Arid Zone Journal of Engineering, Technology and Environment. August, 2014; Vol. 10: 25-39
Copyright© Faculty of Engineering, University of Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
www.azojete.com.ng

CROP WATER STRESS OF TOMATO AS AFFECTED BY IRRIGATION REGIMES

Ismail, H[1*]., Abubakar, S. Z[2]., Oyebode, M. A[1]., Shanono, N. J[3]. and Dalhat, M. K[1].

(*[1]Department of Agricultural Engineering, Ahmadu Bello University, Zaria, Nigeria*

[2]National Agricultural Extensions and Research Liaison Services (NAERLS),
Ahmadu Bello University, Zaria, Nigeria

[3]Department of Agricultural Engineering, Bayero University, Kano, Nigeria)

*Corresponding author, e-mail address: habfta@yahoo.com, Tel: +234 (0) 8038758660

Abstract

A field experiment was conducted at the Irrigation Research Station, Kadawa Kano State, Nigeria (located 11^o 30’ N, 08^o 30’ E and 486 m above mean sea level) during 2012/2013 dry season to evaluate crop water stress index of tomato (ly*copersicon enculentum; UC82B*) as affected by irrigation regimes. The experiment consisted of four levels of irrigation water application depth of 100%, 75%, 50% and 25% replacement of moisture depleted and three irrigation intervals (7, 14 and 21 days) combined in Randomized Complete Block Design in a Split plot arrangement and laid as treatments in plots (3 m x 3 m basin) and replicated three times. Irrigation water was applied to each basin using a calibrated PVC pipe. The soil moisture was monitored throughout the crop growing season with theta probe. The crop canopy temperature (*T*c) in the experimental plots was measured with a portable hand-held infrared thermometer. The dry and wet bulb temperatures were measured with an aspirated psychrometer in the open area adjacent to the experimental plots. The mean air temperature (Ta) was determined from the average of the dry bulb temperature readings during the measurement period. The mean vapor pressure deficit (VPD) was computed as the average of the calculated instantaneous VPDs, using the corresponding instantaneous wet and dry bulb temperatures. The Crop water stress index increases with decrease in percentage of moisture depletion replacement from 100% to 25% and increase in the irrigation interval from 7 days to 21 days. The most stressed tomato was at 25% replacement of moisture depleted in 21 days (I21D-25%) with stress index of 1.000 and the fully watered (none stressed) tomato was when irrigated fully at 7 days (I7D-100%) with stress index of 0.003. Hence, a tomato can give a best yield and optimum water management with no stress under high water table condition, when irrigated at 7 days with 25% replacement of its moisture depleted.

Key words: Crop water stress index, irrigation regimes, depleted moisture, ground water, basin

1. Introduction

Productivity response to water stress differs with crop and climate. Many factors need to be accounted for in order to obtain a good measure of actual stress levels, but leaf temperature is the most important factor (Smith *et al.*, 1985; Stockle and Dugas, 1992). Therefore, critical values of the crop water stress index (CWSI) should be determined for a particular crop in different climates and soils for use in yield prediction and irrigation management. Predicting yield response to crop water stress is important in both developing strategies and decision-making concerning irrigation under limited water conditions by farmers and their advisors, as well as researchers. A range of empirical studies (Jackson, 1982; Stark and

Wright, 1985; Fangmeir *et al.*, 1989; Hutmacher *et al.*, 1991; Ben-Asher *et al.*, 1992; Stegman and Soderlund, 1992; Nielsen, 1994; Irmak *et al.*, 2000; Alderfasi and Nielsen, 2001) have shown that there may be different non-water stress baselines that can be used to quantify CWSI in the evaluation of plant water stress, and that ideally these need to be determined for each agro-climatic zone in which a particular crop is being grown. The CWSI derived from canopy-air temperature differences (Tc-Ta) versus the air vapor pressure deficit (VPD) was found to be a promising tool for quantifying crop water stress (Jackson *et al.*, 1981; Idso and Reginato, 1982; Jackson, 1982). The calculation of CWSI based on the Idso and Reginato (1982) definition relied on 2 baselines: the non-water-stressed baseline (lower limit), which represented a fully watered crop, and the maximum stressed baseline (upper limit), which corresponded to a non-transpiring crop (stomata fully closed) (Yuan *et al.*, 2004). The lower limit in the CWSI will change as a function of vapor pressure because at lower VPDs moisture is removed from the crop at a lower rate; thus, the magnitude of cooling is decreased.

The aim of this study was to find a best irrigation scheduling for tomato with no stress for best yield and optimum water management.

2. Materials and Methods

2.1 Study Area

The experiment was carried out during 2012/2013 irrigation farming season (November, 2012-April, 2013) at the Irrigation Research Station, Kadawa situated at about 50 km from Kano along the Kano- Zaria high way. The Kano River Irrigation Project is one of the largest irrigation projects in Nigeria and lies at 11^{o} 30’ N, 08^{o} 30’ E and 486 m above mean sea level within the Hadejia Jama’are River Basin, covering an area of about 75, 000 hectares.

