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Research Paper

Assessment of the *Idso* crop water stress index (CWSI) model for detecting water STRESS in maize (*Zea mays L)* in the rainforest Argo-zone, Southeastern Nigeria

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ABSTRACT

In spite of the observed and potential impacts of climatic variability on agricultural sector in Nigeria, little is known about how agricultural yields will respond to climatic variability. Thus, predicting yield response to crop water stress index (CWSI) is important in developing strategies and decision-making concerning irrigation management under limited water conditions by farmers. The present study investigated the applicability of Idso CWSI model in predicting seasonal pattern of water stress in maize over southeastern Nigeria. From our analysis CWSI values ranged from 0.54 to 1.0 indicating periods of moderate to maximum water stress. August is the month in the study area when there is moderate soil moisture supply for maize. Most of the high water stress index values were recorded in March and April except for Calabar and Uyo stations. The high peaks in water stress in the month of August (Ikom) and June (Onitsha) can be explained by the fact that within these periods rainfall and soil moisture are expected to be in their peaks at this region. Generally, it was observed that CWSI results calculated for maize for the eight climatic stations fall within acceptable range of 0 – 1.0. This buttresses the fact that the Idso empirical CWSI model is a good indicator for maize water stress monitoring in South-eastern Nigeria.

Key word: Climatic variability, crop yield, crop water stress index (CWSI) Idso, water stress.

INTRODUCTION

According to UN study (1997) one-third of the world total population live under conditions of relative water scarcity and 450 million people are under severe water stress. Vorosmarty et al. (2000) adopting the global water model and some projections for climate change, population growth and economic growth, observed that the number of people under severe water stress is expected to rise to 2.2 billion by 2025 due to combined effects of population growth and climate change.

Climate change is projected to have significant impacts on conditions affecting agriculture. While some aspects of climate change such as longer growing seasons and warmer temperatures may bring benefits (in cold regions), there will majorly be a range of adverse impacts, such as reduced water availability, greater water need, and more frequent extreme weather in the tropics (Eitzinger and Kubu, 2009). These impacts will put agricultural activities at significant risk.

Water consumption in the agricultural sector is responsible for 84%, while figures for domestic, industry and reservoirs are estimated at 4, 2 and 10% respectively (Shiklomanov, 2003). Experts are concerned that agricultural sector will be highly sensitive to future climate change and any increase in climate variability. Even without climate change, there are serious concerns about agriculture in Africa because of water supply variability, soil degradation, and recurring drought events (Mendelsohn et al., 2000).

According to FAO report about 800 million people in developing countries do not have enough food to eat while another 41 million people in the industrialized countries and countries in transition also suffer from chronic food insecurity (FAO, 2000). Guaranteeing sufficient food to sustain the growing world population is one of the key challenges now and in the coming decades and has prompted the establishment of the Millennium Development Goals (MDGs) to help promote sustainable development in developing countries throughout the world.

Over much of the tropics, rainfall is the most important climatic factor influencing agriculture. It determines to a large extent the crops which can be grown, the farming system and the sequence and timing of farming operations (Webster and Wilson, 1980). Consequently, variability in rainfall will have significant effect on the economies of most tropical countries especially in Africa.

Nigeria is presently not self-sufficient in the production of food crops. Agricultural production is a mirror image of population growth. The dwindling in agricultural production and shrinkages in the belts of food crops in Nigeria have been noted by Olanrewaju (2003) and Adefolalu (2004) among others. For instance, Olanrewaju (2003) noted that the climatic situation in Kwara State is no longer supporting the growth of melon and therefore suggested a shift of melon cultivation to the southern guinea ecological zone of Nigeria where environmental conditions are favourable. Similarly Adefolalu (2004) associated the decline in production of groundnut to climate change and variability.

In spite of the observed and potential impacts of climate change on the agricultural sector, little is known about how agricultural yields will respond to climatic change and variability in the country. Thus, predicting yield response to crop water stress has become important in developing strategies and decision-making concerning irrigation management under limited water conditions by farmers and their advisors, as well as researchers (Erdem et al., 2006).

