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USE OF CROPWAT MODEL TO PREDICT WATER USE IN IRRIGATED TOMATO PRODUCTION AT KABETE, KENYA

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ABSTRACT

This study uses CROPWAT model to predict water use in rainfed agriculture and simulated irrigation requirement for tomato production in the Kabete Field Station. The model predicted increased irrigation requirement for a tomato crop of 33.1, 28.1 and 36.6 mm of water, in the 1st, 2nd and 3rd 10-day periods of development stage, respectively. The crop evapotranspiration (ETc) requirements by tomato crop were predicted as 456.5 mm for the short rainy season while actual evapotranspiration (ETa) was 232.1 mm for the short rains giving a yield response factor of 0.49. The model suggested an addition of 253.7 mm of irrigation water in order to realize optimal tomato yields as the crop experienced an irrigation deficiency of 48.8%. The moisture deficit at harvest was 63.6 mm of water which resulted in total yield reduction of 51.3%. In relation to actual yields calculated, the mean potential optimal tomato yields in the study area were 23.3 Mg/ha with proper soil management and adequate water supply. The suggested supply system was at 10 days irrigation interval/stage where the soils were irrigated just below or above field capacity. Rainfall losses and irrigation requirements would be reduced to 41.9 and 267.7 mm, with minimum water deficit at harvest of 15.5 mm and an irrigation efficiency of 100%. At this point, ETa would equal ETm and optimal tomato yield would be obtained with yield losses predicted at 0.1%. Yield gap analysis revealed that radiation, sunshine and temperature are favourable for crop production, but the heavy dependence on rainfall makes the area very vulnerable to drought.

INTRODUCTION

The variability in crop production has implications for food security in sub-Saharan Africa, particularly at household level amongst resource-poor farmers, whose livelihoods are heavily dependent on agriculture. Climate change will affect smallholder farmers especially through increased crop failure. Crop simulation models can predict yield responses to large variations in weather. At every point of application, weather data are the most important inputs. The main goal of most applications of crop models is to predict commercial output such as grain yield, fruits, roots and biomass for fodder. In general the management applications of crop simulation models can be defined as strategic applications (models run prior to planting), practical applications (models run prior to and during crop growth) and forecasting applications (models run to predict yield both prior to and during crop growth). The two main growth models are the regression models that describe the growth course with some functions (e.g. Richards function & polynomials) and mechanistic models that explain the growth course from underlying physiological processes in relation to the environment (Spitters, 1990).

Uncertainties in crop, soil and weather inputs result in uncertainty in simulated grain yield, evapotranspiration (ET) and nitrogen (N) uptake, which vary depending upon the production environment (Aggarwal, 1994). Uncertainties in outputs increase as the production system change from a potential production level to a level where crop growth is constrained by limited availability of water and nutrients. Most of the uncertainties in outputs are caused by variable soil. Crop and weather inputs could be represented if the outputs are determined using fixed soil and crop data, and a large series of weather data (Aggarwal, 1994).

Maximum crop production is closely related to the availability of water. Transpiration may be reduced by the application of an antitranspirant (AT) that would increase leaf resistance to diffusion of water vapor (Irmak and Jones, 2000).

The CROPWAT model is user-friendly and has been successfully used to calculate the impact of climate change on crop water use (Teklu and Hammer, 2006). The program is used for simulating crop yield response to water and is a decision support system developed by the Land and Water Development Division of the FAO (AQUASTAT, 2009). Its main functions are to calculate reference evapotranspiration, crop water and irrigation requirements in order to develop irrigation schedules under various management conditions and scheme water supply and to evaluate rain fed production, drought effects and efficiency of irrigation practices.

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CROPWAT uses procedures for predicting yields when all the climate, soil and crop parameters are known. The approach allows estimation of actual evapotranspiration (ETa or actual crop water use), after having estimated the stress factor (Ks) from the ratio of actual to potential yield.

The advantage of using the CROPWAT model as a tool for assessing crop water use is that it is simple and easy to use, and its data requirements are less intense than those of other dynamic models such as ARCU, WOFORST and DSSAT (Teklu and Hammer, 2006). CROPWAT requires only monthly inputs of climate and rain data, coupled with crop parameters and soils data, to calculate water and irrigation requirements. CROPWAT is not a crop growth model but an irrigation planning and management aid (Teklu and Hammer, 2006). To calculate crop water use with CROPWAT, the model requires total available soil moisture (mm/m depth), maximum rain infiltration rate (mm/day), maximum rooting depth (m) and initial soil water depletion (%). Production area, and planting date and cropping pattern is also required. For each crop, crop coefficients and growth stage length are essential inputs. To calculate the actual crop water use, the maximum yield of the crop grown (Ym) and the yield reduction factor (Ky) are required. The maximum yields for the different crops grown and the yield reduction factors according to Irrigation and Drainage Paper No. 33 are reported by Durand (2004). The model has been successfully used for analysis of crop water requirements in Kenya (Karanja, 2006), Senegal (Diop. 2006), and scheduling of irrigation in Canada (Doria *et al*., 2009), Syria (Ibrahim and Yacoub, 2009) and in China (Feng *et al*., 2009). The aim of this research was to assess suitability of tomato production in Kabete and predict potential tomato (*Lycopersicon esculentum*, variety Cal J) yields using CROPWAT model.