2.2 Soil Analysis

Soil samples were collected at the experimental site at incremental depth of 15 cm from top soil to 45 cm depth for the determination of soil particle sizes, moisture contents at field capacity and wilting point, and soil bulk density as presented in Table 1.

2.3 Experimental Design

The experiment consisted of factorial combination laid in Randomized Complete Block Design in a Split plot arrangement, with the factors being three irrigation intervals (7 days, 14 days and 21 days) and four irrigation levels ($I_{100\%}$, $I_{75\%}$, $I_{50\%}$ and $I_{25\%}$ replacement of soil moisture depletion) and replicated three times. There were thirty six 3 m x 3 m basins separated by 0.5 m each.

Table 1: Physical properties of soil at the study area

Depth (cm)	FC(%) @ 33 kPa	PWP(%) @1500 kPa	Bulk density (g/cm^3)	Clay (%)	Silt (%)	Sand (%)	Textural class
0 - 15	12.6	3.3	1.49	14	18	68	Sandy Loam
15 - 30	15.2	3.8	1.42	16	12	72	Sandy Loam
30 – 45	16.9	4.4	1.34	20	10	70	Sandy ClayLoam

2.4 Measurement of Soil Moisture

Theta probe was used to determine the soil moisture content in each plot. The instrument was calibrated and moisture readings were taken directly by inserting the instrument into the desired depth of soil through access tubes which were already installed in holes.

2.5 Determination of Water Table Depth

Thirty six PVC piezometer tubes were installed at a depth of 1.2 m (based on the climatic and water table conditions of the area) below the soil surface at each plot. Water table levels in the tubes were measured by employing the use of a locally made water level sounder to which a graduated stalk of 1.5 m length was attached using the method of Nwa (1982). Water table measurements were taken weekly. The initial and final depths of water table for each plot were measured before and after irrigation, respectively and the contribution of irrigation water to the ground water was estimated by the difference between the two depths.

2.6. Determination of Total Volume of Irrigation Water Applied

The net and gross depths of water required to be applied to each basin were determined using equations 1 and 2, respectively and the total volume of irrigation water applied was determined by summing the irrigation water applied throughout the season.

$$dn = \sum_{i}^{n} \frac{M1i - M2i}{100} \times Asi \times Di \tag{1}$$

where:

dn = net depth of water to be applied or net irrigation, cm

M_{1i} = soil water at the time of first sampling in the i-th layer, %

M_{2i} = soil water at the time of second sampling in the i-th layer, %

A_{si} = bulk density of soil, g/cm^3, D_i = depth of the i-th layer of soil in the root zone, cm.

$$dg = \frac{dn}{Ea} \tag{2}$$

dg = gross depth, m

Ea = application efficiency, %

The amount of water to be applied was obtained using the relation:

$$V = dg\ x\ A \tag{3}$$

where:

V = volume of water to be applied, m^3,

A = area to be irrigated, m^2

Application time was obtained using the relation:

$$t = \frac{(dg\ x\ A)}{Q} \tag{4}$$

where: t = Application time, seconds

2.7 Determination of Crop Water Use and Seasonal Water Requirement

Soil moisture content was determined on each plot just before irrigation (moisture content at wilting point) and two days after irrigation (moisture content at field capacity), the amount of moisture used by the crop for each irrigation was determined using equation 5 and the seasonal crop water use for each treatment was determined by summing up the crop water use for the season for the particular treatment.

$$\text{CWU} = \sum_{i=1}^{n}(VMC1i - VMC2i)Di\ /\text{t} \tag{5}$$

where:

CWU is crop water use between successive soil moisture content sampling period (mm/day); VMC_{1i} is volumetric soil moisture content (m^{3}of water/m^3 of soil) at the time of first sampling in the ith soil layer; VMC_{2i} is volumetric soil moisture content (m^3 of water /m^3 of soil) at the time of second sampling in the ith soil layer; D_I is the depth of ith layer; n is the number of soil layers sampled in the root zone depth D, and ‘t’ is the number of days between successive soil moisture content sampling

2.8 Canopy Temperature

The crop canopy temperature (Tc) in the experimental plots was measured with a portable hand-held infrared thermometer (IRT) detecting radiation in the 8–14 µm wave bands (Minolta/Land Cyclops Compaq 3). The IRT was used with the canopy viewed at an angle of 35–45◦ from the horizontal to minimize soil background in the field of view. Four canopy temperatures were measured from different directions (east, west, north, and south) in each plot and averaged to determine the plot's canopy temperature when fully sunlight, at a distance of 0.50 m from the crop. Midday canopy temperature was used which is the best indicator to detect the crop water stress (Alves and Pereira, 2000).

