Irrigation strategies for optimizing water table contribution to soil moisture storage and water use of pepper in a humid tropical zone of Nigeria

Running title: Responses of pepper evapotranspiration to irrigation and capillary rise

Abstract

Aims, methods and results

Aims: This study examines the contribution of water table via capillary rise (upflows) and irrigation, to soil moisture storage and water use (evapotranspiration) of pepper (*Capsicum annuum* var.Tatase), grown in an inland valley swamp (flood plain) in the dry season in a humid zone of Nigeria.

Materials and Methods: The contribution of water table (capillary rise/upflows: Cg) to root zone moisture was quantified based on the soil water balance. Capillary rise (Cg) was taken as the difference between estimated evapotranspiration (ET) and measured soil water depletion (SWD). Irrigation regimes consisted of water application at weekly and fortnight interval using gravity-drip system.

Results: This study examines the contribution of water table via capillary rise (upflows) and irrigation, to soil moisture storage and water use (evapotranspiration) of pepper (*Capsicum annuum* var.Tatase), grown in an inland valley swamp (flood plain) in the dry season in a humid zone of Nigeria. Shoot biomass and fruit yields were higher in treatments involving weekly (153 g plant^{-1}; 8.6 t ha^{-1}) irrigation in addition to enhanced water use efficiency compared to fortnight (141 g plant^{-1} ; 7.9 t ha^{-1}). Capillary rise ranged from 2.3 to 5.2 mm which amount to 81 and 124 % of pepper evapotranspitaion (ETa) across the sampling periods. About 8.2 % yield reductions were obtained under fortnight compared with weekly irrigation which translated to 24 % water savings (reduced water use). The results showed that the weekly and fortnight irrigation intervals produced seasonal ET were 109 and 83 mm and moisture contents of 201 mm within crop root zone was 164 mm for the respective weekly and fortnight irrigation intervals. Average values of water use efficiencies were 0.125t/ha/mm across irrigation regimes. Soil moisture storage and its depletion, Cg, water use and crop water stress index (CWSI: 1-ETa/ETo) differed in the growth stages of pepper, were influenced by irrigation regimes, groundwater table depth, and the prevailing weather conditions (vpd, temperature, thermal time) during pepper growth. Seasonal trends of CWSI indicate the inability of soil moisture storage to satisfy pepper water requirements (ETa). Weekly irrigation offered the best compromise in the circumstance of declining water table depths and high climatic demand of the dry season in the site of study. Results show that irrigation regimes imposed optimized the contribution of groundwater to soil moisture storage and water use of pepper. It is concluded that irrigation management for crops grown in soils under the influence of shallow water tables should be modified to optimize the contribution from groundwater to soil moisture storage and crop evapotranspiration.

Keywords: *Capillary rise, water table, irrigation, evapotranspiration, crop water stress index, inland flood plain.*

Introduction

Inland valley swamps (flood plains), are characterized by seasonal flooding at the peak of the rainy season, and shallow ground water table depths which enhance residual soil moisture regimes in the dry season via capillary rise (upflows). The floodplains are characterized by shallow but variable water table depths (Ogwu and Babalola, 2002, IWMI, 2002), the declining soil moisture storage may predicate the use of irrigation (supplementary) for dry season farming in inland flood plains. In sub-Saharan Africa, inland wetlands (fadama schemes) constitutes about 135 million ha of land (IWMI, 2002), a veritable source of water for dry season crop production (mostly vegetables), this is a common feature of the farming system of the tropics. However, the vast soil, water and agricultural potentials of inland floodplains have not be fully exploited (Ogwu and Babalola, 2002). In soils underlain by shallow groundwater table, the presence of water table impacts land surface processes (soil, vegetation and climate) may be impacted either by capillary rise or direct root water uptake (York *et al.*, 2002; Yeh and Eltahir, 2005; Niu *et al*., 2007; Sun *et al*., 2010; McFadyen and Grieve, 2012). Under field conditions in agroecologies (soil and weather conditions), different results had been reported about the effects of groundwater depth on crop water use and satisfaction index (1- ETa/ETo) and the ratio of actual to potential evapotranspiration (ETa/ETp) (Liang *et al*., 2003; Chen and Hu, 2004; Fan *et al.*, 2007; Maxwell et al., 2007).

