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Modelling Water Productivity Of Maize Crop under Deficit Irrigation Using Aquacrop Model

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Abstract: ***Water virtually and across the world is a dynamic limited resource and the dramatic increasing population mainly in developing countries requires significant increase in food production. Inadequate water utilization in arid and semi-arid regions are used to improve crop water productivity. Irrigation optimization strategy at field level considers scheduling parameters, when and how much to apply, for each water application is viable. Optimizing control and scheduling parameters in irrigation is one major interconnected problems. The study conducted at Eldume irrigation scheme, Kenya sought to highlight the application of AquaCrop model to simulate crop water productivity of maize crop in arid and semi arid climatic condition. AquaCrop model focuses on water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration. An on-field trial experiments were conducted in four randomized block treatments each having three replicates with varied water stress levels. The fields were planted with maize crops Duma 43 cultivar with different irrigation schedules ranging from 5, 7, 10 and 12 days irrigation intervals. The climatic parameters, soil and crop characteristics were used as input to the crop model and the results were used to assess the model performance. The AquaCrop model was calibrated and validated based on data obtained from irrigation schedules for the trial experiments and for the simulation period between 5th December, 2017 to 9th March, 2018. The model prediction indicated reasonable results: canopy cover range (R2 = 0.81 to 0.99), biomass production range (R2 = 0.89 to 0.98), and grain yields range (R2 = 0.82 to 0.96), however the model tracked the influence of soil, climate, crop parameters and seasonal evapotranspiration on crop growth. In 5 days irrigation interval the maize yield produced was 6.18 ton/ha when gross irrigation water depth of 1,631mm (16,310m3/ha) was applied. The 7 days irrigation interval produced 5.26 ton/ha under 1,170mm (11,700m3/ha), 10 days interval yielded 4.09 ton/ha with 792mm (7,920m3/ha) and the 12 days irrigation interval produced 3.02 ton/ha under 672mm (6,720m3/ha) respectively in the growing season. Optimization shown yield felt within 5% of yield target for most of simulated treatments. The weekly (7 days) irrigation interval had the maximum maize yield with corresponding financial benefit achieved under limited water use. This was recommended irrigation schedule fit for effective arid to semi-arid regions water application for short season maize crop variety.***

Keywords: Optimization, simulation, water scarcity, semi-arid environment

1. Introduction

Irrigated agriculture is one of the significant means of increasing agricultural production. It is essential in arid environments and is often used to increase crop water productivity in semi-arid and humid regions. Over years, empirical experience has shown that irrigation increases yield of most crops by between 100 and 400 per cent (FAO, 2009). It is expected that, over the next 30 years, 70% of the grain production will be from irrigated land in the world. Kenya's total irrigated area potential is about 539,000 hectares. The physical environment of these locations is fragile and mainly in the 3rd production zone characterized with inadequate rainfall between 250-750 mm per year (NIB strategic plan, 2008).

Improved water management, notably irrigation is one of the means to increase agricultural production and Kenya's potential for irrigated agriculture is quite substantial (World Bank, 1983). Because of the increasing demand for water resource for general purposes, the supply available for irrigation is decreasing and irrigation costs are rising. In the near future, irrigated agriculture will need to produce two-thirds of the increase in food products required by a larger population (English *et al.*, 2002). The growing dependence on irrigated agriculture coincides with an accelerated competition for water and increased awareness of unintended negative consequences of poor design and water management (Cai *et al.*, 2003). Water stress conditions has resulted in the abandonment of million hectares of irrigated land and reduced maize yields on millions more hectares.

Kenya faces the problem of securing an adequate food supply for its fast increasing population (McCarthy and Mwangi, 1979; Senga, *et al.*, 1981; World Bank, 1983; Kliest, 1985). Despite Kenyan government emphasis on irrigated agriculture, the challenge anticipated is that agricultural sector will compete with domestic and industry for the increasingly scarce water resources, while it is under pressure to produce more food and fibre with less water to satisfy the needs of its rapid growing population. Model results with regard to crop performance, management, and yield estimates will help decision makers to decide which management system is suited best for a particular field, by estimating the yield and crop water productivity optimum. The most frequently applied crop yield models are: CERES, CropWat, CropSyst, DSSAT, EPIC, SWAP/WOFOST, and AquaCrop (Hunink & Droogers, 2011).

In the study of this region, the focus was undoubtedly the improved water use efficiency in distribution of the available limited water resources and scheduling management. AquaCrop modeling tool was applied in this study to simulate irrigation scenarios with the aim of coming up with effective irrigation schedule for optimal maize crop production to water deficit environment.

2. Materials and Methods

This chapter presents the procedure applied in the determination of various input parameters significant to AquaCrop model. The parameters include the meteorological data, soil and crop characteristics in order to investigate the influence of water stress on crop performance in terms of crop water productivity. The study focusing on maize crop (Zeamays) was carried out in Eldume irrigation scheme, Baringo County, an area in semi-arid climate in the north rift part of Kenya that experiences water stress scenarios, low and erratic rainfall pattern throughout the crop growing seasons.

2.1 Meteorological Data

The maximum and minimum temperatures, relative humidity, wind speed and precipitation datasets were downloaded from an automated HOBO weather station at Kenya Agricultural and Livestock Research Organization (KALRO), Marigat station. The weather station records up to 15 channels of measurements, and a broad range of plug-and-play smart sensors installed for monitoring all kinds of environmental conditions ranging from air temperature and relative humidity to soil moisture, wind speed/direction, rainfall, leaf wetness, photosynthetically active radiation (par), solar radiation, and barometric pressure. The data recorded for all weather variables at the station were in five minutes time-step which were subsequently converted to daily time-step basis.

2.2 Soil Data

Soil samples were collected from three randomly selected block treatments using a soil auger and were taken for analysis at KALRO laboratory Njoro station. The samples were excavated from the top layer 0-5cm depth down to the bottom layer at 95-100 cm to the point of maximum rooting depth of the maize crop. Sampling was done between rows at each treatment for maximum representation of the soil characteristics within the rooting zone. The soil samples were determined by hydrometer method and it was found that the soil were uniform sandy clay loam throughout the soil layers from the top profile. The particle size distribution for the cropped area were in the following percentage, for clay content was 27.96%, the sand content was 59.63%, the silt content was 12.4% and the organic material was 0.82% and the bulk density is 1.4 g cm^{-3}. The Saxton equation (Saxton *et al.*, 2006) was used to determine the volumetric water content of the soil at saturation, field capacity, and permanent wilting point as 0.47 cm cm^{-1}, 0.26 cm cm^{-1}, and 0.16 cm cm^{-1} respectively. The saturated hydraulic conductivity was found to be 0.31 cm hr^{-1}.