The dry and wet bulb temperatures were measured with an aspirated psychrometer at a height of 2 m in the open area adjacent to the experimental plots. The mean air temperature (Ta) was determined from the average of the dry bulb temperature readings during the measurement period. The mean vapor pressure deficit (VPD) was computed as the average of the calculated instantaneous VPDs, using the corresponding instantaneous wet and dry bulb temperatures.

2. 9 Crop Water Stress Index (CWSI)

The CWSI values were calculated using the procedures of Idso et al. (1981). In this approach, the measured crop canopy temperature was scaled relative to the minimum canopy temperature expected under non water- stress conditions and the maximum temperature under severe water stress. The non-water-stressed baseline for the canopy-air temperature difference (Tc-Ta) versus the vapor pressure deficit (VPD) relationship was determined using the data collected only from the control treatment (I7D-100%). The upper (fully stressed) baseline was computed by the canopy temperatures of the fully stressed plants (I21D-25%). Using the upper and lower limit estimates, CWSI was calculated for all the treatments, using equation 6

$$CWSI = \frac{(Tc - Ta) - D2}{D1 - D2} \tag{6}$$

where:

D_1 is the maximum canopy and air temperature difference for a stressed crop (the maximum stressed baseline, ^{o}C),

D_2 the lower limit canopy and air temperature difference for a well watered crop (the non-water-stressed baseline, ^{o}C),

Tc is the measured canopy surface temperature (^{o}C), Ta is the air temperature (^{o}C).

VPD is calculated as:

$$VPD = VP_{sat} - VP \tag{7}$$

where: VP_{sat} is the maximum vapor pressure for a given air temperature and pressure and VP is the actual vapor pressure.

2.10 Measurement of Crop Yield

Harvesting of the crop was carried out weekly (from 5th March to 9th April, 2013) by manual picking. The good tomato crop from each plot was weighed using a weighing balance and considered as marketable yield.

3. Results and Discussion

3.1 Existing Water Table Depths in the Study Area

Table 2 shows the various water table depths at different piezometer points in the study area. The initial and final depths of water table were not uniform across the piezometer points as shown in Figure 1. The water table levels for all the piezometer points were higher at the final stage than the initial stage. This is due to the contribution from the irrigation water applied to the ground water which could be seen from the differences between the initial and final water table depths across the piezometers. The piezometers located at 18. 5 m and 27.7 m from the field channel showed the highest contribution of 30 mm where full irrigation was applied at seven days interval. In all, the contribution to water table from irrigation water applied ranged from 10 mm to 30 mm.

Table 2: Water Table depths at different piezometer points at the experimental field

S/N	LDFC (m)	IWTD (cm)	FWTD (cm)	DWTD (cm)
1	1.5	69	67.5	1.5
2	4.5	67	65	2.0
3	7.5	66	65	1.0
4	11.5	72	70.5	1.5
5	14.5	70	68	2.0
6	15	77	76	1.0
7	17.5	72	70	2.0
8	18.5	61	58	3.0
9	20.5	75	73	2.0
10	24.5	70	69	1.0
11	27.5	68	65	3.0
12	29	62	60	2.0

KEY: WTD = water table depth, LDFC = Location (Distance from field channel), IWTD = initial water table depth (as bench mark), FWTD = final water table depth, DWTD = Difference in water table depth (contribution to water table from irrigation)