Unlike deep water table conditions, shallow water table maintains elevated soil moistures in crop root zone through capillary rise driven by soil matric potential gradients (Chen and Hu, 2004; McFadyen and Grieve, 2012). Capillary rise to root zone moisture and crop water use (evapotranspiration) are affected by many factors such as rainfall, irrigation, root water uptake, and soil evaporation (Yeh and Eltahir, 2005; Fan *et al*., 2007; Sun *et al*., 2010; McFadyen and Grieve, 2012). The contribution of water table to crop water requirement is assessed based on a number of approaches such as the computation of capillary upward flux from Darcy's Law using changes in water potential gradients (Van Bavel *et al*., 1968; Ragab and Amer, 1986). In approaches based on soil water balance, capillary upward flux is taken as the difference between estimated evapotranspiration and soil water depletion (Stuff and Dale, 1978; Wallender *et al*., 1979; Ragab and Amer, 1986). Soil-Water-Plant-Atmosphere (SWAP) is an agro- and ecohydrological model developed to simulate water flow and crop growth at field scale level and soil water flow and interaction with groundwater and surface processes and the contribution of water table to crop evapotranspiration (Raes and Deproost (2003). SWAP is the successor of the agrohydrological model SWATR (Feddes et al., 1978: Raes and Deproost, 2003) and some of its numerous derivatives such as earlier versions published as SWACROP by Kabat et al. (1992).

Despite the realization that water table contribution to crop water requirement, knowledge on how best to incorporate capillary rise in irrigation scheduling is inadequate (Hurst *et al*, 2004; Sun *et al.*, 2010; McFadyen and Grieve, 2012). Moreover, there is scanty information on the irrigation requirements of crops grown on inland floodplains characterized by shallow and variable water table depths. This study was designed to investigate the effects of water fluxes from shallow water table and irrigation regimes and their contributions to pepper water use in an inland valley swampland (fadama) in a humid zone of Nigeria. Drip irrigation system was imposed weekly and fortnight irrigation intervals in order to optimize contribution of water tables via capillary rise (upflow) for enhanced soil water storage and uptake by pepper plants.

Materials and Methods

The effects of gravity-drip irrigation system and the contribution of water table to soil moisture storage, water use and fruit yield of pepper grown in the dry season in an inland flood plain (wetland) was examined between January to May, 2009 and 2010, and 2010 and 2011. The trials were conducted at the Teaching and Research Farm of the Federal University of Technology, Akure, in the humid rainforest zone of Nigeria. Table 1 presents the results of the laboratory analyses of some physical properties of soil at site of experiment.

Irrigation strategies

Four-weeks old seedlings of pepper, *Capsicum annuum* var. Shombo, raised in the nursery were transplanted into 20 by 10m field plot at 90 by 30 cm spacing in January, 2009. The field was drip-irrigated weekly and fortnightly from transplanting to fruit harvest. Irrigation water was applied using the gravity-drip irrigation system which delivered water to plants via point source emitters of 2l/h discharge rate. The emitters were installed on laterals per row of crop and were spaced 90 cm apart. Irrigation buckets were suspended on 1.5 m stakes to provide the required hydraulic heads.

Tensiometers were placed in the soil at depths of 20 and 60 cm to measure hydraulic gradient from the irrigated plots. Prior to use, the tensiometers were saturated by pre-pressurizing with distilled water at high pressure (4 MPa), and were calibrated in the positive pressure range while the calibration curve in the negative pressures was extrapolated. All the calibration tests were performed under controlled laboratory conditions at constant pressure and temperature of 29 °C. The tensiometers were installed in the field in holes bored by pushing a PVC tube, which is equipped with metallic leading edge, in the soil.

Soil moisture storage and its depletion (SWD)

Soil moisture depletion (SWD) was obtained from the differences in soil moisture contents measured between two measurement period. Soil moisture contents were determined weekly at incremental depths of 20 cm taken with augers and core samplers and measured by gravimetric method (oven-dried moist soil samples at 105 ^{o}C for 24 hours).