The Crop Water Stress Index (CWSI) has been shown to be closely related to available water in the root zone of a wheat crop (Jackson et al., 1981) and to leaf diffusion resistance in cotton (Idso et al., 1982). Nielsen and Anderson (1989) reported that statistically significant correlations were found between CWSI calculated from single-leaf temperatures and stomatal conductance, CO_2 exchange rate, leaf water potential, transpiration rate and percent available water in the active root zone for sunflower.

A range of empirical studies (Hutmacher et al., 1991; Ben-Asher et al., 1992; Stegman and Soderlund, 1992; Nielsen, 1994; Gencoglan and Yazar, 1999; Odemis and Bastug, 1999; Yazar et al., 1999; Irmak et al., 2000; Alderfasi and Nielsen, 2001; Orta et al., 2002; Colaizzi et al., 2003; Orta et al., 2003; Yuan et al., 2004) have shown that there may be different non-water stress baselines that can be used to quantify CWSI for the purposes of evaluating of plant water stress.

The Crop Water Stress Index (CWSI) is an index which is based on canopy temperature to detect crop water stress (Yuan et al., 2004). The index uses leaf temperature and vapor pressure deficit (VPD) data to determine a relative degree of plant water stress. The index is based on the fact that transpirational cooling reduces leaf temperature relative to air temperature; the reduction being greater at relatively high VPD values (low moisture content) compared to low VPD values (Niemera and Goy, 1990). Leaf temperature increases when the supply of water to a plant limits transpiration and when radiant energy is not dissipated via evaporation.

Maize (*Zea mays* L.) grown mostly under rain fed condition is a major commercial crop in the Southeastern Nigeria. However, due to climatic variability and population expansion, annual yields are hardly enough to meet commercial demands. For an all year round cultivation in an environment that experiences dry seasons, irrigation is necessary during the growing season to maintain and enhance crop growth and yield. Under these variability conditions farmers have to understand the moisture stress of crops and how to choose the most water efficient methods of irrigation scheduling (Anac et al., 1999; Orta et al., 2002).

Unfortunately, no studies have been done to evaluate the CWSI applications in rainforest agro-zone of Nigeria, where climate is highly variable. In this study we adopted the Idso (1982) model for estimating crop water stress index (CWSI) in maize over Southeastern Nigerian.

MATERIALS AND METHODS

Southeastern Nigeria is located between latitudes 4° 10'N and 70° 08'N, and longitudes 5° 30'E and 9° 27'E. It is bounded to the south, east and west by the Atlantic Ocean, Republic of Cameroon and Delta State respectively and to the North by the middle belt states of Kogi and Benue. The region is made up of nine states (that is Anambra, Enugu, Ebonyi, Abia, Imo, Rivers, Bayelsa, Cross-River and Akwa Ibom. There are presently eight synoptic stations within the study area (Figure 1).

Rainfall pattern in the study area is a good reflection of the seasonal variations of the surface location of the inter-tropical discontinuity (ITD) (Oguntoyinbo, 1967).

South-eastern Nigeria lies in the Lowland Rainforest natural vegetation belt with evergreen trees in the south. Northward of the area, the vegetation gradually gives way to rainfall-savannah forest characterized by trees interspersed with grass.

Data collected for these stations are precipitation, minimum and maximum temperature and relative humidity data for the period of 24 years (from 1982-2005). Maize was chosen in the study bearing in mind that it is a seasonal crop and contributes meaningfully as staple crop in the study area after cassavas.