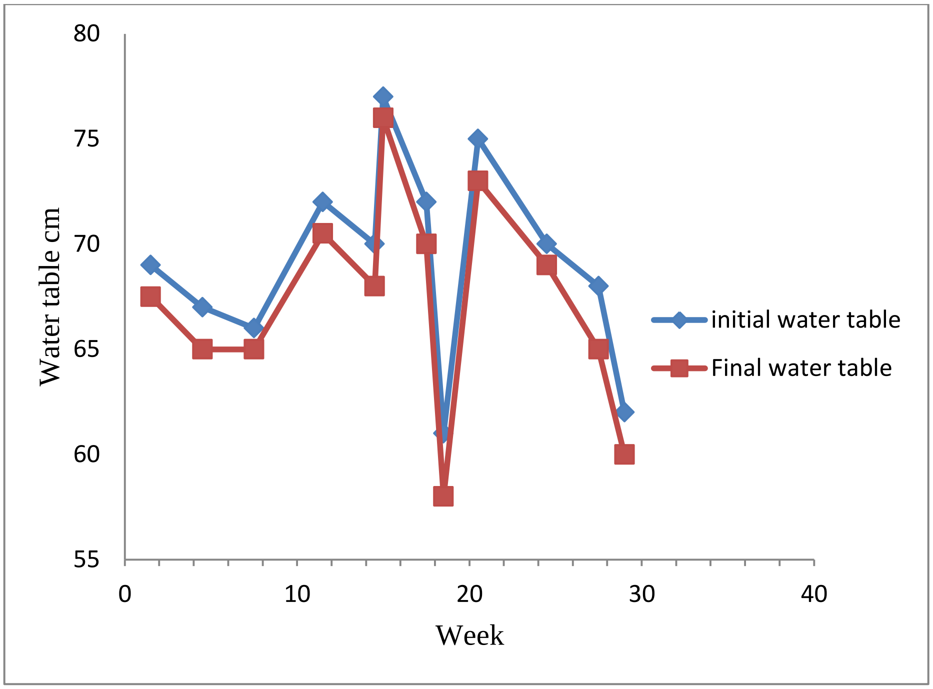

Figure 1: Water table profiles at the experimental field

3.2 Optimum Yield of Tomato

Table 3 shows the irrigation water applied, water use and yield of tomato for various treatments. The plots of tomato yield versus water applied and water use shown in Figures 2, 3 and 4 gave the polynomial Equations 2, 3 and 4, respectively.

$y_1 = -3\ X\ 10^{-5}\ x^2 +\ 0.027x + 20.55$ (8a)

$y_2 = -9\ X\ 10^{-5}\ x^2 +\ 0.098x - 0.141.91$ (8b)

$y_3 = -0.00\ X\ 10^{-5}\ x^2 +\ 0.144x + 6.165$ (9a)

$y_4 = -0.00X\ 10^{-5}\ x^2 +\ 0.235x - 21.20$ (9b)

$y_5 = -5X\ 10^{-5}\ x^2 +\ 0.033x + 17.8$ (10a)

$y_6 = -0.00\ X\ 10^{-5}\ x^2 +\ 0.346x - 21.97$ (10b)

Differentiating Equations 8, 9 and 10 with respect to x and setting the results to zero for optimum yield gave:

y_{1max} = 26.63 t/ha, y_{2max} = 26.68 t/ha and y_{5max} = 23.25 t/ha.

y_3, y_4 and $y_6 = \infty$.

Table 3: Irrigation water applied, water use and yield of tomato

Treatments	Water Applied mm	Water Used mm	Mkt yield t/ha
7D-100%	507.2	507.1	28.21
7D-75%	401.2	510	27.19
7D-50%	248.1	431.1	26.26
7D-25%	154.1	357.1	24.03
14D-100%	336.1	336.2	24.31
14D-75%	259.0	324.1	26.91
14D-50%	186.9	300.5	22.56
14D-25%	119.4	252.4	20.04
21D-100%	313.8	313.9	23.88
21D-75%	254.1	307.6	20.72
21D-50%	165.9	249.7	24.06
21D-25%	109.2	187.5	19.87

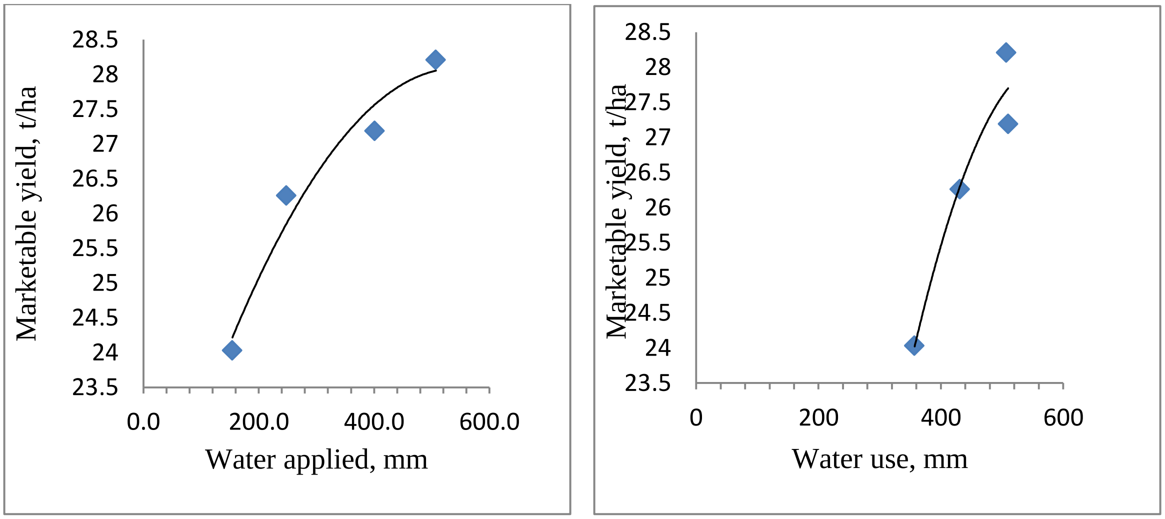

Figure 2: Marketable yield of tomato as influenced by irrigation water applied and water use for 7 days interval

