:

$$\Delta BP_i = 0.01 * RUE * PAR * \left(B_{GLF}\right)^2 \quad (1)$$

Where ΔBPi is daily increase in biomass (t/ha); RUE is crop parameter for converting energy to biomass, referred to as radiation use efficiency (g/MJ); PAR is photosynthetic active radiation (MJ/m^2) (Sharpley & Williams, 1990), B_{GLF} is the biomass growth limiting factor.

The biomass growth limiting factors considered are temperature and water stress. The temperature-limiting factor (T_{GLF}) is expressed as (Stockle & Nelson, 1996):

$$T_{GLF} = 1.0 \quad if\ T_{avg} > T_{opt}\ ; \quad (2)$$

$$T_{GLF} = 0.0 \quad if\ T_{avg} < T_{base}\ ;\ \text{and} \quad (3)$$

$$T_{GLF} = \frac{T_{avg} - T_{base}}{T_{opt} - T_{base}} \quad \text{otherwise} \quad (4)$$

where, T_{opt} is crop parameter optimal temperature for the crop growth; T_{base} is base temperature at which there is no crop growth; and T_{avg} is daily average temperature.

The water stress growth-limiting factor (WSF_{GLF}) is expressed as the ratio of actual transpiration (Ta) to the potential transpiration (T_p); $WSF_{GLF} = \frac{T_a}{T_p}$ (5)

Harvestable yield module

The harvestable yield is obtained as the product of the biomass yield at maturity, crop harvest index (HI), and adjusted water stress factors during flowering and grain filling. The expression is given as (Sharpley & Williams, 1990):

$$CHY = BP_{cum} * HI_{pot} * \left[(WSF_{GLF})_{fl}\right]^{fl} * \left[(WSF_{GLF})_{gf}\right]^{gf} \quad (6)$$

Where, HI_{pot} is potential (non water-stressed) harvest index, $(WSF_{GLF})_{fl}$ is water stress factor at flowering (fl) growth stage; $(WSF_{GLF})_{gf}$ is water stress factor at grain filling (gf) growth stage; αgf and αfl are harvest index adjustment parameters for water stress during flowering and grain yield, respectively.

Leaf area index

The daily increment in leaf area index during the canopy development stage is given as:

$$\Delta LAI_i = (PLAI_i - PLAI_{i-1}) * (WSF_{GLF})^{0.5} \quad (7)$$

Where, and the PLAIi is potential (without water stress) leaf area index on day I; PLAIi-1 is the potential leaf area index the previous day. The other parameter has been previously defined.

The potential leaf area index was defined as:

$$PLAI_i = \frac{LAI_{\max}}{\{1 + GSF * EXP(-b * D_i)\}} \quad (8)$$

Where, LAI_{max} is maximum leaf area index, which is a crop parameter, GSF is growth shape factor and b is a coefficient.

The fraction of the crop growth duration was given as:

$$D_i = \frac{i - i_{pld}}{i_{mtd} - i_{pld}} \quad (9)$$

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.

The leaf area index from the start of decline to end of the growing season was expressed as:

$$LAI_i = DLAI_i * (WSF_{GLF})^{0.5} \quad (10)$$

and

$$DLAIi = LAIo * \left\{\frac{(1.01 - D_i)}{(1.01 - D_0)}\right\} \quad (11)$$

Where, $DLAI_i$ is declining leaf area index on day 'i' under moisture stress-free condition. LAIo is leaf area index on the day (Do) when leaf area index decline began, and beta is the leaf area index decline adjustment factor. Other parameters are as previously defined.