Table 2.1: Mineral Size Distribution, Eldume scheme

Depth (cm)	Particle Size Distribution (%)			Texture	Field Capacity (%)	Permanent wilting point (%)	Bulk Density (g/cm^{-1})
	Sand	Silt	Clay	Deep uniform sandy clay loam			
0-25	59.63	12.4	27.96	„	32	20	1.4
25-75	59.63	12.4	27.96	„	32	20	1.4
50-75	59.63	12.4	27.96	„	32	20	1.4
75-100	59.63	12.4	27.96	„	32	20	1.4

Reference Evapotranspiration

This variable was determined by use of FAO ETo calculator program and it was applied separately as input to the AquaCrop model. The input parameters include maximum and minimum temperatures, relative humidity, wind speed and sunshine hours obtained from HOBO Weather Station. The dataset for weather variables were first processed using microsoft excel collected at 5 minutes interval were averaged to daily time step for easy handling by ET_0 calculator. The values computed by FAO-56 Penman-Monteith Equation (Allen *et al.*, 1998) were tabulated for the simulation period from 5th December, 2017 to 9th March, 2018 during the season of maize crop sowing to the harvest.

3. Experimental Setup

The maize crop cultivar (Duma 43) were planted on an experimental field of approximately 1000 m^2 (0.1 ha) and were manually harvested after about 3 months on March 9, 2018. The experimental trials consisted of four maize crop plots on a randomized complete block design with sub plot sizes measuring approximately (15m × 5m) replicated three times with the same water stress levels for each replicate. The four plots were cultivated and ridges prepared with furrow sizes of row spacing to plant spacing as 35cm × 20cm in dimensions. There was no rainfall during the study period and irrigation water was applied through the water canals, main and secondary canals, laterals and furrows to apply water to the four maize crop treatments throughout the season. The experimental plots comprised of planted maize crops with four irrigation water stress levels of different fixed irrigation intervals ranging from 5 days, 7 days, 10 days and 12 days throughout the crop growing period. The plots area sizes were as indicated in Table 2.2 labeled 1a, b, c 2a, b, c, 3a, b, c and 4a, b, c with the indicated area plot dimensions.

Table 2.2: Irrigation schedules of sub-plot area for each of the four treatments.

Treatments	Dimensions			
Plot 1 5 days irrigation interval	Replicate Sub Plots	Length (m)	Width (m)	Area (m^2)
	1a	15.5	5.3	82.15
	1b	15.8	5.2	82.16
	1c	15.5	5.7	88.35
	Total area			252.66
Plot 2 7 days irrigation interval	2a	16.0	5.4	86.40
	2b	15.5	5.0	77.50
	2c	15.5	5.2	80.60
	Total area			244.50
Plot 3 10 days irrigation interval	3a	15.8	5.6	88.48
	3b	15.2	4.9	74.56
	3c	15.0	5.5	82.50

	Total area			245.54
Plot 4 12 days irrigation interval	4a	15.5	5.8	89.90
	4b	15.5	5.5	84.50
	4c	15.7	5.3	83.10
	Total area			257.50
	Summation of Total area used			1,000.20

Four irrigation/planted plots were each divided into three sub-plots for treatments with fixed irrigation intervals were prepared as indicated in (Figure 2.1) namely: furrow irrigated raised wavy beds with dimensions of (45 cm by 20 cm) in furrow widths and furrow heights respectively.

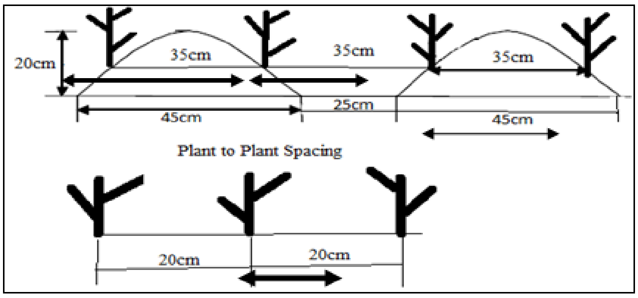


Figure 2.1: Side view of the furrow beds and plants spacing

Plant spacing in each plot was illustrated in (Figure 2.1) with the indicated dimensions. The distance from the top of the bed to the bottom of the furrow was 20 cm. The widths of the ridges were 45 cm for all the furrows. The distance between the rows per bed configuration was spaced 35 cm apart. The sowing location of the seeds were on the opposite sides of the furrow beds and had a plant to plant spacing of 20 cm and a seeding rate of approximately 4 plants/m^2 for all the treatments. The results from the ETo Calculator indicated that the highest reference evapotranspiration in the period under the study was 8.5 mm/day and the lowest was 3.7 mm/day. It was noted that with integrated high temperatures, relative humidity and wind speeds the reference evapotranspiration assumes an increasing trend indicating that ETo was directly influenced by the three stated climate parameters. Reference evapotranspiration is a climatic parameter required in the simulation of crop yield under water stress scenarios and is influenced by the evaporative demand of the atmosphere.

Model Calibration and Validation

AquaCrop version 4.0 was calibrated for maize crop in Eldume irrigation scheme. The reference evapotranspiration, soil, sowing date, irrigation applications and crop data sets were fed as observed into the model for each of the simulation runs. After several iterations, the maize crop input parameters were adjusted in a first step of the calibration procedure followed by the simulation runs using the crop, soils and climate inputs data sets for the 5 days irrigation intervals (non water stressed) treatment (Table 2.3), through trial and error the output from the model were compared to the observed canopy cover, biomass and yields. Many of the parameters employed in AquaCrop are not measurable properties and were determined iteratively through calibration until reasonable results were obtained. Final calibrations were based on comparisons between observed canopy cover, biomass and yield. The calibration results were as showed in Table (2.3). Part of the obtained data from trial irrigation schedule experiments were used in calibration and for validation, data from measured standalone reference treatment (B1) were used as independent dataset to accurately validate with the rest of the field trials of 3, 5, 7 and 12 days irrigation intervals.