MATERIALS AND METHODS

Study area

The study was carried out at Kabete Campus Field Station, University of Nairobi. The Field Station farm lies 1°15′ S and 36° 44′ E and is at an altitude of 1940 m a.s.l. The site is representative, in terms of soils and climate, of large areas of the Central Kenya highlands. The geology of the area is composed of the Nairobi Trachyte of the Tertiary age. The soils are well-drained, very deep (> 180 cm), dark red to dark reddish brown, friable clay. The soil is classified as humic Nitisol (FAO, 1990, WRB, 2006). There is no surface sealing or crusting and the profile has clay cutans throughout the B-horizon. The groundwater is more than 30 m deep and runoff is negligible in the research plots. Slope gradient is relatively flat. According to the Kenya Soil Survey agro climatic zonation methodology (Sombroek *et al*., 1980), the climate of the study area can be characterized as semi-humid. The ratio of annual average rainfall to annual potential evaporation, r/Eo is 58%. The site experiences a bimodal rainfall distribution with long rains in mid March – May and the short rains in mid October – December. The mean annual rainfall is 1006 mm. The land is suitable for horticultural crops such as kales (*Brassica oleracea*), tomatoes (*Lycopersicon esculentum*), cabbage (*Brassica oleracea*), carrots, (*Daucus carota*), onions (*Allium fistulosum*), fruit trees such as avocadoes (*Persea americana*) and coffee (*Coffee Arabica*). Tomato was transplanted at 90 x 90 cm in all plots from the nursery and grown under rainfed conditions. All agronomic practices such as weeding, pest and disease control were carried out according to the prevailing local conditions. Weeding was initially done two weeks after transplanting and thereafter any weeds growing in the field were uprooted. Spraying with Dithane M45 (2.5 kg/ha) was done early in the season. Thereafter, the plants were closely monitored for any disease or pest incidences.

CROPWAT model

The program used for simulating crop yield response to water (CROPWAT) is a decision support system developed by the Land and Water Development Division of the FAO (AQUASTAT, 2009). Its main functions are to calculate reference evapotranspiration, crop water requirements and crop irrigation requirements in order to develop irrigation schedules under various management conditions and scheme water supply and to evaluate rain fed production, drought effects and efficiency of irrigation practices. It uses procedures for predicting yields when all the climate, soil and crop parameters are known. This approach allows estimation of ETa and Ks, from the ratio of actual to potential yield.

The test crop was tomato (*Lycopersicon esculentum*), variety Cal J. The crop cycle length was 120 days with development stages of 15, 30, 40 and 35 days for initiation, vegetative, reproductive and maturity, respectively. The start and end of the growing cycle was 22nd November 2001 and 21stMarch 2002, respectively. The overall crop coefficient (Kc) values were calculated using Smith (2000), and Van Ranst and Verdoodt (2005) methods. Data on wind speed, temperature, relative humidity, radiation and rainfall were collected from the Kabete Field meteorological station. Soil chemical properties for the surface soil was determined in the laboratory and data used to calculate fertility index. The fraction of Readily Available Moisture (RAM), p, was calculated as described by Taylor and Ashcroft (1972). The crop factor was calculated at four different stages, namely, the initiation, vegetative, reproductive and maturity stages. Graphs and equations were used to obtain initial crop coefficient (Kc-ini) using initial potential evaotranspiration (ETo) and frequency wetting events and taking into consideration soil texture (Doorenbos and Pruitt; 1977; Van Ranst and Verdoodt, 2005). The effective precipitation was calculated using CROPWAT version 8 model according to USDA method (FAO, 2009). Water use efficiency (WUE) was computed as the dry matter yield per unit of water evapotranspired by the tomato crop following Cooper *et al.* (1988) method. Calculation of reference evapotranspiration (ETo) was done using the Penman-Monteith method (Allen *et al.*, 1998).

Rainfall data collection and effective rainfall method

The precipitation data required for CROPWAT 8.0 can be daily, 10-day period (decade) or monthly rainfall, commonly available from many weather stations. To account for the losses due to runoff or percolation, a choice can be made of one of the four methods given in CROPWAT 8.0 (Fixed percentage, Dependable rain, Empirical formula, USDA Soil Conservation Service). In general, the efficiency of rainfall decreases with increase in rainfall and for most rainfall values below 100 mm/month, the efficiency is approximately 80%. In the water balance calculations included in the irrigation scheduling part of CROPWAT, it is possible to evaluate actual efficiency values for different crops and soil conditions.

