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Calibration and validation of a soil water simulation model (WaSim) for field grown *Amaranthus cruentus*

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Abstract

A water simulation model (WaSim) to simulate the growth and development of *Amaranthus cruentus* as well as the components of water balance for a typical sandy-clay-loam soil of Akure has been described. Dry season experiments were carried between January and March of 2005 and 2006. Amaranthus seeds were established on the field and three irrigation water managements were imposed on the crop to determine its response to water deficit at its different phenological stages. Amaranthus growth and development, evapotranspiration (ET) and rooting depth were calibrated by fitting the most sensitive variables to obtain the corresponding model output. The model simulated crop growth and crop cover well, the coefficient of determination r^2=0.9 and the difference between simulated and measured root depth is not significant at $P<0.001$. The actual evapotranspiration (AET) from the model prediction and the measured value gave a fairly high coefficient of correlation r=0.7 at $P<0.001$. The mean bias error (MBE) and the root mean square error of yield estimates between the measured and the model prediction are -0.4444 and 1.35 respectively at $P < 0.001$. The model was considered effective and appropriate for daily simulation of water balance, water requirement of crops and in climate effects on crop production.

Keywords: Irrigation; Evapotranspiration; Soil moisture; Water balance; Crop cover

Introduction

The developments of dynamic crop growth simulation models have made substantial progress over the years. However, the developed models possess different levels of complexity depending on the parameters involved. Some of the available models consist of empirical relationships, which require local calibration and validation. Whisler et al., 1996; Crosby, 1996; Walker et al., 1995 published a comprehensive review of wheat model, and Mottram and De Jager (1994) provided an overview of soil water balance and reference evaporation models. Advantages and disadvantages of several models were also described by Hanks and Ritchie (1991). Among the most recently developed is the water simulation model (WaSim), a daily water balance model that stimulates the soil water in response to different management strategies and environment scenarios (Hess and Counsell, 2000).

Many benefits of this model have been cited among which are: ease of operation, minimal data requirement, good visualization of model calculations, a reasonable level of accuracy and flexibility in terms of water management situations that can be simulated.

The objective of this research therefore was to calibrate and validate a soil water simulation model (WaSim) for *Amaranthus cruentus* grown under tropical condition. An existing model of evapotranspiration and selected empirical equations existing in literature were assembled to simulate the crop evapotranspiration at different phonological stages. A field experiment using micro-sprinkler system was used to test the model.

Materials and methods

Description of the model

The water simulation model (WaSim) was developed in UK by HR Wallingford and Cranfield University (Hess et al., 2000). The model carries out a one-dimensional, daily soil water balance. It simulates the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to climate. The algorithms used from the model include the followings:

i. Crop cover fractions
ii. Available water and soil water deficit
iii. Actual and potential transpiration
iv. Root zone deficit
v. Runoff estimation

Crop cover fraction

The crop cover fraction on a particular day was determined following the method described by (Hess et al., 2000). The day at which the crop attains 20% cover, maximum cover, maturity and harvest. If the maximum cover fraction is less than 20% then the first stage is ignored. Senescence is simulated by a linear reduction in crop fraction between maximum cover at maturity and zero at harvest.

Available water and soil water deficit

(i) Root depth

The root depth on a particular day is calculated from the following table:

Table 1. Calculation of root depth.

	Condition	Root depth
i)	Planting depth	r_o
ii)	Planting to maximum root depth	$r_{i-1} + \Delta r$
iii)	Maximum root depth to harvest	r_{max}
iv)	After harvest	O

where

r_i = root depth on day i, (m)

Δr = daily root growth, (m)

r_o = planting depth, (m)

r_{max} = maximum root depth,(m)

The root growth on a particular day is determined from a sigmoid root growth curve (Borg and Grimes 1986).

$$\Delta r = [(0.5 + 0.5 * \text{Sin}\ (0.03 * (t_p/n) - 1.47)] * (r_{max} - r_o) \quad (1)$$

where

t_p = time since planting, (days)

n = duration of root growth, (days)

The root growth is limited by the water table, but is not reduced if a water table rises into an established root zone.