Table 2.3: Crop parameters and program settings calibrated for maize crop as well as the soil and climate inputs used for calibration of Eldume Irrigation Scheme

Inputs	Calibrated Value
Crop Inputs	
Initial canopy cover, (%)	2
Water stress factor for canopy expansion	0.35
Water stress factor stomatal closure	0.25
Water stress factor for early senescence	0.35
Maximum canopy cover, (%)	93
Time to flowering, calendar days	55
Length of flowering stage, calendar days	10
Time to maximum canopy cover, calendar days	45
Time to senescence, calendar days	75
Time to harvest, calendar days	95
Water productivity factor, g m^{-2}	32
Maximum rooting depth, m	0.65
Canopy decline coefficient, % d^{-1}	10.3
Time to maximum rooting depth, calendar days	45
Reference harvest index (HIo), %	41
dHI/dt, % d^{-1}	8
Negative HI adjustment grain filling	7
Water extraction pattern	40–30–20–10% per quarter of soil profile
Shape factor for the water stress functions	Positive (concave) shape
Inputs	**Calibrated Value**
Soil Inputs	
Initial soil water content	Dry top soil (10%Vol) and wet subsoil (30% Vol)
Soil water content at permanent wilting point, Vol% per layer	16
Saturated hydraulic conductivity, mm d^{-1}	0.31
Soil water content at field capacity, Vol% per layer	26
Readily evaporable water from the soil, mm	0.47
Inputs	**Calibrated Value**
Climate Inputs	
Rainfall	Daily data
Reference evapotranspiration	Daily data
Changed program settings	
Effect of drought stress on root expansion	None
Minimum soil water content for germination	TAW(applied)
CC minimum for HI build up, %	1

Crop Management

The maize crop (Duma 43 cultivar) were hand sown in rows on December 5, 2017 on an area of approximately 1000 m^2 (0.1 ha) and were manually harvested on March 9, 2018. The crops were fertilized with nitrogenous (N) fertilizers at a rate of 107kg N ha^{-1} using urea, with nitrogen application in each plot done before fourth to seventh irrigation events in four equal splits of 26.85kg N per treatment. The fertilizers were applied in the furrow beds uniformly from plant to plant over the surface close to the crop to leach into the root zone under irrigation water. Irrigation water was applied in each plot following specific schedules as experimented since no rainfall was received. Weeds were controlled by hand weeding twice during the growing season.

Plate 2.4: Physical characteristics of maize crop on 8/1/2018 in (block 1) 34 days after sowing.

Plate 2.5: Physical characteristics of maize crop on 8/1/2018 in (block 2) 34 days after sowing.

Plate 2.6: Physical characteristics of maize crop on 8/1/2018 in (block 3) 34 days after sowing.

Plate 2.7: Physical characteristics of maize crop on 8/1/2018 in (block 4) 34 days after sowing.

Optimization of Effective Irrigation Schedules

Optimization model was developed based on linear programming. The selected decision variables were land (ha) and water applications (m^3) which were computed on each individual treatment plot as indicated in (Table 2.4). For optimum irrigation schedule benefits, computations were done according to the following objective function equation (2.1).

$$Max\ benefit = Yield\,(ton/ha) \times Area\,(ha) \times Price\ (ksh/ton) - (Production\ cost\,(ksh/ton) \times Area\,(ha)$$

Net benefit from each maize crop treatment was obtained as,

$$Max\ B = (Y_{m(i)} \times A_i \times P_m) - (P_c \times A_i) \quad \textbf{(2.1)}$$

where,

$Max\ B$, is the maximum benefit resulting from the four maize crop treatments i_{1-4} (KSh)

Y_m is the maize crop yield (tons/ha) i_{1-4}, where, i denote treatments, i =1 to 4

A_i is cultivated area (ha) i_{1-4}

P_m, is the price of maize commodity (KSh/ton) at the current market price (constant for all treatments) and,

P_c, is the production cost (KSh/ha) of maize associated with labor cost and other cost including land, fertilizers, seeds, planting, top dressing, irrigation water application and harvesting costs. Irrigation water and labor costs are functions of the water used and number of irrigation events.

Table 2.4: Cropped system

Block/Treatment	B1	B2	B3	B4
Irrigation (mm)	I_1	I_2	I_3	I_4
Area (ha)	a_1	a_2	a_3	A_4

Water Volume (m^3) 10a$_1$I$_1$ 10a$_2$I$_2$ 10 a$_3$I$_3$ 10a$_4$I$_4$

Decision variables considered in the optimization model were irrigated area and irrigation water. In order to maximize the objective function (Equation 2.2) the following constraint equations were taken into account:

i) Allocated area (ha), $a_1 \geq 0$, $a_2 \geq 0$, $a_3 \geq 0$, $a_4 \geq 0$

$$\sum_{i=1}^{4} a_{\max(i)} \leq A_T \qquad (2.2)$$

where, i denote treatments

$i = 1\ to\ 4$,

$a_1 \leq A_T$, $a_2 \leq A_T$, $a_3 \leq A_T$, $a_4 \leq A_T$

Where,

$a_{\max(i)}$, designates maximum cultivable area for maize crop plots 1 to 4.

A_T, total area available for irrigation (treatments $i = 1\ to\ 4$)

ii) Water (m^3),

$10\ a_i I_i$, is the volume (V_i) in m^3 of water applied at a particular plot/treatment.

$10\,a_1 I_1 \geq 0$, $10\,a_2 I_2 \geq 0$, $10\,a_3 I_3 \geq 0$, $10\,a_4 I_4 \geq 0$

Or, $V_1 \geq 0, V_2 \geq 0$, $V_3 \geq 0$, $V_4 \geq 0$

$$\sum_{i=1}^{4} V_{\max(i)} \leq V_T, \qquad (2.3)$$

i denote treatments $i = 1\ to\ 4$

$10\,a_1 I_1 \leq V_T$, $10\,a_2 I_2 \leq V_T$, $10\,a_3 I_3 \leq V_T$, $10\,a_4 I_4 \leq V_T$

where,

V_i, Volume of irrigation water applied to a particular treatment and i denote block $1\ to\ 4$

V_T, the summation of total available irrigation water volumes

The relations, a_1, a_2, a_3, and a_4 designates cultivated area for maize crop treatments plots (1- 4), A_T, total area that can be irrigated, $a_{\max(i)}$, is the maximum possible cultivable area for maize crop treatment and $V_{\max(i)}$ is the maximum possible water application volumes allocated to maize crop treatments $i = 1\ to\ 4$.

4. Evaluation of Model Performance

Four statistical measures of performance were used to evaluate the model using simulation results and compared to measured data as follows;

i) Percentage Root Mean Square Error (%RMSE):

$$\%RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \times \frac{100 \times n}{\sum_{i=1}^{n} O} \qquad (2.4)$$

where,

S_i and O_i are the predicted/simulated and measured/observed values respectively, and *n* is the number of observations. The unit for RMSE is the same as that for S_i and O_i; and a model's fit improves as it approaches zero.

ii) Model efficiency (EF);

$$EF = \frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 - \sum_{i=1}^{n}\left(S_i - \bar{S}\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \qquad (2.5)$$

These statistics are more descriptive of the models goodness of fit. EF tells us how well the model is performing in prediction, a value of one indicates a perfect one-to-one relationship and any negative value tells us that the model is worse at predicting observed data than when using the mean of observed values to predict the data.

iii) Coefficient of Determination (CD)

$$CD = \frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}{\sum_{i=1}^{n}\left(S_i - \bar{O}\right)^2} \qquad (2.6)$$

CD is similar to R^2 as it measures the proportion of the total variance of observed data explained by predicted data, a perfect fit also being one with a lower limit of zero and upper limit of infinity. It tells us whether the model is over predicting (a value under one) or under predicting (a value over one).

iv) Coefficient of Residual Mass (CRM)

$$CRM = \frac{\left(\sum_{i=1}^{n} o_i - \sum_{i=1}^{n} s_i\right)}{\sum_{i=1}^{n} o_i} \qquad (2.7)$$

The CRM is a measure of the tendency of the model to over-estimate or under-estimate the measurement. A negative CRM shows a tendency to over-estimate.