The ratio of annual actual to potential evapotranspiration (ETa/ETo) and crop water stress index (CWSI: -ETa/ETo) and the ratio of capillary upflow to pepper evapotranspiration (Cg/ETa) were calculated.

Data on the changes in ground water table depths of the site of study were obtained from the Benin-Owena River Basin Development Authority (BORBDA), Akure, Nigeria. BORBDA takes records of water table depths from observation wells and Piezometers and via the use of the FAO method which calculates potential capillary rise from ground water table below the root zone according to the graphical relationships (Doorenbos and Pruitt, 1975; Sepaskhah *et al*., 2003). Observation wells were made with a porous casing (constructed with a 10 cm diameter PVC pipe, buried vertically in the ground which permits the groundwater level to rise and fall inside it as the water level in the adjacent soils. The observation wells were installed with a simple float indicator which provide rapid evaluation of shallow water table depths. The float indicator assembly was lowered into the well. The float indicator moves with the water table thus allowing above ground indication of the water level.

Pepper growth and fruit yield

Data were collected on pattern of soil moisture storage and depletion, and agronomic parameters of root and shoot biomass, leaf area and fruit yield characters of pepper. The dry weights of root and shoot biomass were obtained from their respective fresh weights oven-dried at 80 ^{o}C for 48 h. The effective root zone depth was estimated by excavating the root system (Agele *et al*., 2002). Pepper plant leaf area was measured at 50% flowering date using a leaf area meter (Delta T, UK).

Water table contribution to soil moisture storage and crop water use (evapotranspiration)

In estimating ground water table contribution was estimated via capillary rise (upflow) to soil moisture storage, direct estimates can be made by measuring soil water potential and interpreting an effective unsaturated conductivity between the measurement points using the steady state analysis of Gardner (1958) and Talsma (1963). Other estimates of upflows are also made from point water balance which derives upflow as the error term after other components (total evaporation, rainfall, irrigation, soil storage change, and drainage) are measured or estimated.

Quantifying capillary upward flux from soil water balance

Capillary rise (upflow) from water table to the soil surface can be estimated using the Darcy's Law:

$$Q = k\left(\frac{d\ddot{U}}{dz} - 1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where Q is the capillary rise (cm/day), k is the hydraulic conductivity (mm/day), dU is the soil matric suction (cm), and z is the distance from soil surface to the bottom of the root zone.

Solving equation 1 for z:

$$\int dz = \int \frac{K}{K+Q} = dw \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Water table contribution to root zone soil moisture can also be estimated based on the soil water balance in which capillary rise is taken as the difference between crop evapotranspiration (ET) and soil water depletion (SWD). Thus, using the water balance equation, the individual components which govern the net soil water changes (ΔS) in the crop root zone can therefore be obtained:

$$P = \Delta S - ET + L - R + W - D \ldots\ldots\ldots\ldots\ldots\ldots 3$$

where P is precipitation, ET actual evapotranspiration, L lateral inflow, R lateral outflow, W is capillary rise from the water table, and D deep percolation.

For soils under the influence of shallow water tables, equation 4 can be rewritten in the form:

$$ET = P + I + Cg - DP - Rs - \Delta S \ldots\ldots\ldots 4$$

where ET crop evapotranspiration, P is precipitation, I is irrigation water applied, Dp is deep percolation, Rs is surface runoff, Cg is water table contribution and S is soil water storage.

During pepper growth in the dry season, P, Dp, and Rs components of the water balance equation in Equation 4 were assumed zero except for periods when irrigation occurred. This means that there are periods when P, Dp and Rs are zero between irrigation. Equations 3 and 4 were simplified to account for crop evapotranspiration in the form:

$$ET = Cg - \Delta S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Solving equation 5 for Cg:

$$Cg = -\Delta S - ET \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

Equation 6 indicates that during the rainless dry months and for soils under the influence of shallow water tables.