Crop and cropping pattern information and data collection and data processing

To determine the irrigation requirements of the study area, an assessment was made on the various crop characteristics such as length of the growth cycle, crop factors and rooting depth. Essential information collected from the field included crop and crop variety, planting and harvesting dates. The information on length of individual growth stages, reference evapotranspiration, rooting depth, allowable depletion levels and yield response factors were collected from the Research Station.

Crop water requirement (CWR) calculations

Calculation of the CWR was carried out by re-calling successively the appropriate climate and rainfall data sets, together with the crop files and the corresponding planting dates entered initially in the model. Soil data was also required, together with soil categories such as texture, depth and drainage qualities and suitability for upland crops. The Soil module is essentially data input, requiring the following general soil data; Total Available Water (TAW), maximum infiltration rate, maximum rooting depth and initial soil moisture depletion.

Irrigation scheduling

An important element of CROPWAT 8.0 is the irrigation scheduling module, which has several application possibilities: 1) to develop indicative irrigation schedules, 2) for the agricultural extension service to promote better irrigation practices, 3) for the irrigation service to establish improved rotational delivery schedules, 4) to evaluate existing irrigation practices on water use efficiency and water stress conditions, 5) to evaluate crop production under rainfed conditions, 6) to assess feasibility of supplementary irrigation and to develop appropriate irrigation schedules and, 7) to develop alternative water delivery schedules under restricted water supply conditions.

The calculations of the scheduling module were based on a soil water budget, where, on a daily basis, the soil moisture status was determined, accounting for incoming and outgoing water in the root zone.

Development of indicative irrigation schedule and scheduling procedures

To determine the irrigation water supply for a given crop in terms of frequency and irrigation depth, and assuring optimal crop growth and efficient water use, the irrigation schedule should meet the requirements of the field irrigation method practiced and the operational criteria of the irrigation system. The validity of the schedule for different soil types and for variable rainfall conditions was assessed. The essential information required for the development of an indicative schedule was planting date, climate, soil type, irrigation method, net application and Irrigation supply. After processing of CWR calculations and soil data input, the timing and application options were selected on the basis of the information previously collected.

To obtain optimal tomato yield for the study area, the CROPWAT version 8 was used to schedule irrigation required to cater for the water deficit and to reduce water stress (Ks) which was calculated as follows: Ks = (TAM - Dr) / RAM, where TAM is Total Available Moisture, RAM is the Readily Available Moisture and Dr is the drainage flux. The best practice was to maintain water at the level of extraction that does not affect yield to save on energy for pumping water. For tomatoes, it is the point reached after 60 % of available water has been extracted (P = 0.4) (FAOSTAT, 2001). In order to develop the irrigation schedule which would fit these requirements, an interactive procedure was followed in which several runs were made with different timing and application options.

RESULTS AND DISCUSION

Climatic data

The climatic data and the potential evapotranspiration during the study period are presented in Table I. The ETo on average was 3.64 mm while wind speed was 103 km/day. The average sunshine hours were 6.6 meaning the sky was overcast most times of the day. The Tmax and

TABLE I- CLIMATIC DATA AND POTENTIAL EVAPOTRANSPIRATION (ETO)

Month	T Min oC	T MaxoC	RH%	Wind km/day	Sunshine hours	Rad MJ/m2/day	ETo mm/day	Rain (mm)	Eff rain (mm)
January	13.9	24.5	70	117	9.7	23.5	4.2	52.0	47.7
February	13.5	26.0	60	139	9.3	23.7	4.8	69.1	61.5
March	14.4	24.6	70	108	7.3	20.9	4.1	84.2	72.9
April	15.2	23.5	80	112	6.8	19.7	3.7	278.7	152.9
May	14.2	22.7	70	55	5.9	17.4	3.3	134.3	105.4
June	12.2	21.6	70	42	4.8	15.2	2.8	1.6	1.6
July	11.3	22.1	70	59	3.9	14.2	2.7	6.6	6.5
August	12.5	20.1	70	64	4.1	15.1	2.8	6.1	6.0
September	12.3	23.8	60	108	6.3	19.1	3.8	22.3	21.5
October	14.1	24.3	70	143	7.2	20.4	4.1	58.6	53.1
November	14.1	22.0	80	116	6.6	18.9	3.5	192.5	133.2
December	13.8	22.9	70	167	7.5	19.8	3.84	12.4	12.2
Total	-	-	-		-	-	-	918.4	674.4
Average	13.5	23.2	70	103	6.6	19.0	3.64	-	-

T = temperature; min = minimum; max = maximum; RH = relative humidity; Rad = radiation; ETo = evapotranspiration

Tmin were 23.2 and 13.5°C which was ideal for optimal tomato growth (Peralta and Spooner, 2007).