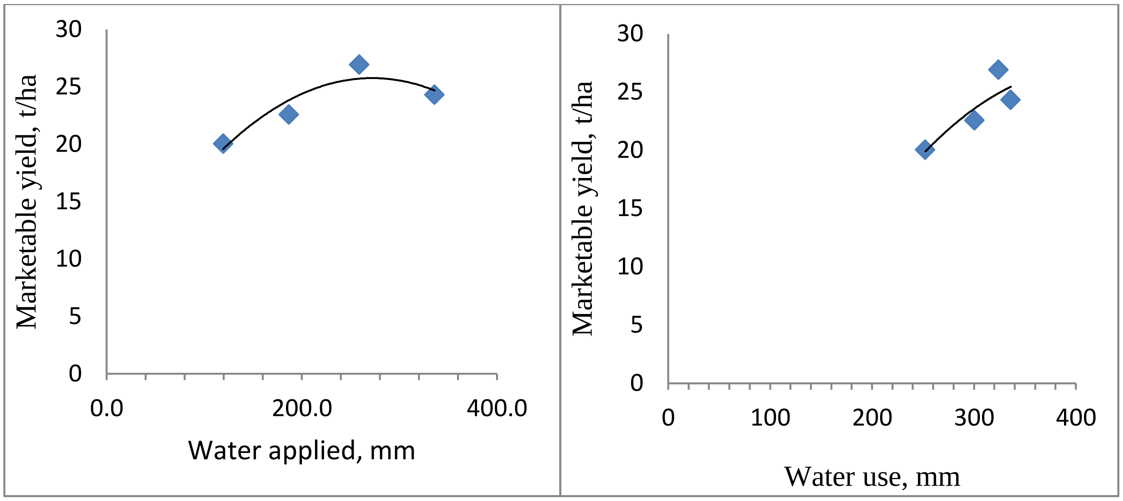

Figure 3: Marketable yield of tomato as influenced by irrigation water applied and water use for 14 days interval

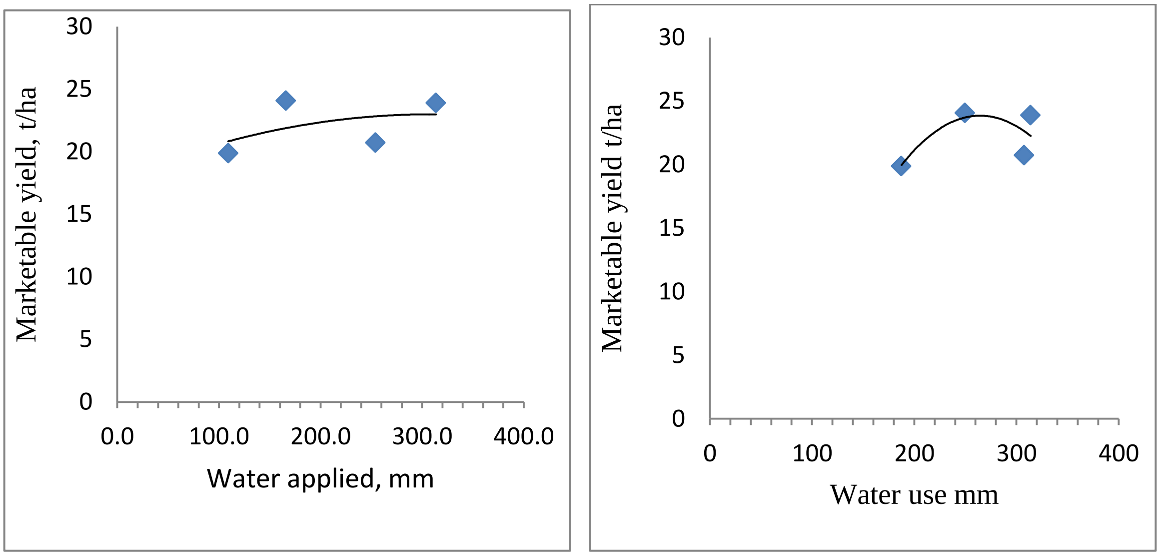

Figure 4: Marketable yield of tomato as influenced by irrigation water applied and water use for 21 days interval

3.3 Crop Water Stress Index

Table 4 shows weather data for non stressed crop (I7D-100%) and fully stressed crop (I21D-25%). Canopy temperature for the non stressed tomato was less than the air temperature throughout the growing period because of enough transpiration by the crop when not water stressed which makes the evaporated water to cool the leaves below that of air temperature.

As the crop becomes water-stressed transpiration decreased, and thus the leaf temperature increased above the air temperature. Consequently, the canopy temperatures for non-water stressed and fully-stressed tomato increased around the late-season to harvesting periods because of the fruiting and shading of the leaves around that time which reduced the rate of transpiration by the crop as shown in Figure 5.