Actual evapotranspiration (ETa) was calculated by means of a water balance equation as:

$$SW1 + P + Ir = Ro + D - ETa + SW2 \ldots\ldots\ldots 7$$

where Sw_1 and Sw_2 are initial and final moisture contents of soil profile, P is precipitation received, Ir is irrigation water applied, R is surface runoff and D, was assumed capillary rise from water table to crop root zone. Both P and R are assumed negligible. Equations 6 (ET = ΔS - Cg) and 7 (SW1+P + Ir = R_o + D-ETa + SW2) were employed to calculate capillary rise from water table to crop root zone and crop evapotranspiration.

Crop evapotranpiration (ETa) was also estimated using the FAO method (Doorenbos and Pruitt, 1975; Allen *et al*., 1998) in the form:

$$ETa = KcETo \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

where ETo is potential evapotranspiration and Kc is the crop coefficient (Doorenbos and Pruitt, 1975; Allen *et al*., 1998).

Crop coefficient (Kc) for pepper in the tropics: initial (0.3), rapid development phase (0.6), mid season/peak vegetative growth (1.15), maturity (0.8) were obtained from Allen *et al*. (1998). Potential evapotranspiration (ETo) values for the months of Dec - April were computed. Data for computing Potential evapotranspiration (ETo) was computed by the Penman-Monteith combination equation (Doorenbos and Pruitt, 1977; Allen *et al*., 1998) using data obtained from the agrometeorological station of the University.

The second year experiments which involved identical treatments as in 2009 were sown on December and January 2009 and 2010 respectively. the results for the two-years experiments were separately analyzed, and were not significantly different from one year to the other. Therefore, data collected o for the two-years of study were averaged and means are presented in tables and figures in the text (Tables … to … and fig. … to …

Data presented in the tables were means of the two year (2009 and 2010) field experiments

Results

Weather condition of the site of study site

Trends in weather variables at site of study is presented in Fig.1. November marks the unset of the dry season which span December of a year to April of another. The period of experiment (January to early May) falls within the dry season, low amount of rainfall (79 mm)was received from transplanting to fruit filling (1 - 10 WAT), average minimum and maximum temperatures during period of experiment were 21 and 29 ^{o}C with high air vapour pressure deficits.

Pepper growth and yield, evapotranspiration and crop water stress index (CWSI: 1-ETa/ETo).

Irrigation regimes produced differences in growth and yield characters of pepper (Table 2). For weekly irrigation, values of roots and shoot dry weights and leaf areas were higher and the onset of flowering was delayed and this appeared to have translated to fruiting advantages under this treatment. Higher efficiency of water use for fruit production was obtained for pepper plants that were irrigated weekly in addition to higher.

The ratio of seasonal actual to potential evapotranspiration (ETa/ETo) varied during pepper growth stages, values ranged from 0.7 to 1.1 during pepper establishment/mid season and at reproductive growth phases and maximum values which were 0.61 to 1.8 for weekly and fortnight irrigation treatments occurred earlier for weekly as compared to fortnight irrigation (Table 2). The values of crop water stress index (CWSI; 1-ETa/ETo) ranged from 0.45 at establishment/mid season to less than 0.1 at reproductive growth phases.

Soil water balance, ***profile moisture and water table contribution (Cg) to pepper evapotranspiration (Cg/ETa).***

The time course in water table depths at various sampling points at the site of study (an inland swamp/flood plain) is shown in Fig.1. Capillary rise was high between January to mid February which coincides with establishment and development stages of pepper (when cop root zone depth was under the influence of the upper threshold of water table depth). The pattern of soil water suction sampled at 20 and 60 cm soil depth during pepper growth are presented in Fig.2a and b. Soil moisture tension ranged from -2 to -10 and -9 to -2 bars -5 to -3 and -11 to –7 bars at transplanting to establishment/mid season (15 and 45 DOY: 1 to 6 WAT) and -3 to -13 and -17 to -9 bars at mid season (45 DOY: 6 WAT). In general, soil water suction ranged between -7 to -13 and -3 to –9 bar at the surface (0 – 20 cm) and subsoil depths (20 – 60 cm) respectively.