The climatic factors most affecting crops are the intensity and duration of rainfall, the relationship between annual rainfall and potential evapotranspiration, and the year-to-year variation in rainfall. The length of the growing season depends on rainfall, evaporation and temperature, soil factors and on crop factors (Sombroek *et al*., 1980; Macharia, 2004).

The shows effective precipitation of the study area (USDA Soil Conservation Service) was 674.4 mm throughout the year (Table I). The effective precipitation was high in November, the time the growing season commences for the short rains. This effective rainfall decreased to 47.7 mm in January and at harvest in March, rainfall increased to 72.9 mm. Excess rain is not conducive to maturity as it damages the crop. Rosenzweig *et al*., (2002) indicated crop damage would occur due to excess rainfall. Tomato requires a relatively cool, dry climate for high yield and premium quality though it is adapted to a wide range of climatic conditions from temperate to hot and humid tropical (Njonga, 2009; Varela *et al.*, 2003)

The effective precipitation was highest from March to May and from October to November, a reflection of the long and short rains, respectively. In between the two periods, effective rainfall was very low and tomato production therefore required irrigation. Karanja (2006) observed that the effect of rainfall changes could implicitly be demonstrated by the decrease in the amount of irrigation water needed following an increase in the amount of rain. Also the patterns of irrigation water requirement and field water supply deviated from the observed trends in response to temperature changes. This is likely to be the case in this study because the increase in rainfall satisfies a greater portion of crop water requirement so that less irrigation water is required. Planting crops in low rainfall months of June, July, August and December would therefore mean higher irrigation to meet crop water requirements.

Crop water requirements for tomato under rain fed agriculture during the short rains are shown in Table II. The Kc at initiation stage was 0.58 while ETc was 20.4 and 18.3 mm per day and per decade, respectively. Effective rainfall at this stage was 33.6 mm per decade, suggesting it was sufficient for tomato growth. The leaf area was minimal, and actual evapotranspiration was predominantly in form of soil evaporation. The low Kc value observed at this stage was because the crop was just establishing itself with low canopy and there was very little ground cover hence minimal water requirement. This is because the higher the evaporative demand from the atmosphere, the faster the soil dries and the smaller the Kc value (Van Ranst and Verdoodt, 2005). The typical initial Kc values (Kc-ini) reported for vegetables such as tomatoes, cucumbers and egg plants are 0.6 (FAO, 2008) and are similar to those observed in the study area. Amount of available water in the top soil for evaporation and time for soil to dry is a function of the magnitude of wetting events. The time for soil surface to dry was determined by the time interval between wetting events (rainy days), evaporative demand of the atmosphere (ETo) and the importance of wetting events.

At vegetative stage, the Kc values increased to 0.6, 0.73 and 0.9 in decade 1, 2 and 3, respectively. The ETc

TABLE II - CROP WATER REQUIREMENT FOR TOMATO UNDER RAIN FED AGRICULTURE AT KABETE FIELD STATION

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/decade	Eff rain mm/dec	Irr. Reqmm/decade
Nov	3	Init	0.58	2.04	18.3	33.6	0.0
Dec	1	Dev	0.60	2.21	22.1	9.1	13.1
Dec	2	Dev	0.73	2.81	28.1	0.0	28.1
Dec	3	Dev	0.90	3.60	39.6	3.2	36.3
Jan	1	Rep	1.04	4.33	43.3	12.6	30.7
Jan	2	Rep	1.06	4.57	45.7	16.9	28.8
Jan	3	Rep	1.06	4.73	52.0	18.1	33.9
Feb	1	Rep	1.06	4.96	49.6	19.0	30.6
Feb	2	Mat	1.04	5.05	50.5	20.5	30.0
Feb	3	Mat	0.96	4.41	35.3	21.8	13.5
Mar	1	Mat	0.87	3.75	37.5	20.9	16.7
Mar	2	Mat	0.77	3.16	31.6	21.0	10.5
Mar	3	Mat	0.72	2.84	2.8	2.8	2.8
Total					456.5	199.5	275.1