Table 4: Weather data for none stressed and fully stressed tomato at Kadawa during 2012/2013 dry season

Date	Week	@T_1 Tc (°C)	@T_{12} Tc (°C)	Ta (°C)	RH %	es (kPa)	ea (kPa)	vpd (kPa)	@T_1 (Tc-Ta)	@T_{12} (Tc-Ta)
08-01-13	5	28.9	30.8	26.5	19	3.462	0.658	2.804	2.4	4.3
15-01-13	6	30.8	36.5	32.3	15	4.836	0.725	4.111	-1.5	4.2
22-01-13	7	32.4	38.5	34.5	18	5.469	0.984	4.485	-2.1	4
29-01-13	8	27.4	32.2	28.1	14	3.802	0.532	3.270	-0.7	4.1
05-02-13	9	29.6	35	31	14	4.493	0.629	3.864	-1.4	4
12-02-13	10	30.7	37.2	33.3	9	5.115	0.460	4.655	-2.6	4
19-02-13	11	29.4	34.8	30.8	11	4.442	0.489	3.953	-1.4	4
26-02-13	12	33.5	40.6	37	10	6.275	0.627	5.647	-3.5	4
05-03-13	13	31.0	42	38	5	6.625	0.331	6.294	-7	4.2
12-03-13	14	33.9	40.7	36.8	16	6.207	0.993	5.214	-2.9	3.9
19-03-13	15	30.8	41.4	37.4	9	6.413	0.577	5.836	-6.6	4
26-03-13	16	32.9	42	38.3	14	6.733	0.943	5.790	-5.4	3.7
02-04-13	17	31.3	42.2	38.1	12	6.661	0.799	5.861	-6.8	4.1

Source: Meteorological Station, Kadawa 2012/2013 dry season

T_I = none stressed tomato,T_{12}= fully stressed tomato, T_c = canopy temperature, Ta = air temperature

es = saturated vapour pressure, ea = air vapour pressure, vpd = vapour pressure deficit = es-ea

Table 5 shows weekly and average crop water stress indices. The results show that as tomato crop transpired, that is when not water stressed; the evaporated water cooled the leaves below that of air temperature. As the crop becomes water stressed transpiration decreased, and thus the leaf temperature increased.

Moreover, graphical method was used to determine the CWSI. Thus, from the graph:

CWSI = a/b = (6-3.5)/ (4+6) = 0.25. (The measurement was done at the point where Tc-Ta = -6 °C on Figure 6).

Table 5: Weekly and average crop water stress indices at Kadawa during 2012/2013 dry season

	WK5	WK6	WK7	WK8	WK9	WK10	WK11	WK12	WK13	WK14	WK15	WK16	WK17	
Treatments	08.01.13	15.01.13	22.01.13	29.01.13	05.02.13	12.02.13	19.02.13	26.02.13	05.03.13	12.03.13	19.03.13	26..03.13	02.04.13	Average
I7100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.002
I775%	0.03	0.04	0.11	0.10	0.06	0.06	0.09	0.03	0.09	0.02	0.05	0.11	0.18	0.075
I750%	0.08	0.08	0.19	0.15	0.13	0.11	0.27	0.12	0.17	0.09	0.17	0.10	0.35	0.155
I725%	0.11	0.11	0.23	0.22	0.15	0.18	0.40	0.20	0.29	0.17	0.31	0.22	0.35	0.226
I14100%	0.16	0.18	0.44	0.28	0.20	0.24	0.43	0.32	0.37	0.24	0.33	0.25	0.33	0.290
I1475%	0.23	0.24	0.60	0.36	0.42	0.25	0.50	0.46	0.49	0.61	0.34	0.33	0.36	0.399
I1450%	0.31	0.42	0.73	0.53	0.63	0.31	0.51	0.55	0.69	0.70	0.44	0.35	0.45	0.509
I1425%	0.37	0.49	0.76	0.59	0.66	0.38	0.64	0.59	0.79	0.74	0.43	0.45	0.53	0.571
I21100%	0.48	0.57	0.85	0.75	0.73	0.53	0.76	0.61	0.80	0.75	0.53	0.46	0.55	0.644
I2175%	0.58	0.68	0.89	0.88	0.84	0.53	0.84	0.77	0.85	0.88	0.62	0.57	0.60	0.733
I2150%	0.57	0.71	0.92	0.93	0.98	0.86	0.85	0.80	0.90	0.93	0.65	0.58	0.63	0.793
I2125%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.000