Capillary rise from water table (Cg) was taken as the difference between the crop evapotranspiratoion (ETa) and soil water depletion (SWD) (Equation 5 and 6 ; Ragab and Amer, 1986). Using these equations, the estimated capillary rise (Cg) from 2 weeks after transplanting (WAT) to termination of experiment (16 WAT) for each irrigation interval (weekly and fortnight intervals), were summed up to determine Cg for each sampling period (Table 2). The estimated capillary upflow from a water table, as a percentage of total water use by (Cg/ETa) values differed for the different growth stages of pepper as a function of soil moisture contents and atmospheric factors (Tables 3 and 4). The results show that Cg/ETa is affected by the water table depth and atmospheric conditions and the irrigation regimes. For the irrigation treatments, the estimated water table contribution via capillary rise to crop evapotarnspiration (ETa) varied during pepper growth according to the soil water balance which amount to 43 to 88 % of pepper ET (Table 3). Although, trends in irrigation regimes were similar: as frequency of irrigation increased from fortnight to weekly irrigation intervals, values of Cg varied from 0.66 - 1.24 to 0.63 - 1.23 and respectively which averagely amounts to 65 and 124 % of crop evapotranspiration. About 8.2 % yield reductions were obtained under fortnight compared with weekly irrigation this translated to 24 % water savings (reduced water use). The results showed that actual evapotranspiration was higher in the various growth stages of pepper (Fig. 3), which amounted to seasonal ETa of 109 and 83 mm and soil moisture storage of 201 and 164 mm within crop root zone for the respective weekly and fortnight irrigations (Table 3).

The temporal pattern of water fluxes from the ground water table via capillary rise (upflow: Cg), soil moisture storage and its depletion, pepper water use (ETa) and water satisfaction index (CWSI : 1-ETa/ETo) were related with the prevailing weather conditions (evaporative demand, thermal time accumulation,) under the weekly and fortnight irrigation regime (Fig. 4). The ETa/ETo ratio, soil moisture depletion (SWD) and crop water stress index (1-ETa/ETo) closely associate with thermal time requirement (TT^{o}Cd) and R^2 values obtained ranged from 0.5 to 0.9 (Fig. 4). In particular, maximum temperatures were more closely associated with CWSI (R^{2} : 0.9) (Fig. 4). The high temperatures and evaporative demand during pepper growth in the dry season affected its water use (evapotranspiration). However, the contribution from the ground water table via upflows was not adequate in meeting pepper water requirement the growing environmental conditions of the dry season and hence the magnitude of crop water stress index (1-ETa/ETo) ranging from 0.03 to0.5 were obtained. The time dynamics of capillary upflow (Cg), Cg/ETa (crop evapotranspiration) and crop water stress index (CWSI; 1-ETa/ETo) as affected by irrigation frequency is presented in Fig. 5a and b. Weekly irrigation offered the best compromise in the circumstance of the declining contribution from the ground water table depths and high climatic demand of the dry season at the site of study.

Discussion

This study was designed to investigate the contribution of water from water table and irrigation regimes to pepper water use in an inland valley swamp (fadama) in a humid zone of Nigeria.

Irrigation regimes (weekly and fortnight intervals) were imposed in order to optimize contribution of water table via capillary rise (upflow) to soil water storage and moisture uptake by pepper plants. The root zone moisture and pepper evapotranspiration were affected by the presence of variable ground water table depths. There were interactions among capillary fluxes of water from the water table, irrigation, soil moisture storage and pepper water use with the prevailing weather conditions (vpd, temperature, thermal time/heat accumulation) of the dry season during pepper growth.