(ii) Available Water Capacity

$$FC = \theta_{Fc} \text{ x } r_i \text{ x } 1000 \quad (2)$$

where

FC = water content of root zone at field capacity (mm)

θ_{Fc} = volumetric water content at field capacity.

r_i = root depth on day I, (m)

$$PWP = \theta_{PWP} \text{ x } r_i \text{ x } 1000 \quad (3)$$

where

PWP = water content of root zone at permanent wilting point, mm

θ_{PWP} = volume water fraction at permanent wilting point,

r_i = root depth on day i, (m)

$$EAWC = TAWC * P \quad (4)$$

where

EAWC = easily available water content (mm)

TAWC = total available availability water root zone, (mm)

P = fraction of total available water that is easily available, dimensionless.

All soil parameters are weighed according to the fraction of the root zone in the top soil and subsoil where the physical characteristics may be different.

Root zone deficit

The soil water deficit of the root zone is calculated from:

$$SWD = (\theta_{Fc} - \theta) \text{ x } r \text{ x } 1000 \quad (5)$$

where

SWD = Soil water deficit of root zone, mm

r = root depth, m

θ_{Fc} = volume water fraction at field capacity, dimensionless.

θ = volume water fraction at root zone, dimensionless.

Crop transpiration

(i) The potential crop transpiration on any day is given by:

$$T_m = ET_{oi} * Kc_{max} \quad (6)$$

where

Toi = potential transpiration on day i, mm

Kc_{max} = ratio of potential to reference evapotranspiration at maximum cover.

(ii) Actual Crop Transpiration

Actual plant transpiration per unit area of plant, assumed to occur at the potential rate whilst the root zone soil water content is between field capacity (Fc) and the easily available water capacity (EAWC). For excess water, it decreases linearly to zero when the root zone soil water content reaches saturation (SAT), for restricted water supply, it decreases linearly to permanent wilting point (PWP) and remains zero thereafter. This has been shown to be an acceptable simplification for irrigated condition (Ritchie, 1972). Actual crop transpiration was estimated using the method suggested by Brisson (1998).

Runoff estimation

Runoff was estimated using the expression developed by the USDA soil conservation service (SCS, 1972). The impact runoff curve number used in this study is 75, which represents grass as soil surface cover and where the land is used for growing small grain on a sandy loam soil.

Model input and output

The model requires specification of inputs such as weather data soil parameters, crop parameter and model constants. Weather data include daily rainfall, temperature, humidity, and solar radiation. The climatic variables are used to calculate reference crop evapotranspiration using Penman-Monteith equation (Allen et al., 1998). Climate data was imported from text files and screened for missing or out-of-range data. The climate data were then tabulated and saved as a WaSim climate file. Soil parameters consist of moisture content at saturation, field capacity, permanent wilting point and soil type crop parameters include information on cover development and rooting depth (Borg and Grimes, 1989). Irrigation schedules were developed for the three different water treatments.

The model performs the soil water balance of the using a daily time step to give an output including daily values of crop root depth, crop cover, rainfall, runoff, actual ET, irrigation and root zone deficit (Raes and van Aelst, 1985). The model can simulate several growing seasons for one or more crops at the same time.

Field experimentation

The experiment was conducted on a sandy clay loam soil at the teaching and research farm of the Federal University of Technology, Akure Nigeria (latitude 7^o16^1N and longitude 5^o13^1E). A 50 m × 80 m portion of the farm was ploughed and harrowed for effective seed bed formation. Eighteen seed beds each 2.0 m long, 2.0 m wide and 0.15 m deep with 1m spacing between beds forms the micro-sprinkler plots and another eighteen tied-ridges each 10.0 m × 12.0 m forms the drip plot. One micro-sprinkler each was installed at the centre of the eighteen sprinkler plots. The micro-sprinklers were connected to separate supplies (0.04 m^3 capacity reservoir) placed adjacent to each of the beds and deliver water at uniform pressure head of 2 m. The experiment was a 2 × 3 × 3 combination of two irrigation methods (drip and sprinkler systems), three crop phonological stages (emergence/vegetative, fruiting and maturity) and three irrigation levels (M1– well watered, M2 – moderately stressed and M3- severely stressed. The well watered plots were supplied irrigation water at 50 KPa. The moderately stressed plots were supplied water at 60 KPa while the severely stressed plots were supplied water at 70 KPa.