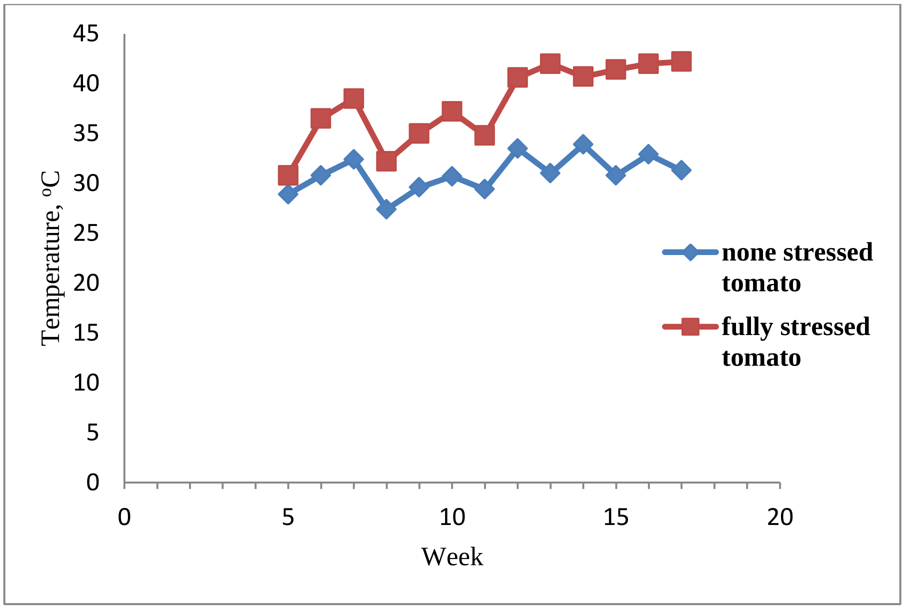

Figure 5: Tomato temperature rise and fall as influenced by irrigation interval and amount

Figure 6 shows the upper and lower base lines for the stressed and fully watered crop, respectively. Relative distance between the two lines was used to calculate the crop water stress index. A crop water stress index of 0.25 obtained from Figure 6 indicated that all treatments with less than or equal 0.25 were not stressed and those above the value of 0.25 were stressed. However, irrigation at 7 days interval with full irrigation (I7D-100%) was considered to be fully watered and irrigation at 21 days interval with only 25% replacement of moisture depleted (I21D-25%) was critically stressed.

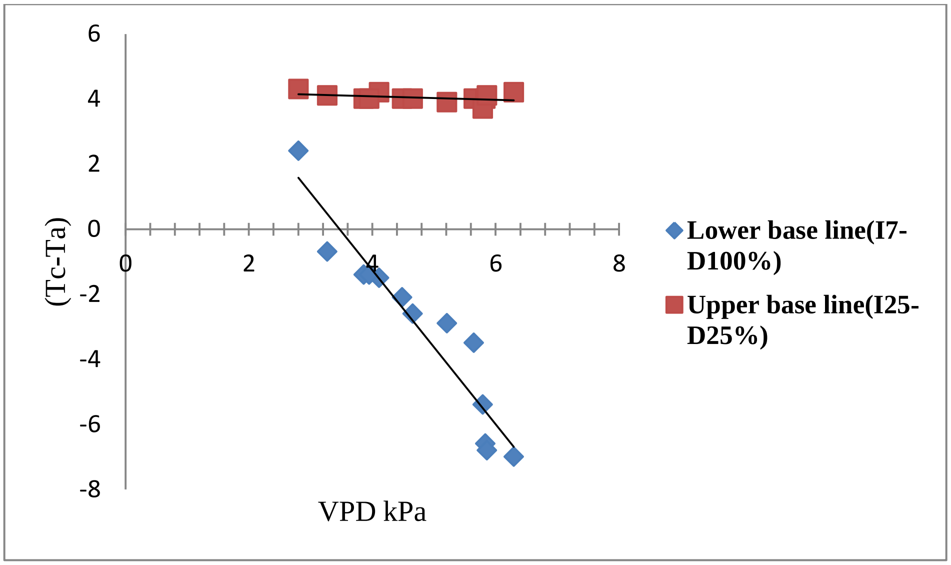

Figure 6: Upper and lower base lines for a fully stressed and none stressed tomato as influenced by irrigation interval and amount at Kadawa during 2012/2013 dry season

3.4 Effect of Irrigation Depth and Interval on Crop Water Stress Index

From Table 6, the most stressed tomato under irrigation depth was at $I_{25\%}$ with stress index of 0.5978 followed by $I_{50\%}$ with 0.4856 then $I_{75\%}$ with 0.4033. The less stressed tomato was at $I_{100\%}$ with stress index of 0.3111. However, tomato was stressed most at 21 days with stress index of 0.7942 followed by 14 days with 0.4433 then 7 days which was less stressed with 0.1108. Generally CWSI increases with decrease in % of moisture depletion replacement from 100% to 25% and increases with increase in the irrigation interval from 7 days to 21 days.