Capillary upflow (Cg) contributed about 60% to pepper water use (ETa) and the contribution decreased as water table depth declined (less than 0.7 m at planting (January) to a little over 1.5m at crop maturity (April/May). However, capillary rise was not able to fully satisfy pepper evapotranspiration possibly due to inadequate root densities to enhance access to water from the upper fringe of the water table. The estimated capillary upflow from a water table, as a percentage of total water use by (Cg/ETa) values differed during the growth stages of pepper and were affected by water table depth, irrigation regimes, soil moisture contents and prevailing weather conditions. As frequency of irrigation increased from fortnight to weekly irrigation intervals, Cg values ranged from 0.66 - 1.24 to 0.63 - 1.23 which averagely amounts to 65 and 124 % of crop evapotranspiration. ***Increasing the frequency of irrigation from fortnight to weekly intervals improves root zon***e soil water storage, but the effects of this on capillary contribution to crop ET was not profound. Stuff and Dale (1978) reported for maize that capillary water supplied an average of 27% of the ET in periods with little or no precipitation. As the water table deepens and water content in the upper layers declines, so water table contribution to the crop evapotranspiration (Cg/ETa) declines. The decline in Cg may possibly be due to deepening of the depth to water table in addition to increases in soil water evaporation, temperatures and climatic/ evaporative demand. The Kruse et al. (1993) reported that the proportions of daily Cg to daily ET were different for different periods within the year and were affected by fluctuations in water table depths. Changes in Cg/ETa ratios with declining ground water table depths means declining contribution of water table to crop evapotranspiration (ETa). The soil at site of study is an inland valley swamp (an inland floodplain) influenced by water table, in addition to capillary rise, water storage in the root zone is also affected by irrigation regimes. It therefore implies that crop water use is sourced from soil water storage fed by the two sources: capillary rise (upflow) from a water table and irrigation.

As the water table depth deepens and the upper surface of the soil dries out so its contribution to crop root zone moisture and crop water use declined. Our results were consistent with those of Ragab and Amer (1986) and Ayars et al. (2006). Yang *et al*. (2007) among other studies confirmed the variations of contribution of capillary rise to soil water storage as function of ground water table depths. High capillary rise is obtainable when water table depth is within the upper threshold of capillary rise during which crop evapotranspiration may be sourced entirely from water table (Beverly *et al*., 1999). Conversely, during mid season to fruiting and fruit harvest (Mid February to April) of pepper, capillary rise from the water table becomes negligible (the lower threshold of water table depth: Beverly *et al.,* 1999). In this situation, large fraction of crop evapotranspiration would come from water storage in the unsaturated zone (Beverly *et al.*, 1999). Inverse relationships had been found between capillary rise and depth-to-groundwater table (Kollet and Maxwell, 2008). Crop evapotranspiration is strongly influenced by changes in water table depth. Yang *et al*. (2007) observed water movement upward and downward from the water table using trends of water potential in the soil profile.

The ratio of seasonal actual to potential evapotranspiration (ETa/ETo) varied during pepper growth stages. The values of ETa/ETo ranged from about 0.9 during pepper establishment/mid season and at reproductive growth phases and maximum values which were about 1.2 (Table 2). Crop water stress index (CWSI; 1-ETa/ETo) ranged from 0.45 at establishment/mid season to less than 0.1 at reproductive growth phases. Trends in the values of CWSI indicates the inability of soil moisture storage (replenishment trends by irrigation and capillary upflow from the ground water table) to satisfy pepper water requirements (ETa). Sepaskhah *et al*. (2003) attributed time-course changes in ETa/ETo ratio to the influence of water table and irrigation. Capillary rise from the water table might have influenced crop evapotranspiration (ETa) and hence the differences in ETa/ETo in this study.

About 8.2 % yield reductions were obtained under fortnight compared with weekly irrigation this translated to 24 % water savings (reduced water use).

Although, capillary flux enhanced soil moisture storage in the unsaturated layer (crop root zone) above the ground water table, the magnitude of crop evapotranspiration (ETa), Cg/ETa ratio and crop water satisfaction index (1-ETa/ETo) indicate that upflows from water tables was not adequate to satisfy pepper evapotranspiration and that pepper appeared not to be adequately adapted to a drying soil profile even in the presence of unsaturated fringe within 1m GWT depth. Thorburn et al. (1995) observed that root growth (biomass and root length densities) increased with declining capillary upward flux above ground water table. The authors concluded from their conductance simulation models of root, soil and water, that water should have been readily available from the near saturated conditions above the water table given the magnitudes of root length densities. Pepper has a well adapted dicotyledonus root system with small axial resistance, this attribute would have enhanced soil moisture extraction from depths (from the near saturated conditions above the water table). An exclusive reliance on upflows from water tables will subject pepper crop to soil moisture deficit stress. Since upflows from water table was not adequate to meet pepper water requirement, irrigation is required in addition in order to recharge soil moisture in crop rootzone. This observation is interpreted to mean that despite the presence of a shallow water table in the profile (unsaturated fringe within crop root zone), water was extracted preferentially from soil storage presumably from the irrigation enhanced soil moisture replenishment within crop root zone) and not necessarily the supplies from the ground water table via upflows. Numerous studies have demonstrated the importance of incorporating capillary flux from ground water tables into irrigation scheduling strategies in soils affected by variable but shallow ground water table depths such as inland valley swamps of the humid tropics.