The experimental design was a randomized complete block design (RCBD) with two replications. The experiments were conducted on the same field for 2yr (2005 and 2006). The climate data for these years are as shown in Table 2.

Table 2. Climatic data of the study site during 2005 and 2006.

Year	Month	Mean Maximum Temperature (°C)	Mean Relative humidity (%)	Wind Speed (Km/hr)	Rainfall (mm)
2005	January	33.8	76.5	3.7	0.0
	February	35.1	93.3	4.8	1.4
	March	33.7	95.3	4.3	2.9
2006	January	32.5	99.0	3.3	0.7
	February	34.7	97.5	4.4	0.1
	March	33.2	98.8	4.4	1.5

Soil moisture contents were monitored before and after each irrigation using EC – 5 echo-probes over a depth of 50 cm at an increment of 10 cm. Soil moisture tension over the same range were monitored with tensiometers which were installed at the three irrigation levels. The drainage and actual evapotranspiration were estimated from the water balance approach (Hillel, 1998). Weather data were obtained from an automatic weather station located in the farm and used to estimate reference crop evapotranspiration, using the Penman – Monteith equation (Allen et al., 1998). Irrigation/rainfall depths were measured using catch cans. There were sixteen (16) cans per irrigation level. Rain gauges were placed alongside the catch cans and the average estimated over the total area.

The date of attainment of the different phenological were observed and recorded. Four representative plants were selected random from the three irrigation management levels. The leaf area index was calculated from the surface area using the formula of Gong et al (1995). The plant height was monitored weekly beginning from the 29 day of the year (DOY) to the 77 DOY. Harvestable yields of *A. cruentus* were determined weekly starting from the 50DOY to maturity. Fresh vegetables were harvested from representative plants in each of the treatment plots. The leaves, stem and root were carefully detached for ease of measurement of fresh biomass. Roots were extracted using the trench profile method (Olufayo et al., 1996). The weights were converted to yield per hectare.

Calibration of the WaSim model

Calibration was performed on the first thirty days of the dry season experiment. Three parameters (Growth and Development, Evapotranspiration (ET), Root Zone depth) to be determined were calibrated by fitting the most sensitive observed variables to obtain the corresponding model outputs. The difference between measured and predicted evapotranspiration was used for the crop consumptive use while the difference between measured and prediction yield was used for yield parameters.

Input parameters to the model

Table 3 shows a typical soil, climate and crop inputs into the model during the period of experiment. The input parameters are dependent on the treatments imposed as well as the result of actual measurements on field.

Table 3. Input Parameters to the Model.

Parameters	Values
Soil	
Field capacity (%)	20.5
Permanent wilting point (%)	8.4
Saturation (%)	39.8
Drainage	
Diameter (m)	0.54
Depth (m)	1
Spacing (m)	10
Climate	
Daily rainfall (mm)	–
Daily evapotranspiration	–
Crop data	
Planting date	15/Jan
Emergence date	29/Jan
20% cover	10/Feb
Full cover	15/Mar
Harvest	30/Mar
Max root date	25/Mar
Max cover (%)	95
Mulch cover (%)	0
Planting depth (m)	0
Max root depth (m)	0.3
Irrigation	
Timing: Irrigate at fixed depletion (% TAM)	50
Amount: Return to fixed deficit	0

Data analysis

The field estimated and predicted evapotranspiration, crop cover and root depth evaluated the model over time using the average error A_E, standard error or estimates S_E. Coefficient of variation Cv, and correlation coefficient r. These statistics were used to quantity the degree of under/over prediction and correlation by the models as well as reveal systematic deviations as used by Clemente et al (1994) to evaluate some water flow model.