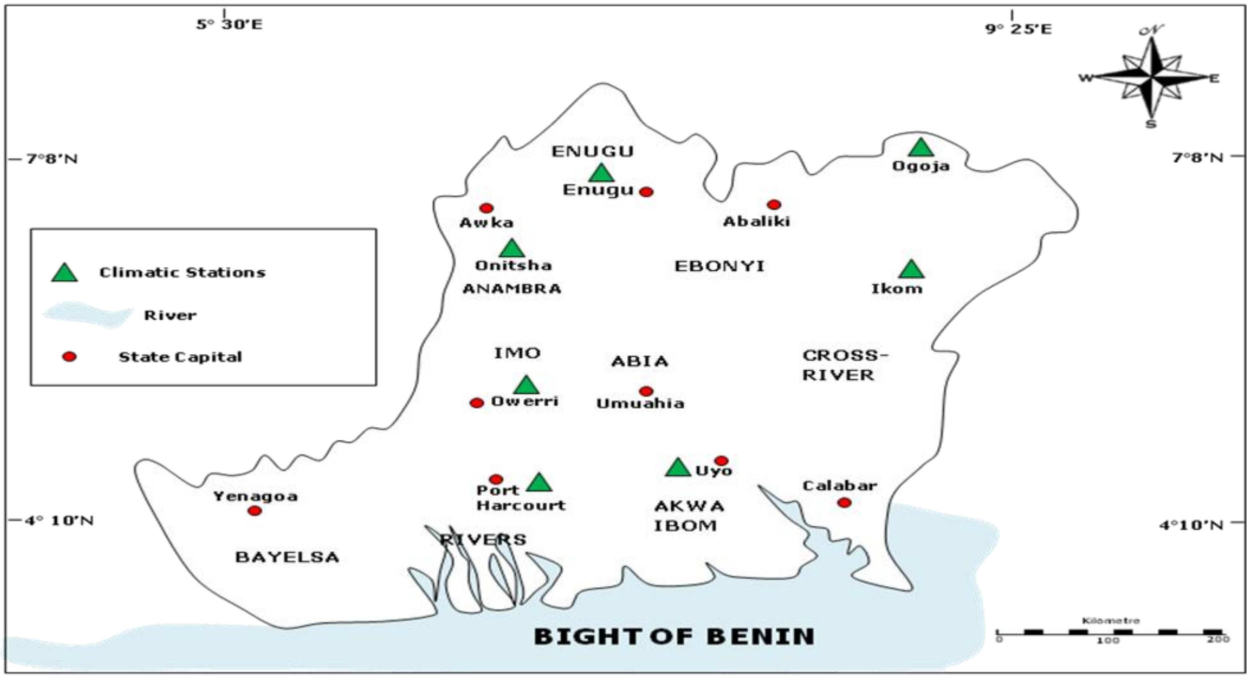

Figure 1. Southeastern Nigeria showing climatic stations.

Estimating CWSI

The calculation of CWSI relies on two baselines: the non-water-stressed baseline, which represents a fully watered crop, and the maximum stressed baseline, which corresponds to a non-transpiring crop (stomata fully closed). There are two popular different non-water stressed baselines for determining the CWSI. One is the Idso definition (Idso et al., 1981), which is derived from the empirical relationship between the canopy–air temperature differences (*T*c − *T*a) and the air vapour pressure deficit (VPD) for a well watered crop. The calculation of CWSI based on Idso definition needs three main environmental variables: crop canopy surface temperature (*T*c), air temperature (*T*a), and air vapour pressure deficit. According to the Idso's definition (Idso et al., 1981), the CWSI can be expressed as:

$$CWSI = \frac{Tc - Ta - D2}{D1 - D2} \qquad \text{(Equation 2)}$$

Where *D*1 is the maximum canopy and air temperature difference for a stressed crop (the maximum stressed baseline).
*D*2 the lower limit canopy and air temperature difference for a well watered crop (the non-water-stressed baseline).
*T*c is the measured canopy surface temperature (°C), and
*T*a is the air temperature (°C).
Canopy surface temperature was determined using the crop coefficient method developed by Alves (1995). The method is based on multiplying the reference crop evapotranspiration, ETo by a crop coefficient, Kc

ETc = Kc ETo

Where: ETc is crop evapotranspiration [mm d-1],
Kc is crop coefficient [dimensionless],
ETo is reference crop evapotranspiration [mm d-1].

The value of Kc was determined from FAO (Allen et al., 2002) Table which has been defined for sub-humid climate with average daytime minimum relative humidity (RHmin) ≈ 45% and having calm to moderate wind speeds averaging 2 m/s.
The mean air temperature (Ta) determined from the average of the meteorological station readings during the measurement periods. Monthly values of PET for individual climatic station were computed using the Linacre model. This model's suitability in tropical climates has been validated (Ayoade, 1976; Anyadike, 1992).

Estimation of Non- water stressed baseline (D_2)

For the calculation of the non-water-stressed baseline, Idso represented an empirical formula (Idso et al., 1981; Idso, 1982):

$D_2 = A + B$ VPD (Equation 2)

Where: D_2 is non-water-stressed baseline, VPD is the air

Table 1. Baseline parameters for various crops - sunlit conditions.