Potential evapotranspiration partitioning module

The ET_o is first converted to crop maximum evapotranspiration (ET_c) using a factor (Kc), expressed as:

$$ET_c = K_c * ET_o \quad (12)$$

Kc factor is defined as (Stockle & Nelson, 1996):

$$Kc = 1 + (Kc' - 1) * \frac{LAI}{3} \quad (13)$$

$$if \ Kc' > 1 \ and \ LAI < 3$$

$Kc = Kc'$ Otherwise

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

Where, Kc' is peak crop coefficient, LAI is leaf area index with a maximum value of three for the reference crop (Stockle & 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:

$$E_p = (1 - FI) * ET_c \quad (14)$$

$$T_p = ET_c - E_p \quad (15)$$

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.

Solar radiation interception module

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

$$FI = [1 - EXP(-REXF * LAI)] \quad (16)$$

Where, FI is fractional radiation interception coefficient by the crop canopy; REXF is radiation extinction coefficient, and LAI is leaf area index.

Actual evaporation module

The actual evaporation rate is expressed as:

$$E_a = E_p \ if \ \bar{\ } \geq \bar{\ }_{fc}; \quad (17)$$

$E_a = E_p * \frac{\bar{\ } - \bar{\ }_{pwp}}{\bar{\ }_{fc} - \bar{\ }_{pwp}}$ Otherwise (18)

When the soil moisture content of the evaporation layer reaches the wilting point, the rate of evaporation becomes (Campbell & Daiz, 1988):

$$E_a = E_p * \left[\frac{\bar{\ } - \bar{\ }_{adwc}}{\bar{\ } - \bar{\ }_{adwc}}\right]^2 \quad (19)$$

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 moisture content, given as one-third of moisture content wilting point (Stockle & Nelson, 1996).

Crop actual transpiration module

The actual transpiration (root water uptake) is expressed as (Plauborg *et al.*, 1996):

$$T_a = T_p \quad if\ \bar{} \geq \bar{}_{fc}; \qquad (20)$$

$$T_a = 0.0 \quad if\ \bar{} \leq \bar{}_{pwp} \quad \text{and} \qquad (21)$$

$$T_a = T_p * \left[1 - \left(\frac{\bar{}\ \bar{}\ \bar{}_{pwp}}{\bar{}\ \bar{}\ \bar{}_{pwp}} \right)^{\frac{CT}{T_p}} \right] \text{ Otherwise} \qquad (22)$$

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

Rooting depth module

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

$$\Delta RD_i = \left(PRD_i - PRD_{i-1}\right) * \left(RD_{GLF}\right)^{0.5} \qquad (23)$$

Where ΔRD_i is daily increase in rooting depth; PRD_i is potential (unrestricted and non water limited) root depth, and RD_{GLF} is dominant factor which limits rooting depth on a given day i. (This factor could be water stress or soil strength or both (Sharpley & Williams, 1990)). The soil stress factor is as defined by Sharpley & Williams (1990).

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

$$PRD_i = \frac{RD_{\max}}{1 + 442 \ * EXP\left(-8.5 * D_i\right)} \qquad (24)$$

Root density module

The root density module is given as (Campbell & Daiz, 1988):

$$FR_l \ = \Delta Z_l * \frac{2 * \left(RD - Z_l\right) + \Delta Z_l}{RD^2} \qquad (25)$$

$$if \ Z_l \leq RD$$

$$FR_i = \left[\frac{RD - \left(Z_l + \Delta Z_l\right)}{RD} \right]^2 \qquad (26)$$

$$if \ Z_l - \Delta Z_l \ < RD < Z_l$$

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 & Daiz, 1988):

$$T_{al} * T_a \ * FR_l \qquad (27)$$

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

Water response management indices module

This module consists of the water accounting, crop water productivity and seasonal relative deficit indices. The water accounting indices are defined as:

Transpiration efficiency = $F_{Ta} = \dfrac{T_a}{WS}$ (28)

Evaporation index = $F_{Ea} = \dfrac{E_a}{WS}$ (29)

Evapotranspiration efficiency = $F_{ETa} = \dfrac{ET_a}{WS}$ (30)

Runoff Index = $F_{Rf} \ = \dfrac{Rf}{WS}$ (31)

Percolation index = $F_{Dp} \ = \dfrac{DP}{WS}$ (32)

where, WS is the amount of water supplied either through irrigation, rainfall or both; Ta is transpiration, Ea is evaporation, ETa is evapotranspiration; Rf is runoff and DP is deep percolation.