Init = initiation; Dev = development, Rep = reproductive, Mat = maturity, Eff = effective rain, Irr = irrigation requirements, Kc = crop coefficient, ETc = crop evapotranspiration

also increased to 2.21, 2.81 and 3.96 mm/d in decades 1, 2 and 3, respectively. As tomato crop developed and shaded the ground, evaporation became more restricted and transpiration gradually became the major process of water loss from the soil. At this stage, effective rainfall decreased, and irrigation water requirement to meet the crop transpiration demand was 33.1, 28.1 and 36.6 mm water in decades 1, 2 and 3, respectively. The rapid development of the crop at this stage required a lot of water indicating a yield reduction possibility as rainfall was not enough. Water depletion at this stage was very rapid and increased as the crop developed (Figure 2) and was more than the Readily Available Moisture (RAM). This was an indicator that optimal tomato yields could not be realized. Vegetative stage caused the highest tomato yield reduction of 52.3% (Table IV) compared to all other stages as the model indicated. The Kc and ETc reached maximum value of 1.06 and 52 mm per decade at reproductive stage, respectively. The maximum Kc value reported for vegetable crops such as tomato at this stage is 1.15 (FAO, 2008).

The Kc values are within the typical values given by Allen *et al.* (1998) and FAOSTAT (2001) for annual, perennial and horticultural crops. Effective rainfall though low, was higher than at vegetative stage leading to a yield reduction of 47.4% which was 5.8% lower than at vegetative stage. Optimal yields again could not be realized because the crop was not meeting its transpiration requirements as the water depletion from soil was way beyond the RAM (Figure 2). To mitigate the water stress, irrigation requirements of 30.7, 28.8, 33.9, 30.6 and 30.6 mm per decade for the 4 decades in this stage was required.

At maturity, Kc values decreased from 1.04 to 0.72 at the end of harvest while ETc decreased from 5.05 to 2.84 mm d-1 in the same period. Effective rainfall also decreased to 2.8 mm per decade at end of harvest. Irrigation requirement was low at this stage though rainfall was also low indicating a change in crop water requirement. The crop was undergoing senescence at this stage, shedding leaves, leading to less ground cover, roots are moribund, and few fruits remaining hence less water requirements. Less ground cover means the Kc values are also low and moisture loss is both by direct evaporation and transpiration. A typical value of 0.8 is given by FAO (2008) and is close to the value obtained in the study area.

The overall, ETc value required for optimal production with enough water (rainfall and /or irrigation) is given using CROPWAT crop irrigation schedule in Table III as 456.5 mm in the study area. However, the ETa was 232.1 mm, a value which was below the ETa. This resulted in tomato relative yield decrease (Ky) of 0.49 due to water limitation. The model indicated an irrigation deficiency of 48.8%. The crop experienced moisture deficit of 63.6 mm and the model suggested an irrigation requirement of 253.7 mm of water in order to realize optimal tomato yields.

Figure 1 shows the predicted irrigation water requirements from initiation stage to maturity of tomatoes in the study area. Irrigation requirement was low at initiation and increased to a maximum at development and reproductive stages; and then decreased at maturity (Figure 1). The most sensitive growth periods of tomato to water deficit is when actual evapotranspiration is less than maximum crop evapotranspiration (ETa < ETm) and are highest at flowering > yield formation > vegetative period in that order; particularly during and just after transplanting (Doorenbos and Kassam, 1979).

The TAM was 95 mm at maximum compared to RAM that was about 30 mm (Figure 2). The moisture depletion level was high at tomato vegetative stage compared to other development stages reflecting a higher water use by the crop at this stage. This depletion was beyond the RAM during tomato vegetative development stage. The rapid growth combined with the relatively poor ground cover even with enough irrigation water could have led to high atmospheric water demand which gave rise to ETa of less than 100% and higher water irrigation requirements compared to other stages. This situation resulted in yield reduction reflected among the development stages. However, this reduction is negligible and can be ignored when recommending this option. Higher rainfall was experienced at maturity but crop water requirement was low.

The ETc reduced by 48.8 % and this equals deficit irrigation schedule (Table III), and overall crop yield was reduced by 51.3 % (Table IV). This implies that the yield was 51.3 % less than optimal tomato yield that can be obtained with adequate water. At 199.5 mm of effective rainfall, the crop was not able to fully transpire and meet its requirement indicating that 275.1 mm of irrigation water was necessary for optimal tomato yield.

Irrigation scheduling for optimal tomato growth

Results show that tomato yield was substantially affected by stress in the latter part of its growing stage, which may cause premature senescence of the crop (Table V). Supplementary irrigation at this growth stage would result in an increase in tomato yields. Supplementary irrigation of 267.1 mm, when considering data for a wet year, would guarantee an optimal tomato production.

After the processing of CWR calculations and soil data input on the basis of the information previously collected (Table V), option 4 was recommended to irrigate at 10 days fixed interval per stage to refill the soil to below or above field capacity, respectively.