Crop	intercept	Slope
Alfalfa	0.5	-1.92
Barley (pre-heading)	2.01	-2.28
Barley (post-heading)	1.72	-1.23
Bean	2.91	-2.35
Beet	5.16	-2.30
Corn (no tassel)	3.11	-1.97
Cowpea	1.32	-1.84
Cucumber	4.88	-2.52

Source: adapted from Idso (1982).

vapour pressure deficit (kPa),
A (intercept) and B (slope) are the linear regression coefficients of the lower limit canopy and air temperature difference on VPD.
Values of A and B have been defined for various crops under sunlit conditions (Table 1). In this A and B values for maize was determined from Idso baseline parameter (Idso, 1982).
Vapour pressure deficit (VPD), was calculated as the difference between the saturation (es) and actual vapour pressure (ea) for a given time period (Idso, 1982). The equation is given as:

$VPD = es - ea$ (Equation 3)

Where: Vapour pressure deficit of the air (kPa).
es is the saturation vapour pressure and *ea* is the actual vapour pressure.
Values of *es* and *ea* were calculated using Equations 4 and 5 (Allen et al., 1998). Relative Humidity (RH) measurements were used to calculate the actual saturation vapour pressure of the air with procedures given by Allen et al. (1998).

es = 0.6108 exp 17.27 ´Ta / Ta + 237.3 (3) (Equation 4)

$ea = es$ ´ (RH / 100) (Equation 5)

Where Ta is the air temperature (°C),
RH, the relative humidity of the air (%)

Maximum stressed baseline

For calculating the CWSI, the maximum stressed baseline must also be obtained. This study will use their definitions respectively to determine the maximum stressed baseline to calculate CWSI. For the CWSI based on Idso's definition (CWSI I), the maximum stressed baseline is expressed as (Idso et al., 1981):

$D1 = A + B$ VPG (Equation 6)

Where A and B is the same with Equation (2), VPG is the difference between the saturation vapour pressure (es) evaluated at air temperature (Ta) and a temperature equal to Ta + A.

Using the baseline parameters for maize (Table 1) and Equations 2 and 6, the canopy air temperature difference for a well-watered crop (lower limit) and severely stressed crop (upper limit) was calculated. Values of CWSI range from 0 to 1. Where the value 0 indicates no water stress in crop, 1 represents maximum crop water stress.

RESULTS

The average (1982 – 2005) monthly patterns of water stress in Maize for eight climatic stations are summarized in Figures 2 to 9. Generally, CWSI was observed to be very high in all the stations, ranging from 0.52-1.0 indicating partial to maximum water stress.

In Ikom station (Figure 1), the lowest value of CWSI was recorded in July with CWSI value of 0.63. In August however, the value peaked to 1.0 indicating maximum water stress. High water stress was generally recorded in Ikom station in 10 months of the year, while the months of July and September recorded values that were not up to the maximum water stress level. Ogoja station recorded the lowest water stress index was in August with an index value of 0.59. The highest water stress values of 0.83 and 0.82 in Ogoja station were recorded in March and February (Figure 3).

High values of CWSI were recorded in all the month of the year in Port-Harcourt station (Figure 4). The values range from 0.65 being the lowest stress value to 0.80. It is noteworthy that all the water stress values in Port-Harcourt station exceeded the lowest limit of 0.50. In Onitsha station (Figure 5), it was observed that 2 months, March and June with water stress values of 0.90 and 0.97 respectively recorded near-maximum water stress, while the lowest water stress for this station was recorded in August with a stress index of 0.61.

For the Calabar station (Figure 6), values of CWSI varied remarkably. Figure 6 depicts that through the months of September to December, water stress values were observed to be stable at an Index of 0.75. In January, water stress index declined by 0.06. August recorded the lowest water stress in Calabar station. The highest water stress index was recorded in February with water stress value of 0.59.

In Owerri station (Figure 7), high values of CWSI were recorded in all the months. The highest water stress value was however recorded in February with CWSI value of 0.86. It is noteworthy that there is no month in this station with water stress index less than 0.60.