The crop water productivity indices are defined as:

Productivity of water supplied

$$= CWP_{WS} = \frac{Crop \ yield}{WS} \qquad (33)$$

Productivity of water used in evapotranspiration =

$$CWP_{ETa} = \frac{Crop \ yield}{SET} \qquad (34)$$

Productivity of water used in transpiration =

$$CWP_{Ta} = \frac{Crop \ yield}{T_a} \qquad (35)$$

The seasonal relative deficit/losses indices relate the yield and crop water use outputs of the scheduling strategy to the potential output (non-water limiting) expected in the local area. These include:

Seasonal relative biomass yield loss

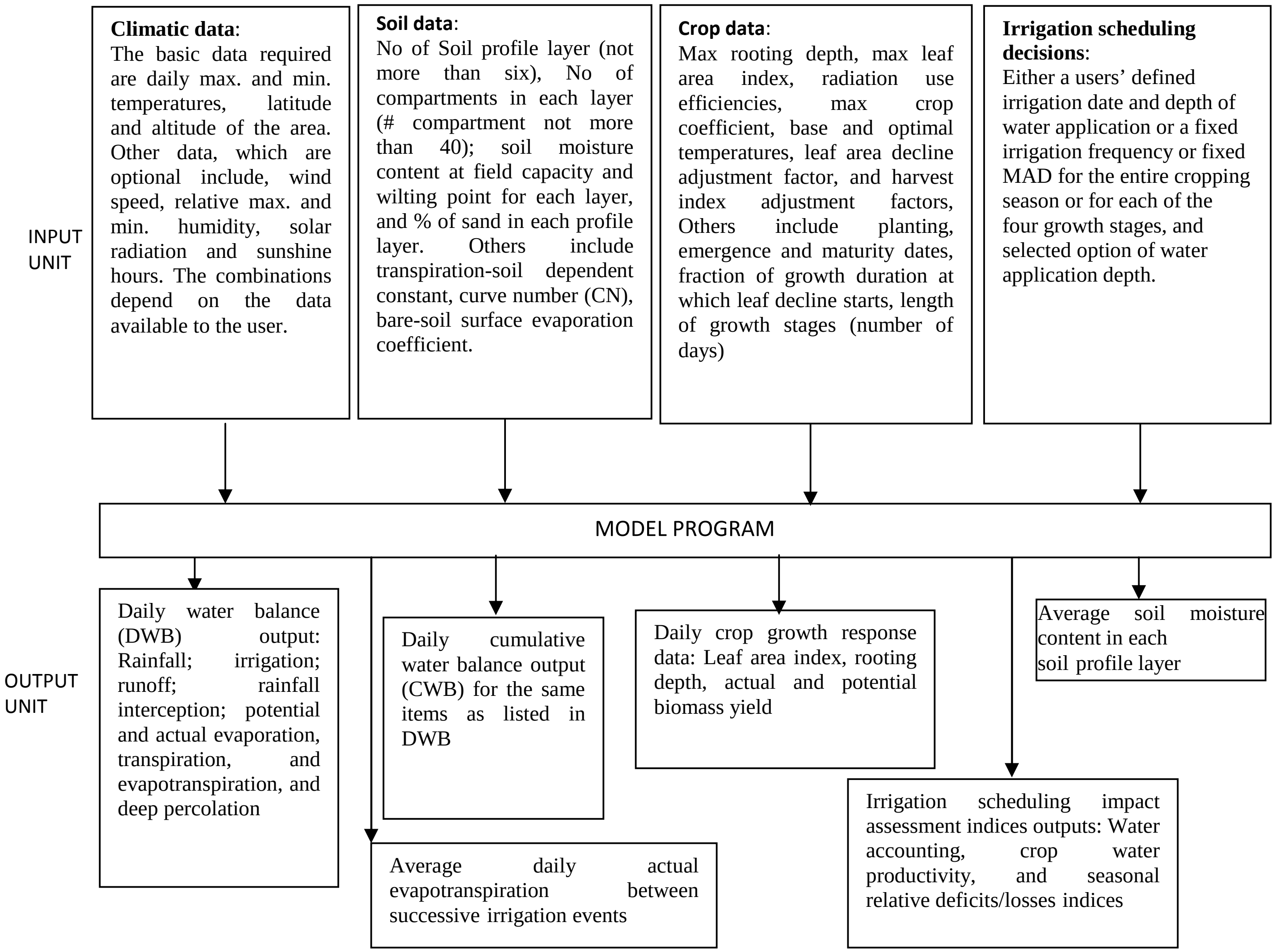
$$SRL_{DM} = \left(1 - \frac{DM_a}{DM_p}\right) \qquad (36)$$