5. Results and Discussion

Meteorological Data

The climatic data was a significant input in AquaCrop model since the parameters were the major influence to crop growing environment which affects the crop genotype. They include rainfall, ETo with crop coefficients which were the key parameter in the computation of crop water requirement, maximum and minimum temperature of the area as inputs. The calculated reference evapotranspiration with the crop coefficients at each growth stage were used to compute water requirements for the crop growing season.

Seasonal Cumulative Evapotranspiration

The graph shows consistent rise with respect to seasonal cumulative irrigation water for all treatments (Figure 3.1), a clear indication of corresponding evaporative demand of the atmosphere to irrigation water. Canopy cover plays an important role in simulating ET and consumptive use of water as run in AquaCrop model.

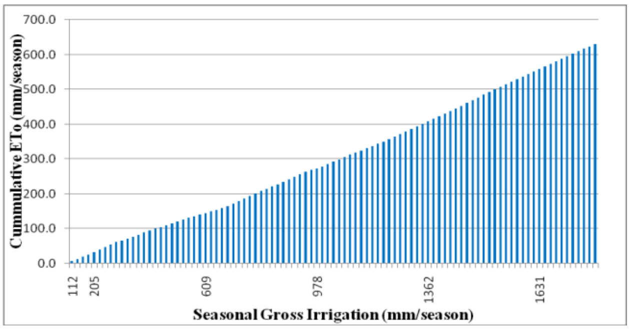


Figure 3.1: Comparison of cumulative reference evapotranspiration versus cumulative seasonal irrigation requirement for maize crop under calibration block (5 days irrigation interval).

The slopes of the two parameters, that is, cumulative ETo and Irrigation water curves appear to be relatively parallel during the growing season. The graph explains direct influence of climate parameters to soil water balance suitable for crop grown under a given environment. Water productivity translates to the daily transpiration divided by the daily crop reference evapotranspiration (ETo) to the amount of biomass produced seasonally. The three replicates of the same treatment schedule results in constant standard variation for each plot.

The statistical performance of the irrigation system shows that the mean of the four treatment schedules of the observed yield is correct with a standard deviation of 0.0057, 0.0563, 0.4042 and 0.3690 respectively for the four plots 1 to 4 for all replicates of each treatment (Table 2.4 and Figure 3.2). The mean observed grain yield is 4.64 ton/ha and the total standard deviation is 1.2707 for all the four blocks which is reasonable outcome for an irrigation system located in arid and semi-arid area.

Table 2.4: Dependent Variable: Observed grain yield (ton/ha)

(I) Block	(J) Block	Mean Difference (I-J)	Std. Error	Sig.^{c}	95% Confidence Interval for Difference^{c} bound	
					Upper	Lower
Plot 1 – 5 days irrigation interval	Plot 2 - 7 days irrigation interval	0.919*,a,b	0.225	0.003	0.401	1.437
	Plot 3 - 10 days irrigation interval	2.096*,a,b	0.225	0.000	1.578	2.614
	Plot 4 - 12 days irrigation interval	3.169*,a,b	0.225	0.000	2.651	3.687
Plot 2 – 7 days irrigation interval	Plot 1 - 5 days irrigation interval	-0.919*,a,b	0.225	0.003	-1.437	-0.401
	Plot 3 - 10 days irrigation interval	1.177*,a,b	0.225	0.001	0.659	1.695
	Plot 4 - 12 days irrigation interval	2.249*,a,b	0.225	0.000	1.731	2.767
Plot 3 - 10 days irrigation interval	Plot 1 - 5 days irrigation interval	-2.096^{*,a,b}	0.225	0.000	-2.614	-1.578
	Plot 2 - 7 days irrigation interval	-1.177^{*,a,b}	0.225	0.001	-1.695	-0.659
	Plot 4 - 12 days irrigation interval	1.073^{*,a,b}	0.225	0.001	0.555	1.591
Plot 4 - 12 days irrigation interval	Plot 1 - 5 days irrigation interval	-3.169^{*,a,b}	0.225	0.000	-3.687	-2.651
	Plot 2 - 7 days irrigation interval	-2.249^{*,a,b}	0.225	0.000	-2.767	-1.731
	Plot 3 - 10 days irrigation interval	-1.073^{*,a,b}	0.225	0.001	-1.591	-0.555

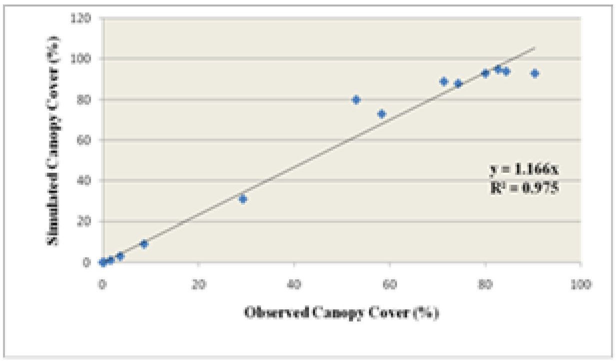


Figure 3.2: Comparison of simulated and observed canopy cover for 5 days irrigation interval non-water stressed field trial.

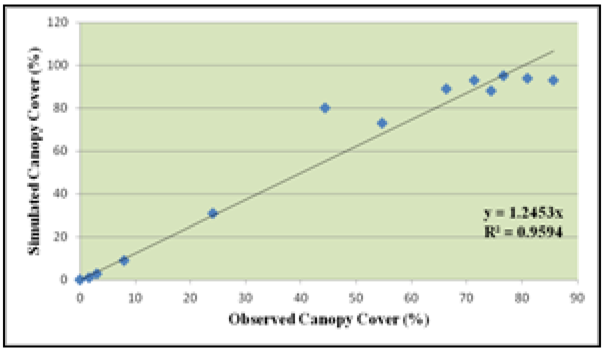


Figure 3.3: Comparison of observed and simulated canopy cover for 7 days irrigation interval a slightly water stressed field trial.