Enugu station (Figure 8) had CWSI that were generally high from January to March (ranging between 0.7 and 0.79). From June, water stress index was low, up to the month of December before a rise occurred in January. The lowest water stress index value recorded in this station was

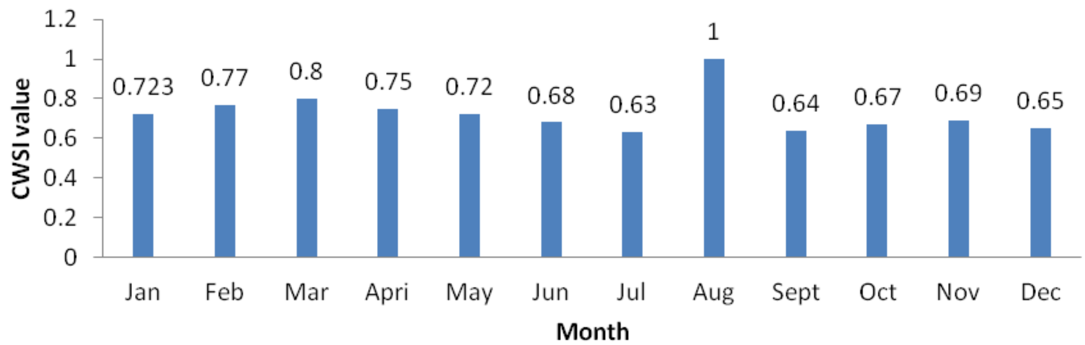

Figure 2. Pattern of water stress in maize, Ikom station.

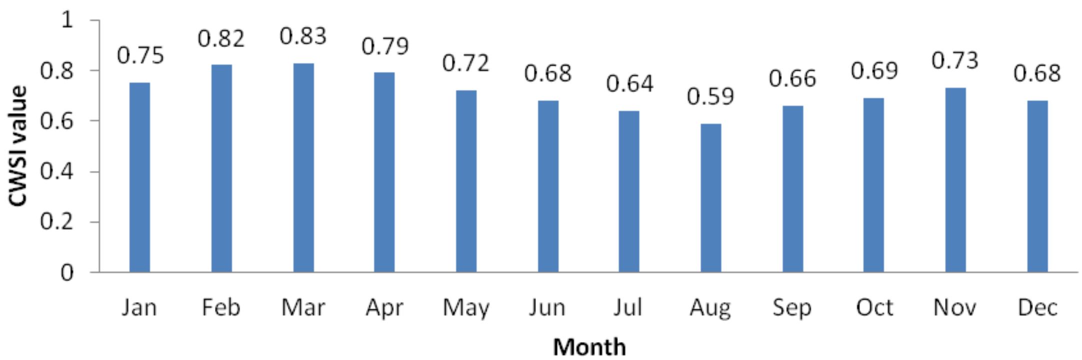

Figure 3. Pattern of water stress in maize, Ogoja station.

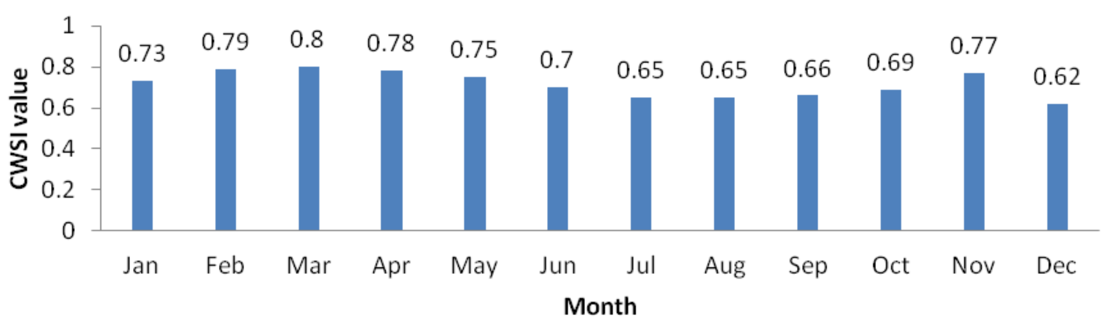

Figure 4. Pattern of water stress in maize, Port-Harcourt station.

0.61. In Uyo station (Figure 9), CWSI values ranged from 0.5-0.70 with February having the lowest water stress index. The highest water stress index was recorded in January with a water stress index value of 0.70. This station also had the month with the lowest water stress when compared to the other six stations.