Seasonal relative grain yield loss $SRL_{GY} = \left(1 - \dfrac{GY_a}{GY_p}\right)$ (37)

Seasonal relative ET deficit $SET_{Deficit} = \left(1 - \dfrac{SET_a}{SET_c}\right)$ (38)

Seasonal relative transpiration deficit $STR_{deficit} = \left(1 - \frac{STR_a}{STR_p}\right)$ (39)

Fig. 1. Schematic diagram of the ISIAMod with input and output information



Climatic data: The basic data required are daily max. and min. temperatures, latitude and altitude of the area. Other data, which are optional include, wind speed, relative max. and min. humidity, solar radiation and sunshine hours. The combinations depend on the data available to the user.

Soil data: No of Soil profile layer (not more than six), No of compartments in each layer (# compartment not more than 40); soil moisture content at field capacity and wilting point for each layer, and % of sand in each profile layer. Others include transpiration-soil dependent constant, curve number (CN), bare-soil surface evaporation coefficient.

Crop data: Max rooting depth, max leaf area index, radiation use efficiencies, max crop coefficient, base and optimal temperatures, leaf area decline adjustment factor, and harvest index adjustment factors, Others include planting, emergence and maturity dates, fraction of growth duration at which leaf decline starts, length of growth stages (number of days)

Irrigation scheduling decisions: Either a users' defined irrigation date and depth of water application or a fixed irrigation frequency or fixed MAD for the entire cropping season or for each of the four growth stages, and selected option of water application depth.

Daily water balance (DWB) output: Rainfall; irrigation; runoff; rainfall interception; potential and actual evaporation, transpiration, and evapotranspiration, and deep percolation

Daily cumulative water balance output (CWB) for the same items as listed in DWB

Daily crop growth response data: Leaf area index, rooting depth, actual and potential biomass yield

Average soil moisture content in each soil profile layer

Average daily actual evapotranspiration between successive irrigation events

Irrigation scheduling impact assessment indices outputs: Water accounting, crop water productivity, and seasonal relative deficits/losses indices

Relative water supply index $RWSI = \left(1 - \frac{WS}{SET_c}\right)$ (40)

where, DM_a is actual biomass yield at harvest; GY_a is actual grain yield; SET_a is seasonal evapotranspiration; STR_a is seasonal transpiration; DM_p potential biomass yield of the crop in the local area; GY_p potential grain yield of the crop in the local area; SET_c is maximum evapotranspiration for the crop in the cropping season, and STR_p is potential season transpiration for the crop in the local area.