The overall reduction in yield was negligible at 0.1% meaning optimal yields would be attained at this irrigation schedule since ETa is equal to ETm at 453.7 mm (Table VI). Irrigation was only done at 10 day intervals (one decade) in various stages on the dates shown when Ks approached a unit and moisture depletion was above 16% of the total available moisture content. Reduction in ETc was negligible at 0.5% during vegetative growth and overall reduction in the season was 0.1% leading to the yield loss of 0.1%. The yield response factor depicts amount of loss expected at certain stages in the development of a crop due to moisture stress. For tomatoes, the highest yield reductions of 1.1 and 0.8 are likely to take place at vegetative and reproductive stages, respectively. These are the critical stages that must be given adequate water to achieve optimal yields (Nurrudrin and Madramootoo, 2001; Obreza *et al*., 2010; Patanè and Cosentino, 2010). Water can therefore

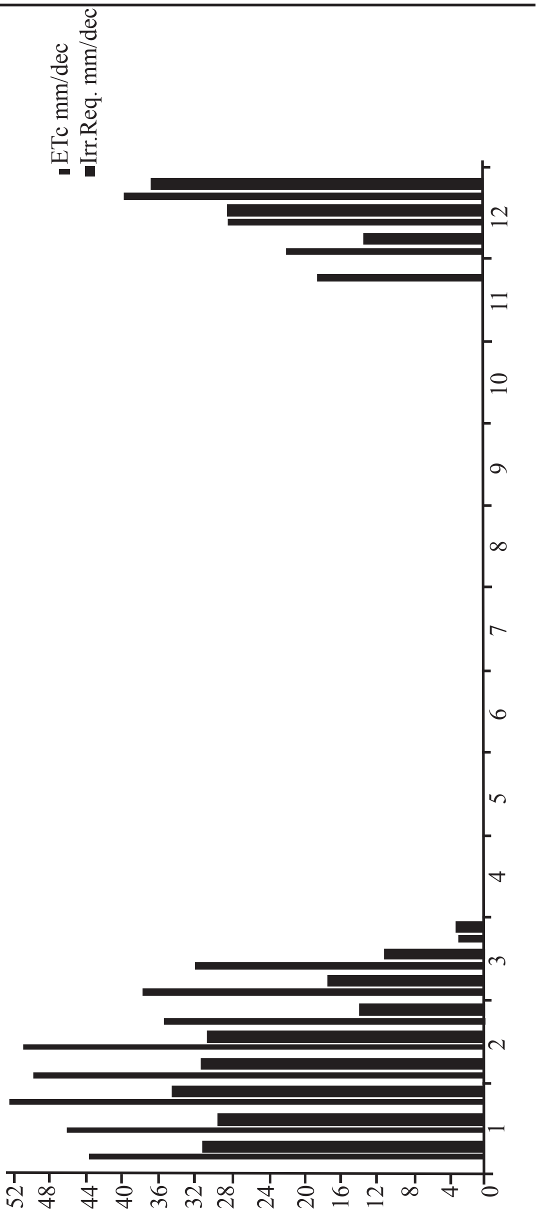

Figure 1. Irrigation water requirement to meet optimal production of tomato crop using CROPWAT

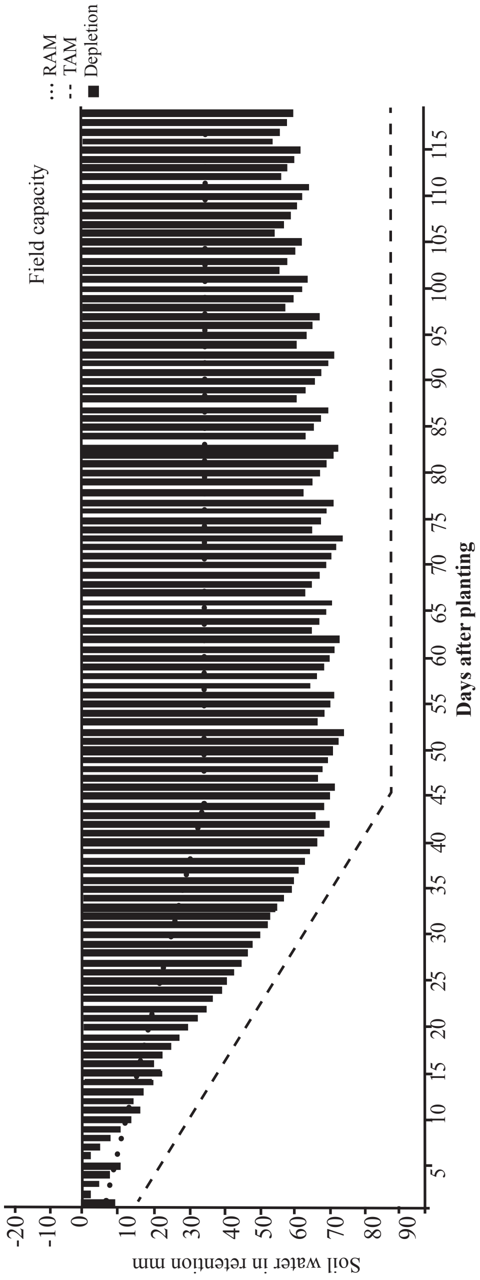

Figure 2. CROPWAT suggested irrigation scheduling graph showing total available water (TAM), readily available water (RAM), water depletion and field capacity during tomato development of rain fed tomato

be saved at initiation and maturity as its demand at these stages is minimal.