Table 2.5: Summary of results per block field trials on average

Sown date – 05/12/2017 Harvested on - 09/03/2018
C4 crop – Cereal Crops - Zeamays Variety – Duma 43 – Maize
Block 1 - 4 – Experimental results Soil type – Deep uniform sandy clay loam

Block	Area (m^2)	Plant popn/plot	Plants density/m^2	Observed Biomass(ton/ha)	Simulated Biomass(ton/ha)	Observed yield(ton/ha)	Simulated yield(ton/ha)	Seasonal net applic depth(mm)
1	84.22	349	4.14	14.040	14.538	6.183	6.403	819
2	81.50	311	3.82	13.272	13.724	5.264	5.435	597
3	81.85	326	3.98	9.950	10.217	4.087	4.183	349
4	85.53	385	4.50	8.249	8.453	3.015	3.078	309

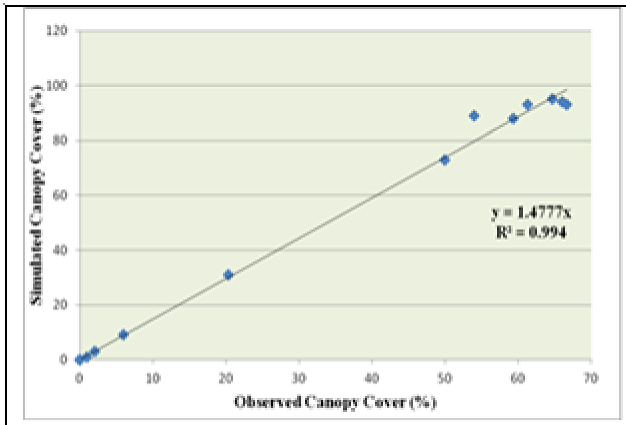


Figure 3.4: Comparison of Simulated versus observed canopy cover for 10 days irrigation intervals a moderately water stressed field trial.

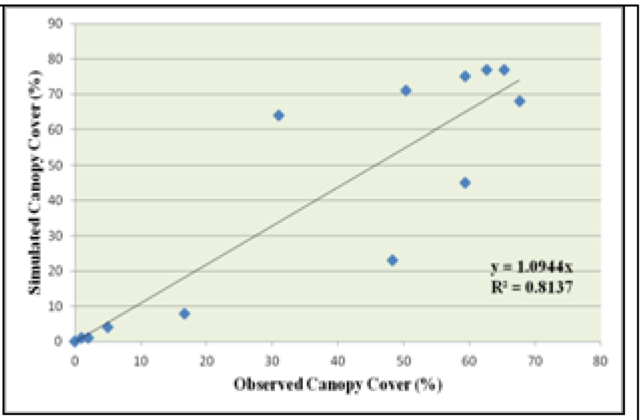


Figure 3.5: Simulated versus observed canopy cover for 12 days irrigation intervals a severely water stressed field trial.

On comparing the simulated and observed results the model overestimated the canopy cover with a linear regression slope (1.09) and R^2 (0.81).

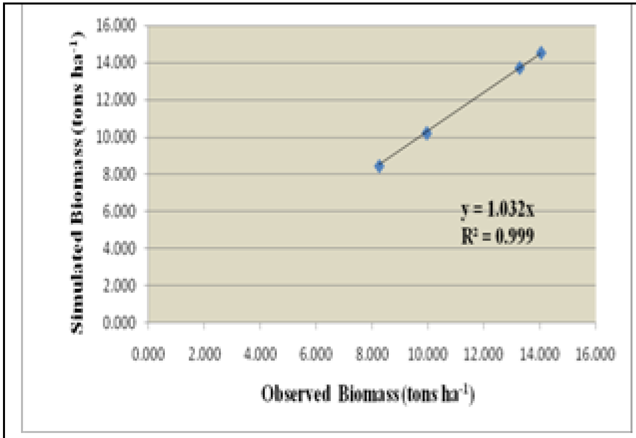


Figure 3.6: Comparison of the simulated versus observed above ground biomass of averaged block treatments for 5, 7, 10 and 12 days irrigation intervals.

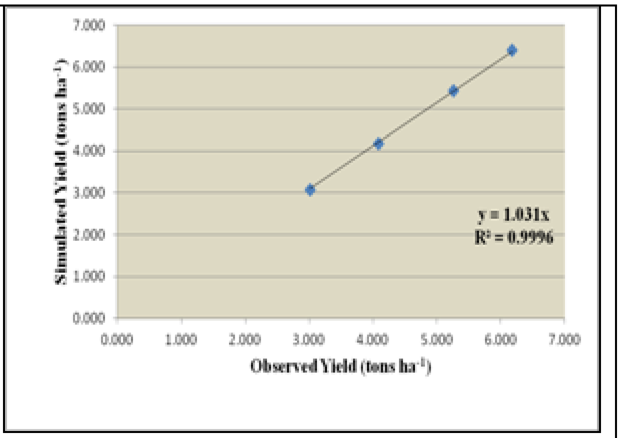


Figure 3.7: Comparison of the simulated versus observed yield of averaged block treatments for 5, 7, 10 and 12 days irrigation intervals.

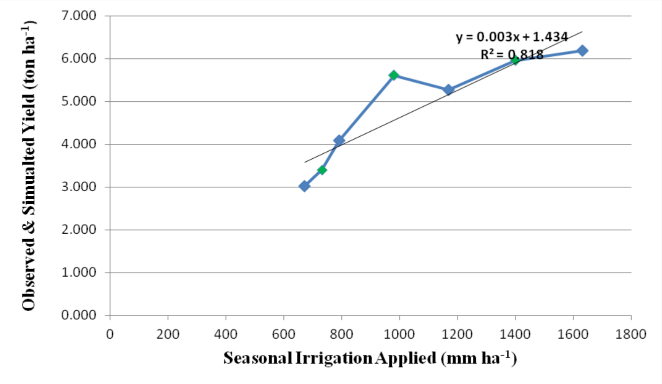


Figure 3.8: Combined observed (blue) and simulated (green) maize grain yields versus seasonal irrigation water plotted in a single graph for block 4 to 1

Table 2.6: Summary of model validation statistics for maize yields across other independent three treatments in Eldume irrigation scheme

BLOCKS 2- 4 (Validation blocks)	RMSE (%)	d	EF	CD	CRM
Optimum Value (Canopy Cover (CC) (2-4)	10^a	1^a	1^a	1^a	0^a
Treatment 2(CC)	95.3	0.910	0.78	0.64	-0.27
Treatment 3(CC)	97.0	0.996	0.54	0.46	-0.31
Treatment 4(CC)	94.5	0.880	0.71	0.69	-0.10

a'- implies the best possible results indicating the values for a perfect fit between observed and predicted values.