The temporal pattern of water fluxes from the ground water table via capillary rise (upflow: Cg), soil moisture storage and its depletion, pepper water use (ETa) and water satisfaction index (CWSI : 1-ETa/ETo) were correlated with the prevailing weather conditions of maximum temperatures, evaporative demand and thermal time accumulation. The ETa/ETo ratio, soil moisture depletion (SWD) and crop water stress index (1-ETa/ETo) closely associate with thermal time requirement (TT^{o}Cd) with medium to high regression coefficients (R^2) and maximum temperatures and were closely associated with CWSI (R^2 : 0.9) in particular (Fig. 4). The high temperatures and evaporative demand during pepper growth in the dry season affected its water use (evapotranspiration). There were strong influences of irrigation frequency on the time dynamics of capillary upflow (Cg), Cg/ETa (crop evapotranspiration) and crop water stress index (CWSI; 1-ETa/ETo). The equations generated from the regression analysis of Cg/ETa, ETa/ETo and soil moisture storage and ground water contribution (Cg) are possible indicators of stress tolerance and ability of the tested crop to use effectively use soil moisture as fed by ground water contribution and irrigation.

Conclusion

The changes in root zone soil moisture storage and crop evapotranspiration for pepper grown in the dry season in an inland swamp (fadama) affected by the presence of variable ground water table depths were examined in a humid tropical zone of Nigeria. Irrigation regimes and temporal pattern of capillary upflow affected soil moisture storage and pepper water use (ETa). Soil water depletion (SWD) tended to increase and water table contribution decrease, as frequency of irrigation increased (comparing weekly to fortnight irrigation intervals). Capillary flux contributed to replenishment of root zone soil moisture following depletion by soil evaporation and pepper water use (ETa) from the unsaturated root zone layer above the ground water table. Water table contribution (capillary flux) was taken as the difference between estimated evapotranspiration (ET) and measured soil water depletion. Capillary upflow (Cg) ranged from 0.03 to 0.50 which is 60 % on the average, of pepper water use (ETa) over the sampling period decreased as water table depth declined. There were interactions among capillary fluxes of water from the water table, irrigation, soil moisture storage and pepper water use with the prevailing weather conditions (vpd, temperature, thermal time/heat accumulation). From the estimated Cg/ETa and measured values of soil moisture contents, shallow water tables via upward flux affected soil moisture storage, crop water use (ETa) and satisfaction index (1- ETa/ETo) and so offset the need for full irrigation. Capillary flux from ground water tables should be incorporated into irrigation scheduling strategies for soils under the influence of water table such as inland valley swamps (fadama). It is concluded that in the presence of shallow water tables, irrigation management should be modified to optimize the contribution from water table to rootzone moisture storage and crop evapotranspiration in inland swamps of the humid tropics.

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Table 1. Some physical properties of soil at site of experiment

Soil properties	
Sand (%)	40.9
Silt (%)	30.8
Clay (%)	28.3
Textural class	Sandy clay loam
Bulk density ($g.cm^{-3}$)	1.24
Porosity (%)	81
Infiltration rate ($mm.s^{-1}$)	3.18
Saturation (%)	40.1
Field capacity moisture (%)	27.9
1500 KPa moisture (%)	17.2
Water holding capacity (%)	21

Table 2. Effects of irrigation regimes on the growth and yield characters of pepper*.