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TABLE III- ACTUAL IRRIGATION REQUIREMENT, DEFICIENCY IRRIGATION AND MOISTURE DEFICIT AT HARVEST OF RAINFED TOMATO CROP

	Rainfed tomato
Total rainfall loss	28.1 mm
ETa	232.1 mm
ETm	453.7 mm
Yield response ky = $\frac{ETa}{ETm}$	0.49
Deficiency irrigation schedule	48.8 %
Moisture deficit at harvest	63.6 mm
Actual irrigation requirement	253.9 mm
Efficiency rain	87.7%

ETa = actual crop evapotranspiration; ETm = maximum crop evapotranspiration

TABLE IV- CROP YIELD AND EVAPOTRANSPIRATION REDUCTIONS AT EACH DEVELOPMENT STAGE

Development stage	Initial	vegetative	reproductive	maturity	season
Reduction in ETc	0.2	47.5	59.2	46.7	48.8%
Yield response factor Ky	0.4	1.1	0.8	0.4	1.05
Yield reduction	0.1	52.3	47.4	18.7	51.3%
Cumulative yield reduction	0.1	52.3	74.9	79.6	51.3%

ETc = crop evapotranspiration; Ky = yield reduction factor

TABLE V - EVALUATION OF TIMING AND APPLICATION OPTIONS

Runs	Timing and Application options	R loss (mm)	Deficit at harvest (mm)	ETa (mm)	ETm (mm)	Irr Loss (mm)	Irr eff (mm)	R eff, (mm)	Actual irr Req (mm)	Yield reduction %
1	Irrigate at below or above FC and refill above or below FC	44	15.5	453.7	453.7	0.0	100.0	80.7	269.9	0.0
2	Irrigate at critical depletion and refill at below or above FC	47.3	12.6	453.7	453.7	0.0	100.0	79.3	273.1	0.0
3	Irrigate at critical depletion and fixed depth (40 mm)	65.1	12.6	453.7	453.7	90.4	77.0	71.4	290.9	0.0
4	Irrigate at 10 days interval/ stage and refill below or above FC	41.9	15.5	453.2	453.7	0.0	100.0	81.6	267.7	0.1
5	Irrigate at fixed depletion and fixed depth of 40 mm each	50.2	15.5	441.8	453.7	0.0	100.0	78.0	276.0	2.7
6	Rain fed agriculture	28.1	63.6	232.1	453.7	0.0	-	87.7	253.9	51.3

R = rainfall; Eta = actual evapotranspiration; ETm = maximum evapotranspiration; irr = Irrigation; eff = efficiency

REFERENCES

[1.] Aggarwal, P.K. (1994). Uncertainties in crop, soil and weather inputs used in growth models: Implications for simulated outputs and their applications. *Agric Systems*. 48 (3):361-384.

[2] Allen, R.G; Pereira, L.S; Raes, D and Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation and drainage paper* 56, FAO, Rome.

[3] AQUASTAT. (2009). FAO's Information System on Water and Agriculture.

[4] Cooper, P.J.M., Campbell, G.S., Heath, M.C. and Hebblethwaite, P.D. (1988). In: World Crops: Cool Season Food Legumes. (Ed. Summerfield, R.J.)(Kluwer Academic Publishers, Dordrecht, Netherlands). Pp. 813-829.

[5] Diop, M. (2006). Analysis of crop water use in Senegal with the CROPWAT model. Agro-climatologist, Institut Sénégalais de Recherches Agricoles (LERG/ISRA), Campus universitaire del'ESP.

[6] Doorenbos, J. and Kassam, A.H. (1979). Yield response to water. *FAO Irrigation and Drainage* Paper 33, FAO, Rome, 193 pp.

[7] Doorenbos, J. and Pruitt W.O. (1977). Crop water requirements. *FAO Irrigation and Drainage* paper No 24.

[8] Doria, R., Madramootoo, C.A. and Mehdi, B.B. (2009). Estimation of future crop water requirements for 2020 and 2050 using CROPWAT. Brace Center for Water Resources Management, Macdonald Campus of McGill University, Montreal, Canada.

[9] FAO (2009). Climate change talks should include farmers. Agriculture in developing countries could play crucial role in mitigating greenhouse gas emissions. FA Newsroom. 2ndApril , Rome.