DISCUSSION

From results obtained from the study and depicted as Figures 2 to 9, water stress in relation to maize water need is experienced in all the months of the year irrespective of rains experienced at these periods. Apart from Calabar and Uyo stations, high water stress index values were recorded in the other stations during the months (March and April) which coincide with the onset of rains.

In Ikom station, the monthly values of water stress fluctuated between 0.7 and 0.8 from January to May before a sudden decline occurred in June up to July. In August however, water stress peaked at 1.0. This sharp peak in water stress in August maybe attributed to coincidence

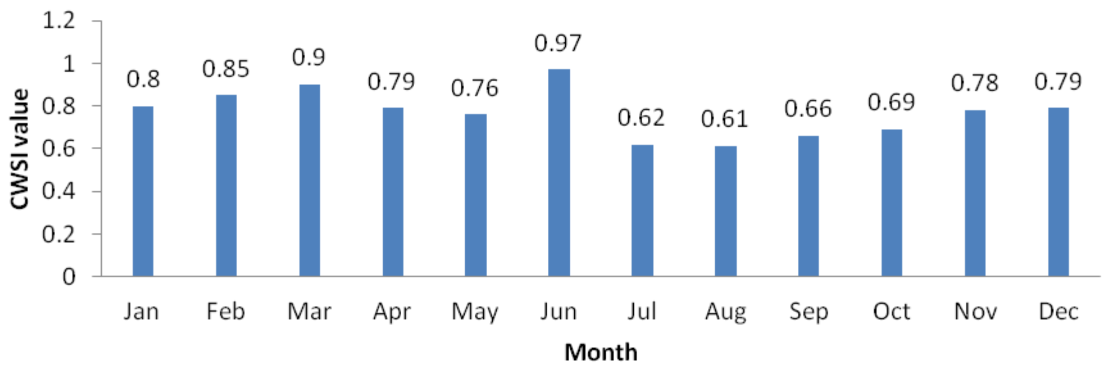

Figure 5. Pattern of water stress in maize, Onitsha station.

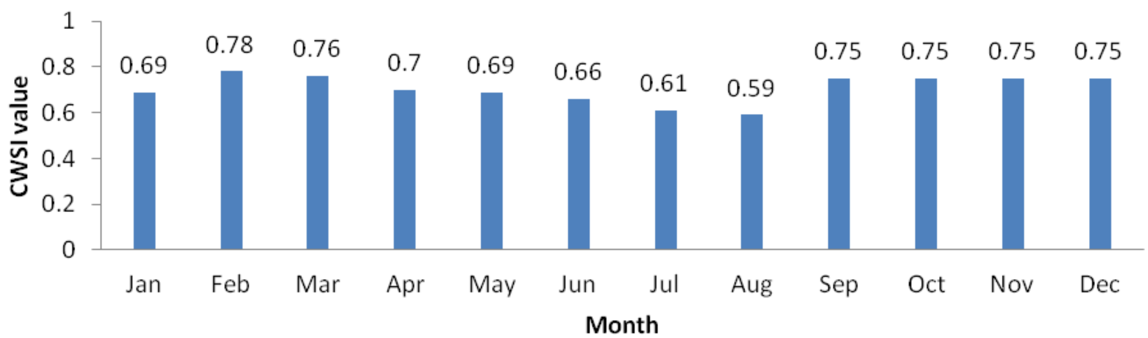

Figure 6. Pattern of water stress in maize, Calabar station.