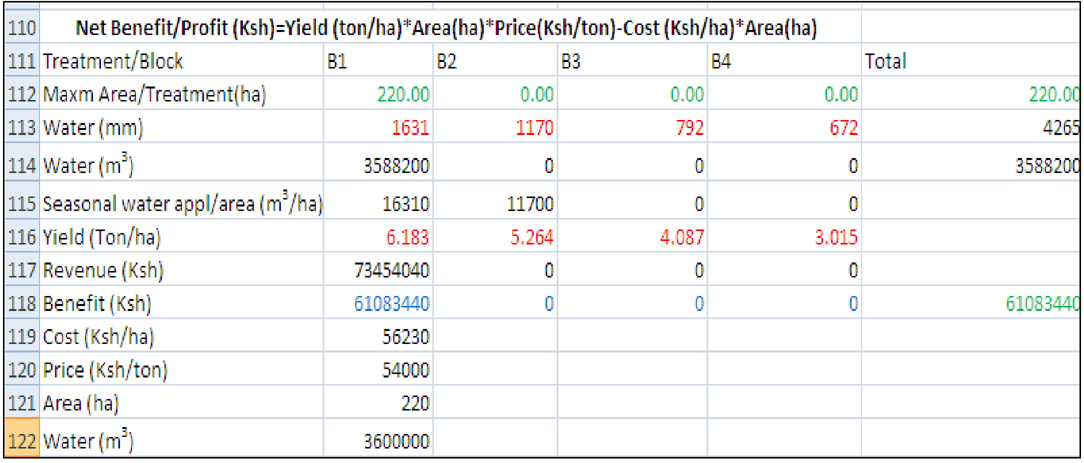
Table 2.7: Statistical comparison of observed and simulated yield

BLOCKS 1- 4	RMSE (%)	d	EF	CD	CRM
Optimum Value (Yield Prediction)	10^a	1^a	1^a	1^a	0^a
Averaged Biomass (1-4)	9.10	0.880	0.76	1.03	-0.01
Averaged Grain Yield (1-4)	23.35	0.987	0.972	0.927	-0.03

`a'- implies the best possible results indicating the values for a perfect fit between observed and predicted values.

The Root Mean Square Error (RMSE) for biomass resulted into 9.10 while average grain yield had 23.35, coefficient of determination of the average biomass was 1.03 and average grain yield was 0.927, model efficiency gave 0.76 and 0.972 for biomass yield respectively while the index of agreement gave 0.880 and 0.987 for biomass and yield in that order. This statistically indicates a reasonably good correlation between observed and simulated yield against water application in that season as was influenced by semi-arid environmental conditions.

Table 2.8: Scheme maximum maize production benefit for the period under full irrigation scenario for 100% water application

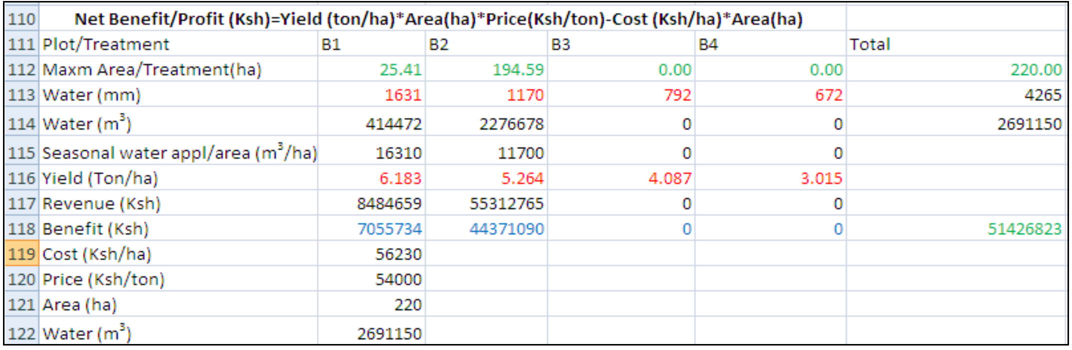


110	Net Benefit/Profit (Ksh)=Yield (ton/ha)*Area(ha)*Price(Ksh/ton)-Cost (Ksh/ha)*Area(ha)					
111	Treatment/Block	B1	B2	B3	B4	Total
112	Maxm Area/Treatment(ha)	220.00	0.00	0.00	0.00	220.00
113	Water (mm)	1631	1170	792	672	4265
114	Water (m^3)	3588200	0	0	0	3588200
115	Seasonal water appl/area (m^3/ha)	16310	11700	0	0	
116	Yield (Ton/ha)	6.183	5.264	4.087	3.015	
117	Revenue (Ksh)	73454040	0	0	0	
118	Benefit (Ksh)	61083440	0	0	0	61083440
119	Cost (Ksh/ha)	56230				
120	Price (Ksh/ton)	54000				
121	Area (ha)	220				
122	Water (m^3)	3600000				

Water supply of 75% scenario

And if 75% irrigation volume was applied to the four plots, that is, 2,691,150 m^3 (25% less) then the model distributed the irrigated area as B1(25.41 ha) and B2(194.59 ha) with water volumes as 414,472m^3 and 2,276,678m^3 and the benefit achievement as KSh 7,055,734 and KSh 44,371,090 respectively with a total benefit of KSh 51,426,823 indicating 73% profitable. Due to the water and land allocation the model shows that B3 and B4 has 0.0m^3 and 0.0 ha. respectively with no benefit achievement. Plot B2 under 25% water shortage fetches the most benefit than the rest of the other treatments and most prefferably the best choice that farmers can practice for maize production.

Table 2.9: Scheme maximum benefit attained under 75% water application for four trial treatments.

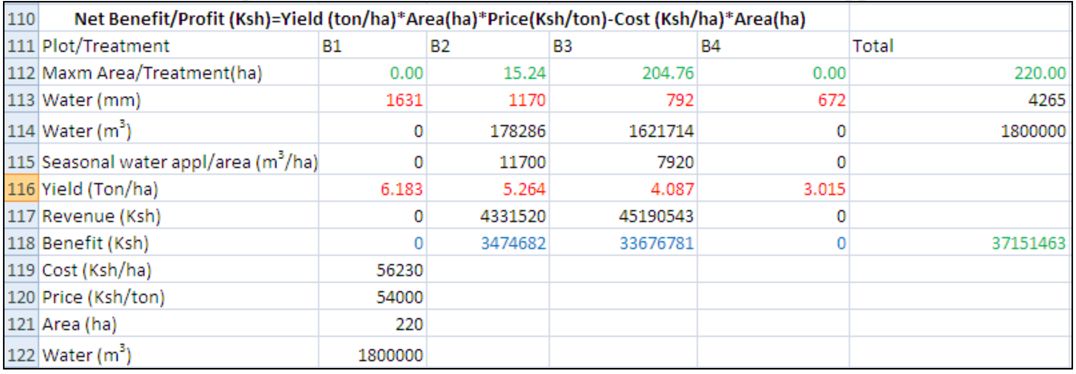


110	Net Benefit/Profit (Ksh)=Yield (ton/ha)*Area(ha)*Price(Ksh/ton)-Cost (Ksh/ha)*Area(ha)					
111	Plot/Treatment	B1	B2	B3	B4	Total
112	Maxm Area/Treatment(ha)	25.41	194.59	0.00	0.00	220.00
113	Water (mm)	1631	1170	792	672	4265
114	Water (m^3)	414472	2276678	0	0	2691150
115	Seasonal water appl/area (m^3/ha)	16310	11700	0	0	
116	Yield (Ton/ha)	6.183	5.264	4.087	3.015	
117	Revenue (Ksh)	8484659	55312765	0	0	
118	Benefit (Ksh)	7055734	44371090	0	0	51426823
119	Cost (Ksh/ha)	56230				
120	Price (Ksh/ton)	54000				
121	Area (ha)	220				
122	Water (m^3)	2691150				