[10] FAO (2008). Global map of monthly reference evapotranspiration – 10 arc minutes, GeoNetwork: grid database, Food and Agriculture Organization, Rome, http://www.fao.org/geonetwork/srv/en/resources.get?id=7416\&fname=ref evap fao 10min.zip\&access=private, last access: 15 October 2008.

[11] FAO (2006). Agricultural data FAOSTAT. Food and Agriculture Organization of the United Nations. Rome, Italy.

[12] FAO (1990). Soil map of the world, revised legend. Food and Agricultural Organization of United

Nations, Rome.

[13] FAO-AGL. (2002). Crop Description and Climate. Land and Water development division. *Agriculture* 21.

[14] FAOSTAT. (2001). Extent and Productivity of Cultivation and Livestock Production Systems in Northern. Africa Environment Outlook. Past, Present and Future Perspectives.

[15] Feng, Z; Liu, D. and Zhang, Y. (2009). Water requirements for irrigation. Scheduling of spring maize using GIS and CROPWAT model in Beijing-Tianjin-Habei region. *Earth Environ. Sci. Chinese Geographical Science*. Vol. 17(1): 6-63.

[16] Gachene, C.K.K., Wanjogu, S.N. and Gicheru, P.T. (1989). The distribution, characteristics and some management aspects of sandy soils in Kenya. Paper presented at the International Symposium on Managing Sandy Soils, Jodhpur, India.

[17] Ibrahim, B. and Yacoub, A. (2009). Using CROPWAT model for scheduling irrigation and determining water use of cotton in two areas of Syria. *Arab Gulf J.of Sci res*. Vol. 27(1-2). Pp 70-77.

[18] Karanja F.K., 2006: Cropwat model analysis of crop water use in six districts in Kenya. CEEPA discussion paper no. 35, ISBN 1-920160-35-3, Center for Environmental Economics and Policy in Africa, University of Pretoria.

[19] Landon, J.R. (1991). Booker Tropical Soil Manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman, Essex.

[20] Macharia, P. (2004). Gateway to Land and Water Information: Kenya National Report.Kenya Soil Survey, 29th July 2004.

[21] Njonga, B. (2009). Tomato: Conditions for successful production. Farmer's voice.

[22] Nuruddin, M. Md, Madramootoo, C.A., Dodds, G.T. (2003). Effects of water stress on tomato at different growth stages. *J. of HortScience* vol. 38 (7): 1389-1393.

[23] Obreza, T.A., Pitts, D. J., McGovern, R.J. and Spreen, T.H. (2010). Deficit Irrigation of Micro-Irrigated Tomato Affects Yield, Fruit Quality, and Disease Severity No 4626. Florida Agricultural Experimental Station, University of Florida. 2001.

[24] Patanè, C. and Cosentino, S. L. (2010). Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. *Agric. Water Management* 97 (1): 131-138.

[25] Peralta, I.E., Spooner, D.M. (2007). History, origin and early cultivation of tomato (Solanaceae). In: Genetic improvement of solanaceous crops. In M. K. Razdan and A.K. Mattoo (eds). 2. Enfield, NH: *Science Publishers*. 1-27. Tomato.

[26] Smith, M. (2000). The application of climatic data for planning and management of sustainable rainfed and irrigated crop production. *Agric and For. Meteo*., 103(1-2): 99-108.

[27] Sombroek, W.G., Braun, H.M.H. and Van Der Pouw, B.J.A. (1982). The Exploratory Soil Map and Agro climatic Zone Map of Kenya. Report No.E1. *Kenya Soil Survey, Nairobi, Kenya.*

[28] Spitters, C.J.T. (1990). Crop Growth Models: Their Usefulness and Limitations. ISHS *Acta Horticulturae* 267: VI Symposium on the Timing of Field Production of Vegetables.

[29] Taylor, S.A. and Ashcroft, G.M. (1972). Physical Edaphology. *The physics of irrigated and non-irrigated soils,* Freeman, San Francisco, CA (1972) 435 pp.

[30] Teklu, Y. and Hammer, K. (2006). Farmers' perception and genetic erosion of tetraploid wheats landraces in Ethiopia. *Genetic Res. and Crop Evolution*, 53: 1099-1113.

[31] Van Ranst, E. and Verdoodt, A. (2005). Land Evaluation. *Quantitative Methods in Land Evaluation* 1-3.

[32] Varela, A.M., Seif, A.A. and Loehr, L. (2003). A Guide to IPM in Tomato Production in Eastern and Southern Africa. ICIPE, Kenya. ISBN: 92 9064 149 5

[33] World Reference Base for Soil Resources (WRB). 2006. A framework for International Classification, Correlation and Communication. *World Soil Resources Reports 103.*