Results and discussion

Soil water retention characteristics

The soil moisture retention characteristics are presented in Table 4. The soil profile considered which 500 mm deep is was divided into five distinct layers. The field capacity corresponded to a tension of 24KPa while the wilting point corresponded to a tension of 1500KPa. Optimum water extraction occurred over a range of 20 – 600KPa. The depth of root zone of *Amaranthus cruetnus* on average is 30cm depth from soil surface and the maximum allowable deficit for the crop is 50% (0.5).

Table 4. Parameters of the Soil Water Retention for the Sandy Clay Loam Soil.

Soil depth (mm)	Saturated moisture content (Ms), m^3/m^3	Wilting point moisture content (M_w), m^3/m^3	Field capacity moisture content (M_f), m^3/m^3
0 – 100	0.39	0.08	0.20
100 – 200	0.40	0.10	0.23
200 – 300	0.42	0.16	0.24
300 – 400	0.43	0.20	0.26
400 – 500	0.45	0.21	0.27

Crop parameters

The crop growth inputs of rooting depth determined during the experiment is presented in Figures 1. The root reached a depth of 13 mm at 30 days after planting and thereafter reached a maximum of 35 mm at the 78 DOY. The leaf area index rose to about 0.59 at 50 DOY and decreased back to 0.15 at harvest. The measured values of root depth (mm), crop cover (mm) and actual evapotranspiration (mm) and the calibrated values are shown in Table 4.

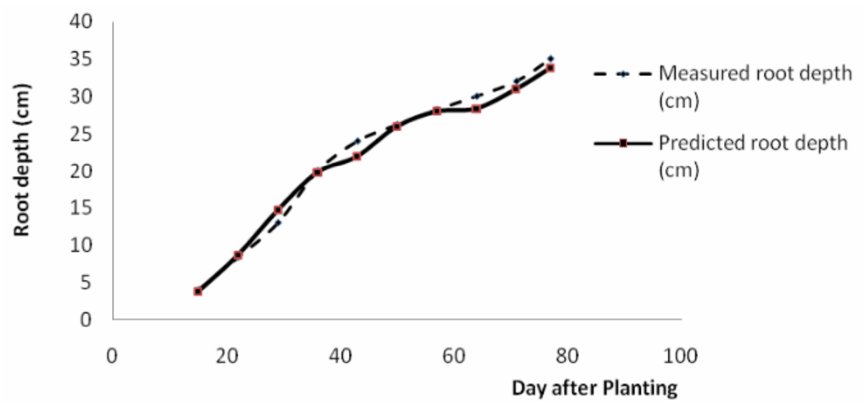

Figure 1. Measured and Predicated root depth on function of days after planting.

The results presented in Table 5 show that the values of the calibrated parameters agree reasonably well with the orders of magnitude published in literatures. A fairly good agreement in the simulated and measured actual evapotranspiration was as a result of the scenario where evaporation and transpiration an inseparable natural phenomenon from soil surface becomes limited due to the canopy interception of solar radiation when the crop is well developed and completely covers the soil, and transpiration becomes the main process of water loss (Jensen et al., 1990).

Table 5. Summary of Crop Parameters Calibrated using WaSim.

Variable used for Calibration		Field Calibrated Value	Values Found in Literature
Root depth (mm)	50KPa	13	10 – 15
	60KPa	10	(Myer, 1996)
	70KPa	8	
Crop cover (mm)	50KPa	27	25 – 30
	60KPa	26	(Walker et al, 1995)
	70KPa	23	
Actual evapotranspiration	50KPa	3.4	3.2 – 5.4
	60KPa	3.2	(Jensen, 1990)
	70KPa	3.0	

The results of simulation for 2005 and 2006 with parameters estimated using data obtained from the field shows that the water simulation model (WaSim) is capable of predicting the root development, crop cover, runoff, actual evapotranspiration, and root zone moisture deficit under different moisture stress levels. Figure 1 presents measured and simulated root depth. Statistical parameters were used to assess the model accurately. The parameters are coefficient of correlation (r^2) root mean square error (RMSE). The model simulated root growth well, the coefficient of determination $r^2 = 0.98$, $P < 0.001$. Also, the actual evapotranspiration from the model prediction and the measured value gave a fairly high coefficient of correlation $r = 0.7$ at $P < 0.001$. The goodness-of-fit statistics MBE and RMSE used for the comparison of model estimates and observed yield values of 2005 dry season experiment are presented in Table 6.