Field experimentation

Two field experiments were carried out in 2004 irrigation season (June to October) and one in 2005 at the Tanzanian Ministry of Agriculture Training Institute farms located in the *Igurusi ya Zamani* Traditional Irrigation Scheme (IZTIS) in Igurusi town, Mbeya Region, south western Tanzania, for the purpose of calibration and validation of ISIAMOD. 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 detailed description of the climate and soils of the experimental location is reported in Igbadun *et al* (2006a) and SWMRG-FAO (2003). Field data from one of the experiments in 2004 season were used for the model calibration, while data from the other experiment in 2004 and that of the 2005 season were use to validate the model, thus validating the model across fields and irrigation seasons.

Description of experimental treatments

The two experiments for 2004 irrigation season (June-October) and that of the 2005 season comprises of eight treatments each. Each of the experiment in 2004 was replicated three times while that of 2005 was replicated four times. The 2004 experiments ran concurrently on separate fields about 250 m apart. Planting was done on 24th June, 2004. The experiment in the 2005 season was carried out on one of the fields used during the 2004 season. Planting was done on 6th July 2005. The experimental treatments for the three experiments in the two seasons were the same and their description is summarized in Table 1. The treatment variable was the frequency of irrigation, and the variations were created by skipping irrigation every other week at one or more growth stages of the crop. This treatment variation approach is similar to Pandey *et al*. (2000). The experimental treatment design, method of irrigation water application, and other agronomic practices have been reported in Igbadun *et al*. (2006b). Table 2 shows the irrigation schedule observed for the experiments.

Table 1. 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 & 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. Vegetative growth stage = 24-64 days after planting (DAP); flowering stage = 65-93 DAP; grain filling to Maturity = 94-120 DAP.*

Data collection

The data collected for the purpose of calibrating and validating the model include the soil moisture content from every treatment two days after irrigation and just before irrigation; final biomass yield, and the grain yield. The soil moisture contents were monitored using the Theta probe during the 2004 season and a Neutron probe during the 2005 season. The soil moisture contents were determined for soil profile depth of 100cm at interval of 15 cm incremental depth. From the soil moisture content data, the weekly crop water use (evapotranspiration) for each treatment was computed using the soil moisture depletion expression (Michael, 1999).The final biomass and grain yields were obtained for each treatment by harvesting the above ground dry matter from the treatment plots and weighed. The maize cobs were then harvested, threshed, and weighed to obtain the grain weight. The grain moisture content at threshing was about 13%.

Running the model

The input data used for running the model include weather, soil, crop and irrigation scheduling decisions. The weather data were obtained from the meteorological station in the Ministry of Agriculture Training Institute (MATI), Igurusi town, for the two seasons. The soil data were those of the experimental site. The irrigation scheduling decision input data (the timing of irrigation and amount of water applied) was in accordance with Table 2. The crop input data and other parameters are given in Table 3.

Calibration procedure

Calibration of model refers to quantifying parameters of the model using system observations and the

Table 2. Irrigation scheduling

Growth stage	Crop establishment			Vegetative						Flowering				Grain filling				NIE	TWA
Wk 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 (TR$_{1111*}$)	30	30	30	30	30	40	40	40	40	50	50	50	50	50	50	50	40	17	700
2 (TR$_{1011}$)	30	30	30	30	X	40	X	40	X	50	50	50	50	50	50	50	40	14	590
3 (TR$_{1101}$)	30	30	30	30	30	40	40	40	40	50	X	50	X	50	50	50	40	15	600
4 (TR$_{1110}$)	30	30	30	30	30	40	40	40	40	50	50	50	50	50	X	50	X	15	610
5 (TR$_{1001}$)	30	30	30	30	X	40	X	40	X	50	X	50	X	50	50	50	40	12	490
6 (TR$_{1010}$)	30	30	30	30	X	40	X	40	X	50	50	50	50	50	X	50	X	13	500
7 (TR$_{1100}$)	30	30	30	30	30	40	40	40	40	50	X	50	X	50	X	50	X	13	510
8 (TR$_{1000}$)	30	30	30	30	X	40	X	40	X	50	X	50	X	50	X	50	X	10	400