Water supply of 50% scenario

The table (2.9) shows percent shortage under limited application of irrigation water to the four plots and indicates 1,800,000m^3 could be shared by the four treatments insufficiently and as a result of benefits attained based on decision variables of land and water availability, the water shortage is approximately 50% of full irrigation with maximum water volume of 3,588,200 m^3 and full benefit of KSh.61, 083,440 obtained if full irrigation was possible to practice. The benefit under this water shortage scenario is KSh 33,676,781 (55%) profitable under 50% irrigation if 220 ha land was irrigated. A simple Microsoft Excel Solver (MES) was used to optimize available land and water resources for the trial treatments B1, B2, B3 and B4 which exhibited an allocation of 0.00, 15.24, 204.76 and 0.00 ha of land repectively in a total command area of 220 ha in the scheme. The maximum volume of water utilized for an individual irrigated treatment and considering optimal benefit attained from each plot varied from a total volume of 0 m^3 meaning no water application and no benefit for B1, B2(178,286m^3), B3(1,621,714m^3) and (B4) 0 m^3 respectively. The total irrigation water capacity of 1,800,000m^3 (50.2%) was attained as the model upper threshold. This water volume was distributed on cultivated land per season for four treatments and from the model outcome, most of the irrigated land to water allocation appeared to be skewed towards the most beneficial plot which was B3 with a net maximum profit of KSh 33,676,781 based on the decision variables of land and water availability.

Table 3: Optimum benefit for the four treatments with 50% water application



110	Net Benefit/Profit (Ksh)=Yield (ton/ha)*Area(ha)*Price(Ksh/ton)-Cost (Ksh/ha)*Area(ha)					
111	Plot/Treatment	B1	B2	B3	B4	Total
112	Maxm Area/Treatment(ha)	0.00	15.24	204.76	0.00	220.00
113	Water (mm)	1631	1170	792	672	4265
114	Water (m^3)	0	178286	1621714	0	1800000
115	Seasonal water appl/area (m^3/ha)	0	11700	7920	0	
116	Yield (Ton/ha)	6.183	5.264	4.087	3.015	
117	Revenue (Ksh)	0	4331520	45190543	0	
118	Benefit (Ksh)	0	3474682	33676781	0	37151463
119	Cost (Ksh/ha)	56230				
120	Price (Ksh/ton)	54000				
121	Area (ha)	220				
122	Water (m^3)	1800000				

It was noted that maize production from respective units were 6.183, 5.264, 4.087 and 3.015 ton ha^{-1} despite this, each treatment could fetch profit in consideration of water savings. The maximum benefit realized from the cultivation of the maize produce based on realtime cost and market price was indefinate profit for B1 indicating a none profit scenario, B2 (KSh 3,474,682), B3 (KSh 33,676,781), while B4 had also no realization of profit to warrant maize production venture. The difference in input cost and output income based on the four irrigation schedules of the trial treatments ranged from non-stresssed to severely stressed treatment summed up to KSh 37,151,463 with B3 giving the optimal benefit recommended for adoption by farmers in this scheme during the periods of scarce water resource utilization for water saving irrigation (Table 3.0).

The optimization model gave the best scheduling irrigation system for the production of maize in the scheme as plot B3 which yielded the most benefit in terms of land, water and farm inputs. This signifies that, the 10 days irrigation interval depicted an optimum yield despite that a certain water deficit was desirable in that climatic condition. The irrigated cropping system under non-water stress (B1) resulted into maize yield higher, followed by B2 and subsequently B3 and B4 due to crop consumptive water use in the season. The overall model outcome indicates that B1 and B4 treatments were not advisable for use in the scheme since B1 consumed too much water with high yield in a water scarce environment as compared to B4 which utilized less water with low yield. The most appropriate plot was B3 (10 days irrigation interval) which gave high output benefit on water savings based on decision variables of land and water resource in arid and semi-arid climate for maize production.

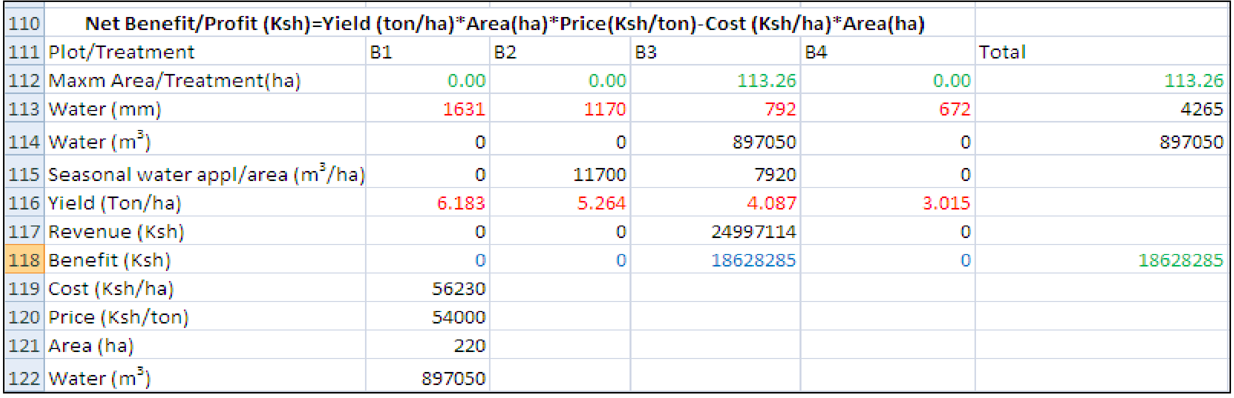
Optimization Scenario Analysis

From the results, it was also noted that despite water scarcity the readily available water if utilized efficiently results into optimum yield within a given area and weather conditions. The best option for the farmers to adopt at the scheme was either the 7 days irrigation interval or the 10 days irrigation interval which followed closely with 73% and 55% benefit respectively when it comes to water savings with high profit attainability; but however the model gave the most optimal benefit as the 7 days irrigation interval with profit margin of KSh. 44,371,090 (73%) under deficit utilization of water volumes 2,276,678 m^3 (63%) on different area coverage for cultivation per treatment table (3.1).