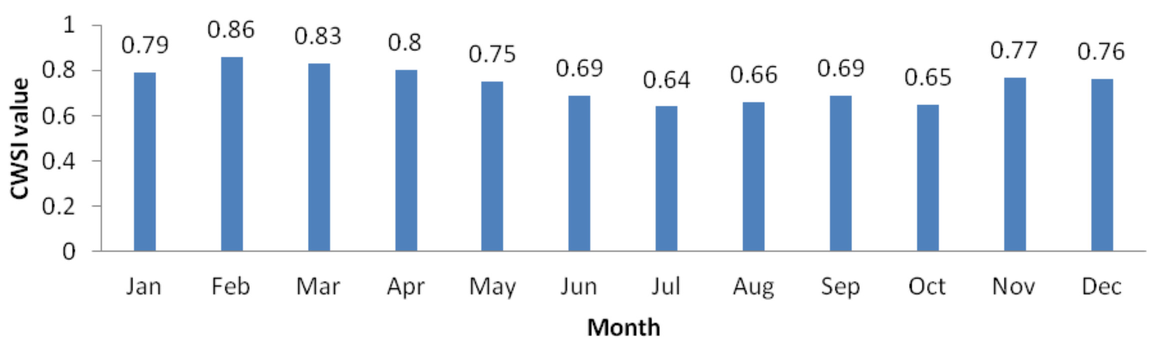

Figure 7. Pattern of water stress in maize, Owerri station.

with the period of the Little Dry Season (August break).

In Ogoja and Port-Harcourt stations the highest CWSI values were recorded in February and April. A gradual decline in water stress values were however, observed from April up to August. Unlike monthly distribution of CWSI in Ikom, monthly water stress pattern in these stations reflect the general pattern of rainfall in Nigeria.

In Onitsha station, CWSI values were observed to be very higher from November to March, ranging between 0.78 and 0.9. In June, when soil moisture recharge is expected peak, there was an unexpected rise in water stress. This may be explained by other factors other than mere availability of rainfall.

Water stress in Calabar station was lowest in January. This may be explained by the fact that onset of rains in some years occur early in January. This station also recorded a steady CWSI values from September to December. This uniformity may suggest the stability in climatic parameters which control water stress, namely canopy evapotranspiration, air temperature and Vapour pressure.

In Owerri and Enugu stations, water stress was observed

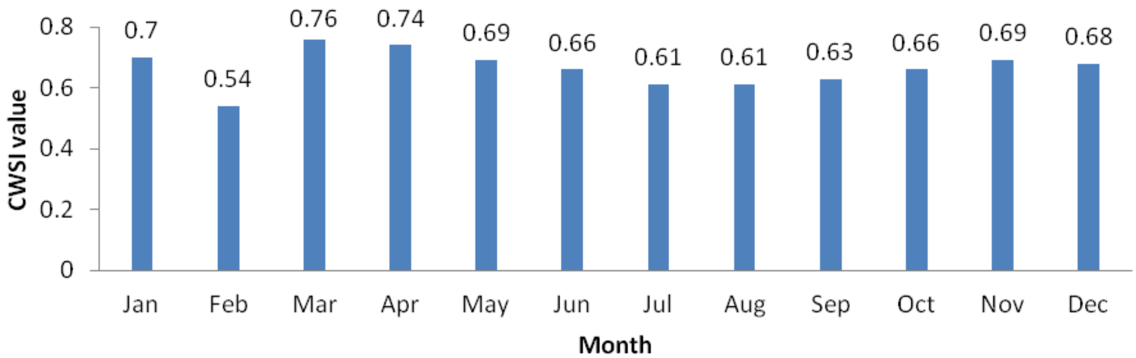

Figure 9. Pattern of water stress in maize, Uyo station.

to be higher from November and peaked in February. The values in February were 0.86 for Owerri and 0.79 for Enugu. In Uyo station, the reverse was the case. The lowest value of CWSI was recorded in February. Generally in this station, little monthly variation in water stress values was observed.

Conclusion

In this research, the upper (water-stressed) and lower (non-water stressed) baselines and crop water stress index (CWSI) values were determined empirically for the periods from 1982 - 2005. The results revealed that, the canopy temperature of maize, under different irrigation programs can be used to determine CWSI values.

It was also observed that in all the stations supplementary irrigation is required to support increased maize yields and an all-year round cultivation to meet the commercial needs for maize. Given that temperature is projected to rise due to global warming, it is likely that this will increase canopy evapotranspiration rate leading to greater soil moisture deficit and crop water stress (CWS), thus emphasizing the need for understanding the crop water need and planning for strategies to curtail the effects of water stress in the study area.

Noteworthy is the fact that CWSI values calculated for all the climatic stations are consistent with acceptable range of 0-1. Thus, Idso CWSI model has proven to be a promising tool for detecting water stress index of maize, its irrigation schedule as well as being good indicator for maize water stress monitoring in South-eastern Nigeria.

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