Table: 6 Statistical means of crop water stress index as affected by irrigation

depths and intervals at Kadawa in 2012/2013 dry season on tomato

Treatment	CWSI
Depths	
I100%	0.3111d
I75%	0.4033c
I50%	0.4856b
I25%	0.5978a
CV	2.695
LSD (5%)	0.0118
Significance	**
Interval	
7-Days	0.1108c
14-Days	0.4433b
21-Days	0.7942a
CV	2.695
LSD (5%)	0.0103
Significance	**

From Table 7, tomato crop was significantly stressed at 21 days followed by 14 days then 7 days when irrigation was fixed at $I_{100\%,}$ $I_{75\%,}$ $I_{50\%}$ and $I_{25\%}$ with stress indices of 1.0, 0.797, 0.737 and 0.643; 0.57, 0.513, 0.403 and 0.287; and 0.223, 0.147, 0.0701 and 0.003, respectively. However, for 7 days, 14 days and 21 days; $I_{25\%}$ recorded the most stressed crop with 0.223, 0.57 and 1.00, respectively followed by $I_{50\%}$ with 0.14, 0.513 and 0.797, respectively then $I_{75\%}$ with 0.0701, 0.403 and 0.737, respectively. The less stressed crop was at $I_{100\%}$ with 0.003, 0.287 and 0.643, respectively.

Generally, the most stressed tomato was those irrigated at 21 days interval and when irrigation was made at 25% replacement of moisture depleted with stress index of 1.000 and the fully watered (non stressed) tomato was at 7 days interval and when irrigation was made at 100% replacement of moisture depleted with stress index of 0.

Table 7: Irrigation depths and intervals interaction on crop water stress index at Kadawa in 2012/2013 dry season on tomato

Depths	CWSI 7-Days	14-Days	21-Days
$I_{100\%}$	0.003m	0.287h	0.643d
$I_{75\%}$	0.070l	0.403g	0.737c
$I_{50\%}$	0.147k	0.513f	0.797b
$I_{25\%}$	0.223j	0.570e	1.000a
CV	2.695		
LSD (5%)	0.021		
Significance	**		

4. Conclusion

Crop water stress index increases with decrease in percentage of moisture depletion replacement from 100% to 25% and increase in the irrigation interval from 7 days to 21 days. The most stressed tomato was at 21 days interval and when irrigation was made at 25% replacement of moisture depleted with stress index of 1.000 and the fully watered (non stressed) tomato was at 7 days interval and when irrigation was made at 100% replacement of moisture depleted with stress index of 0.003. Hence, a tomato can give a best yield and optimum water management with no stress under high water table condition, when irrigated at 7 days with 25% replacement of its moisture depleted.

References

Alderfasi, A A. and Nielsen, DC. 2001. Use of crop water stress index for monitoring water status and scheduling irrigation in wheat. Agricultural Water Management, 47: 69-75.

Alves, I. and Pereira, LS. 2000. Non-water-stressed baselines for irrigation scheduling with infrared thermometers: a new approach. Irrigation Science, 19: 101–106.

Ben-Asher, J., Phene CJ. and Kinati, A. 1992. Canopy temperature to assess daily evapotranspiration and management of high frequency drip irrigation systems.
Agricultural Water Management, 22: 379-390.

Fangmeir, DD., Garrot, DJ., Husman, SH. and Perez, J. 1989. Cotton water stress under trickle irrigation. Transactions of the ASAE, 32:1955-1959.

Hutmacher, RB., Steiner, J., Vail, SS. and Ayars, JE. 1991. Crop water stress index for seed alfalfa: influences of within-season changes in plant morphology. Agricultural Water Management, 19: 135-149.

Idso, SB., Jackson, RD., Pinter, PJ. and Hatfield, JL. 1981. Normalizing the stress degree day parameter for environmental variability. Agricultural Meteorology, 24: 45-55.

Idso, SB. 1982. Non-water stressed baselines: a key to measuring and interpreting plant water stress. Agricultural Meteorology, 27: 59-70.

Irmak, S., Dorota, ZH. and Bastug, R. 2000. Determination of crop water stress index for irrigation timing and yield estimation of corn. Agronomy Journal, 92: 1221-1227.

Jackson, RD. 1982. Canopy temperature and crop water stress. Advances in Irrigation, Vol. 1, Academic Press, New York, 43-85.

Nielsen, DC. 1994. Non-water stressed baselines for sunflowers. Agricultural Water Management, 26:265-276.

Nwa, EU. 1982. Ground water problems of the Kano River Irrigation Project of Nigeria. Proceedings of the 4th Afro-Asian conference of KID, Lagos, Nigeria, Vol. II (pub. 01): 18-27.

Smith, RCG., Barrs, HD., Steiner, JL. and Stapper, M. 1985. Relationship between wheat yield and foliage temperature: theory and its application to infrared measurements. Agricultural and Forestry Meteorology, 36: 129-143.

Stark, JC. and Wright, JL. 1985. Relationship between foliage temperature and water stress in potatoes. American Potato Journal, 62: 57-68.

Stegman, EC. and Soderlund, M. 1992. Irrigation scheduling of spring wheat using infrared thermometry. Transactions of the ASAE, 35: 143-152.

Stockle, CO. and Dugas, WA. 1992. Evaluating canopy temperature based indices for irrigation scheduling. Irrigation Science, 13: 31-37.

Yuan, G., Luo Y., Sun X. and Tang D. 2004. Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain. Agric.Water Manage. 64: 29-40.