* *Pre-planting irrigation; NIE = No. of irrigation event; X = irrigation skipped; TWA = Total water applied in the season (mm)*

Table 3. Crop and other input parameters for the model

Parameters	Value
Maximum rooting depth	1.2 m
Maximum harvest index	0.34*
Harvest index adjustment factor for the flowering stage	0.45**
Harvest index adjustment factor for the maturity stage	0.5**
Radiation extinction coefficient	0.55**
Maximum leaf area index	0.35m^2/m^2
RUE (establishment and vegetative stages)	0.25 g/MJ**
RUE (flowering and maturity stages)	0.23 g/MJ**
Base temperature	8°C
Optimal temperature	24°C
Fraction of the growth duration at which leaf area index starts to decline	0.75*
Days after planting at which establishment growth stage starts	0*
Days after planting at which vegetative growth stage starts	23*
Days after planting at which flowering growth stage starts	64*
Days after planting at which maturity growth stage starts	93*
Peak crop water use (kc) coefficient	1.2
Soil dependent transpiration constant	0.018 m/day**
Evaporation coefficient for bare soil	1.05
Growth shape factor GSF	1120
b = exponent in the LAI equation	-17.2

**= data obtained from field experimental data; ** = final values obtained through model calibration*

simulation outputs (Boote & Jones, 1988). Model calibration involves a systematic adjustment of the parameters of a model such that the model can describe more closely the system behavior for site-specific application. During the process, the structure of the model remain the same and only the model parameters are adjusted until some values are obtained which brings the model simulated outputs close to the real system data. These values obtained are usually retained as the values for those parameters of the model for that site-specific application.

The calibration of ISIAMOD for the site-specific and test crop involved adjusting the base values of some input parameters of the model within a range while the model simulated outputs were compared with field-measured data from Field 1 (2004) The input parameters adjusted include the soil dependent transpiration factor, harvest index adjustment factors, leaf area index module coefficients, canopy radiation extinction factor, and radiation use efficiency. The model outputs during the calibration process that were compared with field-measured data include biomass yield at harvest, grain yield, and seasonal evapotranspiration. The final values of the adjusted parameters at which the model simulated outputs had the highest correlation with the field-measured data were adopted as input data for the model.

Validation procedure

Model validation is a process of comparing model-simulated results to real system data not previously used in calibration or in any parameter estimation process. The purpose of validation is to determine if the model is sufficiently accurate for its application as defined by the objective (Boote & Jones, 1988).

The simulated output variables of the ISIAMOD were validated by comparing model-simulated results with field-measured data from Field 2 in the 2004 and 2005 seasons' experiments. The comparison was made between the field measured and the simulated final biomass yield, grain yield, seasonal evapotranspiration and average soil moisture content of the soil profile. The statistical performance indicators used for the comparison were (Mahdian & Gallichard, 1995; Panda *et al.*, 2004):

$$AE = \frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right)$$

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

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right)^2\right]^{0.5}$$

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

$$CRM = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i}$$

Where AE is average error of bias, CV is coefficient of variation, RMSE is root mean square error, EF is modeling efficiency, CRM is coefficient of residual mass, Pi is simulated values; O_i is measured values; O_m is mean of measured values, and n is the number of the observations.

The average error of bias (AE) is a measure of bias between the simulated and measured data. The coefficient of variation (CV) is a measure of variability while the root mean square error (RMSE) is a measure of precision. The modeling efficiency (EF) also referred to as the coefficient of Nash-Sutcliffe (Mahdian & 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 negative infinity (-∞) for total lack of fit to 1 for an exact fitting (Mahdian & Gallichard, 1995). The coefficient of residual mass (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 under-prediction, while a negative value indicates a tendency of over-prediction (Antonopoulos, 1997).