Water Supply of 25% Scenario

The table (3.1) indicates that the model preferably allocates (B3) 10 days irrigation interval as the choice fit for practice under water scarce scenario where 113.26 ha could be irrigated out of 220 ha available as a result of limited water availability. The benefit attained if this was adopted alone would have given KSh. 18,628,285 which was 31% of the overall benefit.

Table 3.1: Optimum benefit for the four treatments with 25% water application



110	Net Benefit/Profit (Ksh)=Yield (ton/ha)*Area(ha)*Price(Ksh/ton)-Cost (Ksh/ha)*Area(ha)					
111	Plot/Treatment	B1	B2	B3	B4	Total
112	Maxm Area/Treatment(ha)	0.00	0.00	113.26	0.00	113.26
113	Water (mm)	1631	1170	792	672	4265
114	Water (m^3)	0	0	897050	0	897050
115	Seasonal water appl/area (m^3/ha)	0	11700	7920	0	
116	Yield (Ton/ha)	6.183	5.264	4.087	3.015	
117	Revenue (Ksh)	0	0	24997114	0	
118	Benefit (Ksh)	0	0	18628285	0	18628285
119	Cost (Ksh/ha)	56230				
120	Price (Ksh/ton)	54000				
121	Area (ha)	220				
122	Water (m^3)	897050				

Table 3.2: Summary of crop area, water application and financial benefit under 0%, 25% and 50% and 75% water shortage for trial treatments.

0% Water shortage (Reference plot)		**Plots/treatments**			
	Units	**B1**	**B2**	**B3**	**B4**
Allocated Area	(ha)	220	0	0	0
	(%)	100	0	0	0
Optimal water allocation	(m^3)	35,88,200	0	0	0
	(%)	100	0	0	0
Benefit	(KSh)	6,10,83,440	0	0	0
Individual plot benefit	(%)	**100**	0	0	0
25% Water shortage					
Allocated Area	(ha)	25.41	194.59	0	0
	(%)	12	88	0	0
Optimal water allocation	(m^3)	4,14,472	22,76,678	0	0
	(%)	12	63	0	0
Benefit	(KSh)	70,55,734	4,43,71,090	0	0
Individual plot benefit	(%)	12	**73**	0	0
50% Water shortage					
Allocated Area	(ha)	0	15.24	204.76	0
	(%)	0	7	93	0
Optimal water allocation	(m^3)	0	1,78,286	16,21,714	0
	(%)	0	5	45	0
Benefit	(KSh)	0	34,74,682	3,36,76,781	0
Individual plot benefit	(%)	0	6	**55**	0
75% Water shortage					
Allocated Area	(ha)	0	0	113.26	0
	(%)	0	0	52	0
Optimal water allocation	(m^3)	0	0	8,97,050	0
	(%)	0	0	25	0
Benefit	(KSh)	0	0	1,86,28,285	0
Individual plot benefit	(%)	0	0	**31**	0

Key: KSh – Kenya Shillings, ha – Hectares

6. Summary and Conclusions

It is evident from the research findings that:

1) The variation of irrigation water in non-water stressed to severe water stressed experimental blocks indicated that maize production relies majorly on water quantity application for crops growth throughout the season. The trials clearly shown that non-water stressed treatment utilized a total seasonal irrigation water of 1631mm (16,310m^3/ha) while the severely water stressed treatment consumed 672mm (6,720m^3/ha).
2) The AquaCrop model was able to accurately predict the simulation of the system reasonably well as the threshold value of water stress increased/decreased in the water supply resulted in a linear relationship of an increased/decreased yield for maize crop.
3) The crop water productivity model gave more reliable estimates of maize yield, however the yield declined from 6.183 ton/ha to 3.015 ton/ha for non-water stressed to severely water stressed treatment indicating a water deficit scenario.
4) Based on optimal maize crop revenue collected, the best irrigation interval good for practice at Eldume irrigation scheme was the 7 days interval with 13 irrigation events per season. The seasonal revenue collected for the 7 days interval is higher as compared to both the 5 days irrigation interval with 17 irrigation events which utilized huge water volumes per season and 10 days irrigation interval with 9 irrigation events.
5) The revenue obtained under the two blocks of maize, that is, optimal yield in the 5 days interval KSh.61, 083,440 (100%) i.e. reference plot (full irrigation) and 12 days irrigation interval KSh.18, 628,285 (31%) gave lower benefits in water savings as compared to the 7 days and 10 days irrigation intervals which gave KSh.44,371,090 (73%) and 33,676,781 (55%) respectively per season.
6) The SPSS model gave statistical performance of AquaCrop model as acceptable with confidence level at 0.05% and mean error of 0.076 in modeling crop water productivity in scheduling maize crops in arid and semi-arid irrigation systems.
7) AquaCrop and Excel Optimization modeling tools in crop water productivity enables scientists, irrigation engineers, hydrologists, agronomists and economists have sound decision-making in the management of crops especially in arid and semi-arid lands.
8) Hypothetically, the null hypothesis was rejected because the statistical results indicates that there exist a difference in the irrigation schedules from the field experimental outcome and that it is possible to determine whether water stress levels contributes to decline on grain yields of maize production. Therefore, modeling crop water productivity has great significance in irrigation water scheduling management.
9) Under water deficit scenarios, it's advisable to apply the most water economic use with maximum benefits for the farmers. Nearly all of the measured data points fell well below the attainable productivity delimited by the boundary functions for both aboveground biomass and grain yield.

10) The calibrated AquaCrop model for maize field trials demonstrated good statistical performance where the residual variance between the observed and simulated canopy cover values were slightly underestimated and overestimated with the percentage root mean square error %RMSE of B1 (63.4%) B2 (96.4%), B3 (112%), B4 (35.4%) and the index of agreement (d) gave reasonable range of 0.88 to 0.999, model efficiency (EF) values between -0.206 to -0.720 and coefficient of determination (CD) range of 0.46 to 0.706 and coefficient of residual mass (CRM) range of -0.10 to -0.31.
11) The average biomass fell within the acceptable level of %RMSE (6.25%), d (0.999), EF (-0.063), CD (0.922) and CRM (-0.03) while the average grain yield gave %RMSE (5.93%) d (0.987), EF (-0.060), CD (0.927) and CRM (-0.03). The key model input parameters adjusted during the calibration were particularly the crop inputs such as canopy cover sensitive to the environment and as greatly influenced by water deficit.

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