Table 6. Mean bias error (MBE) and root mean square error (RMSE) to compare the simulated and the measured yield values.

Phenological stage	MBE	RMSE
Emergence	0.7600	0.9462
Vegetative/Fruiting stage	-0.4444	1.3526
Maturity/Senescence	-0.3213	1.2341

However, the agreement between the measured and predicted values decreased with decreasing level of irrigation. This could be as a result of the fact that at lower irrigation level, the simulated soil moisture in the upper compartment of the soil profile was generally lower than the measured values and the led to a little variation in the values of actual evapotranspiration.

Conclusion

A model to simulate soil water was calibrated and validated for *A. cruentus*. The model predicted root growth, crop cover and evapotranspiration with reasonable accuracy under three irrigation managements in Nigeria.

The model can be applied to different environmental and water management scenarios mostly in developing countries because only input parameters such as climate, soil, crop parameters and irrigation schedules are needed and these can be obtained from agronomic practice/experiment. The model is useful in regional hydrological studies, crop water requirement and irrigation scheduling in Nigeria.

References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop Evapotranspiration. FAO irrigation and drainage paper 56. Food and Agricultural Organization of the United Nations, Rome, Italy, 300pp.

Borg, H. and Grimes, D.W., 1986. Depth development of root with time: an empirical description. *Trans. ASAE* 29, 194 – 197.

Clemente R.S., De Jong R., Hayhoe H.N., Reyholds W.D., Hares M., 1994. Testing and comparison of three unsaturated soil water flow models. Agricultural Water Management, 25, 135-152.

Crosby, C.T., 1996. SAPWAT 1.0–A Computer Program for Estimating Irrigation Requirements in South Africa. A Water Research Commission Report No. 379/1/96, Pretoria, South Africa.

Gong, P., Ruiliang, Pu, Miller, J.R., 1995. Coniferous Forest Leaf Area Index Estimation along the Oregon Transect Using Compact Airborne Spectrographic Imager Data, PE & RS, 61– 9, 1107–1117.

Hanks, J., Ritchie, J.T., 1991. Modeling plant and soil systems. Agronomy Monograph No. 31, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Hess, T., Counsell, C., 2000. WaSim User Manual, HR Wallingford, Cranfield University, Silsoe, England. Pp: 1-34

Hess, T., Leeds–Harrison, P., Councel, C., 2000. A water balance simulation model for teaching and learning – WaSim. HR Wallingford, Howberg Park, Wallingford, Oxfordshire, OX 108 BA. UK.

Hillel, D., 1998. Environmental Soil Physics. Academy Press, New York. pp. 19–123.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. ASCE Manual and Reports on Engineering Practice No. 70, 332pp.

Mottram R., De Jager J.M., 1994. Research on maximizing irrigation project efficiency in different soil – climate irrigation situations. Water Research Commission Report No. 226/1/94, Pretoria, South Africa.

Myer, R.L., 1996. Amaranth: New crop Opportunity, P. 201-220. Int. J. Jamick (Ed), Progress in New crops. Astts press, Alexandria, V.A.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204 –1213.

SCS, 1972. National engineering handbook. Soil Conservation Service, USDA, Washington, USA

Walker, S., Fyfield, T.P., McDonald, J.P.A., Thackrah, A., 1995. The influence of different water and nitrogen levels on crop growth, water use and yield, and the validation of crop models. Water Research Commission Report No, 307/195, Pretoria, South Africa.

Whisler F.D., Acork B., Baker D.N., Fye R.E., Hodges H.F., Lambart J.R., Lemmon H.E, Mckinion J.M., Reddy V.R., 1986. Crop simulation models in agronomic systems Adv. Agron. 40 (141 – 208).