Results and discussion

Calibration

Table 4. Biomass yield at harvest, grain yield and harvest index of Field 1 (2004 season)

Treatment label	Biomass yield at harvest (kg/ha)	Grain yield (kg/ha)	SET (mm)
TR$_{1111}$	11939.2	3831.7	548.7
TR$_{1011}$	10166.4	3265.0	494.1
TR$_{1101}$	10108.0	2837.4	505.6
TR$_{1110}$	10361.2	3007.1	496.1
TR$_{1001}$	8672.8	2370.9	449.5
TR$_{1010}$	9921.6	2755.6	452.9
TR$_{1100}$	8532.0	2321.2	449.8
TR$_{1000}$	7572.0	1709.5	395.9

Table 4 shows the biomass yield at harvest, grain yield and seasonal evapotranspiration data of Field 1 (2004 season) used in the model calibration. Table 5 shows the statistical comparison of the model-simulated and field-measured data for the final calibration test. The coefficients of variation (CV) between the simulated and measured data were quite low and the measures of the goodness of fit indicated by the modelling efficiency (EF) and the coefficient of determination (r^2) were very good. Based on the statistics, ISIAMOD was considered standardized for the maize crop in the study area.

Table 5. Statistics of the comparison between simulated and measured grain yield, biomass yield and harvest index

Statistical performance indices	Grain yield	Biomass yield	Seasonal ET
AE	-105.5	-125.4	-14.4
RMSE	151.3	426.5	15.7
CV (%)	5.48	4.42	3.32
EF	0.94	0.89	0.87
CRM	0.04	0.01	0.03

Units for AE and RMSE for grain and biomass yield are kg/ha, Units for AE and RMSE seasonal evapotranspiration are in mm.

Model validation

Biomass and grain yield

Table 7. Statistics of the comparison between simulated and field measured biomass yield at harvest and grain yield for the 2004 and 2005 season

Statistical performance Indices	2004 season		2005 season	
	Biomass yield	Grain yield	Biomass yield	Grain yield
AE*	292.6	62.3	235.9	128.6
RMSE	572.7	183.4	448.4	270.8
CV (%)	6.08	6.89	4.32	8.96
EF	0.85	0.90	0.94	0.89
CRM	-0.03	-0.02	-0.02	-0.04

** Unit of AE and RMSE for biomass yield and grain yield is kg/ha.*

Table 6 shows the simulated and field measured biomass yield at harvest and grain yield for 2004 (Field 2) and 2005 seasons. Table 7 shows the statistics of the comparison between simulated and measured biomass yield at harvest for the 2004 and 2005 seasons (columns 2 & 4). The CRM shows that the model has a tendency to either over-predict biomass yield at harvest by 2 to 3 %, and grain yield by 2 to 4 %. The modeling efficiencies (EF) were between 85 and 95%. The close relationship between the simulated and measured data was considered as a good performance of the model ability to predict biomass and grain yields.

Seasonal evapotranspiration

Table 8.Simulated and measured seasonal evapotranspiration for the 2004 and 2005 seasons in mm

Treatment	2004 season		2005 season	
	Simulated	Measured	Simulated	Measured
TR$_{1111}$	545.7	541.1	540.0	514.2
TR$_{1011}$	501.1	486.9	497.7	491.2
TR$_{1101}$	496.4	502.6	499.0	468.0
TR$_{1110}$	501.9	504.6	516.4	488.6
TR$_{1001}$	449.8	443.7	448.6	450.6
TR$_{1010}$	460.6	446.9	474.4	441.1
TR$_{1100}$	437.6	451.6	461.0	439.9
TR$_{1000}$	394.3	385.5	410.3	398.9

Table 8 shows the simulated and the field-measured seasonal evapotranspiration for the 2004 and 2005 seasons, and Table 9 shows the statistics of the comparison between the simulated and the measured data. There was a tendency of over the prediction of the season evapotranspiration by 1% in the 2004 season and 4% in the 2005 season as indicated by the CRM. The

Table 6. Simulated and measured dry matter and grain yields at harvest

Treatment	2004 season				2005 season			
	Biomass yield (kg/ha)		Grain yield (kg/ha)		Biomass yield (kg/ha)		Grain yield (kg/ha)	
	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
TR$_{1111}$	12360.92	12128.22	3949.34	3776.19	13293.02	12672.68	4461.24	4349.206
TR$_{1011}$	10559.59	9600.89	3345.53	3056.08	11572.7	11401.19	3830.52	3828.571
TR$_{1101}$	10294.52	10215.11	2879.79	2770.37	10963.94	11673.73	3163.62	3257.143
TR$_{1110}$	11024.74	10247.11	3057.94	2812.70	12446.87	12104.76	3890.6	3352.381
TR$_{1001}$	8442.15	8252.44	2330.51	2249.74	8834.93	8575.16	2416.68	2476.19
TR$_{1010}$	9374.37	8721.78	2595.85	2734.39	10814.12	10534.92	3345.29	2844.444
TR$_{1100}$	8649.88	9386.67	2014.14	2252.86	9475.01	9026.43	2344.46	2431.746
TR$_{1000}$	6965.4	6778.84	1614.73	1637.04	7442.87	6966.67	1741.43	1625.397

coefficients to variation (CV) very quite low and the modeling efficiency were moderately high (>0.50 in most cases) which can be taken for good model performance. The performance of ISIAMOD in simulating seasonal evapotranspiration compares favourably with the several models reported in literature. For example, Cavero et al. (2000) compared the performance of $EPIC_{phase}$, Modified $EPIC_{phase}$ and CROPWAT models 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 $EPIC_{phase}$, Modified $EPIC_{phase}$ 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 (Arora *et al*., 1987), respectively. The RMSE for ISIAMOD for the two seasons was 9.76 and 22.74 mm, respectively.

Table 9. Statistics of the comparison between simulated and measured seasonal evapotranspiration for the 2004 and 2005 seasons

Statistical indices	2004 season	2005 season
AE (mm)	3.06	19.38
RMSE (mm)	9.76	22.74
CV (%)	2.08	4.93
EF	0.95	0.56
CRM	-0.01	-0.04

Average soil moisture content of the effective root zone depth

Tables 10 shows the result of the statistics of the comparison between the measured and simulated volumetric soil moisture content of the effective root zone depth. The average error of bias (AE) between the simulated and the measured data was ± $0.01 m^3/m^3$ in both seasons. The RMSE was between 0.01 and 0.02 m^3/m^3. The coefficients of determination (r^2) were good (>0.70) in most of the treatments in the 2004 season and were fair (> 0.50) in the 2005 season.

Table 10. Statistics of the comparison between simulated and measured volumetric soil moisture content of the effective root zone

Statistical performance Indicator	2004 season							
	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	5.3	8.23
EF	0.89	0.82	0.92	0.93	0.84	0.79	1	0.82
CRM	0.03	0.01	0.02	0.04	-0.05	-0.01	-0.01	-0.07
	2005 season							
AE (m^3/m^3)	0.00	0.00	-0.01	0.00	-0.01	0.00	0.00	-0.01
RMSE (m^3/m^3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
CV (%)	2.73	3.70	4.80	4.14	5.32	5.15	5.73	6.49
EF	0.68	0.54	0.56	0.56	0.53	0.49	0.61	0.56
CRM	0.01	0.01	0.03	0.01	0.02	0.01	0.01	0.05

Conclusion

A simplified process-based simulation model known as Irrigation Scheduling Impact Assessment Model (ISIAMOD) was developed and validated. It was found to satisfactorily simulate grain yield of a maize crop and the soil water balance components of the cropped field. The model can be useful for on-the-desk assessing of the impact of irrigation scheduling protocols. Thus, the possible consequences of an irrigation scheduling protocol on the crop and its environment (the soil water balance) can be evaluated on the desk without going to the field. This model can be a strong tool in the hands of irrigation extension workers.

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