Irrigation regimes	Root length (cm)	Root dry weight (g)	Shoot dry weight (g)	Leaf area (cm^2)	50% flowering (days)	Fruit yield (t/ha)	Irrigation applied (mm)	Water use efficiency (t/ha/mm)	Harvest index
Weekly	17.8	67.5	153.2	6.4	72	8.6	59.88	0.048	0.54
Fortnightly	19.3	73.4	140.7	6.0	68	7.9	39.92	0.045	0.50
LSD (0.05)	3.4	4. 0	5.1	2.3	4.1	1.8	----	0.004	0.03

**Data presented in the Table are means of the two-year (January to May of 2009 and 2010) field experiments.*

Table 3. Effects of irrigation regimes on water table contribution (Cg: estimated from the soil water balance), crop evapotranspiration and water stress index (CWSI)

DOY	Irrigation regimes	ETo	ETa (mm)	CWSI (1-ETa/ETo)	SWD	Cg (mm)	Cg/ETa
05	Weekly	4.3	4.3	---	1.05	2.29	0.54
	Fortnightly		3.3	0.23	0.98	2.36	0.72
015	Weekly	4.7	3.7	0.21	0.94	2.95	0.61
	Fortnightly		5.2	--	0.90	2.58	0.65
030	Weekly	4.9	4.7	0.11	0.90	2.92	0.57
	Fortnightly		3.9	0.20	0.82	2.73	0.63
045	Weekly	5.1	5.5	--	0.84	2.89	0.61
	Fortnightly		3.1	0.21	0.73	2.80	0.81
060	Weekly	5.0	5.1	0.018	0.78	4.73	0.55
	Fortnightly		4.6	0.34	0.87	4.43	0.77
075	Weekly	5.3	6.5	0.017	0.72	5.16	0.43
	Fortnightly		4.7	0.42	0.62	5.13	0.88
090	Weekly	5.5	7.9	0.09	0.67	4.93	0.51
	Fortnightly		6.5	0.48	0.58	4.77	0.97
105	Weekly	5.2	9.1	0.43	0.63	5.03	0.47
	Fortnightly		7.8	0.59	0.53	4.95	1.10
120	Weekly	5.4	9	0.45	0.58	4.04	0.49
	Fortnightly		8.2	0.65	0.48	3.95	1.13
135	Weekly	5.3	9.3	0.41	0.55	3.96	0.42
	Fortnightly		7.7	0.62	0.39	3.72	0.88
150	Weekly	5.0	8.4	0.40	0.50	3.32	0.41
	Fortnightly		7.3	0.66	0.34	3.15	0.78
165	Weekly	5.3	8.3	0.42	0.48	3.69	0.33
	Fortnightly		6.4	0.63	0.30	3.33	0.74
180	Weekly	5.2	9.5	0.45	0.43	3.55	0.31
	Fortnightly		5.8	0.69	0.28	3.27	0.66

*ETo is calculated from Penman-Monteith combination equation while ETa was obtained as the product of ETo and pepper Kc (Kc*ETo) (Allen et al., 1998). SWD: soil water depletion*

**Data presented in the Table are means of the two-year (January to May of 2009 and 2010) field experiments.*

Table 4. Seasonal trends in water table contribution (capillary rise: Cg) and actual crop evapotranspiration estimated from soil water balance (swb) and crop water stress index (CWSI)

Growth phases	Irrigation regimes	ETa (mm) (Allen et al., 1998)	ETa (mm) (swb)	Cg (mm) (swb)	Soil moisture storage (mm)	CWSI
Establishment	***Weekly***	16.3	27.23	15.4	85.3	0.04
	Fortnight	19.6	26.0	17.7	82.8	0.14
Mid season	***Weekly***	20.8	36.6	12.4	108.6	1.34
	Fortnight	39.0	32.6	17.1	103.5	2.11
Fruiting and fruit harvest	***Weekly***	29.3	39.2	28.2	107.5	3.10
	Fortnight	58.9	27.6	54.7	77.6	4.70
Cumulative Total	***Weekly***	66.9	108.9	56.0	201.4	4.80
	Fortnight	106.8	82.8	89.2	163.7	6.95

Growth stages from planting to maturity: establishment (2-7weeks); mid season/flowering (7-12 weeks); fruiting/harvest (12-18 weeks)

**Data presented in the Table are means of the two-year (January to May of 2009 and 2010) field experiments.*

Caption to Figures

Fig. 1. Yearly trends in ground water table depths, rainfall and open water evaporation at the site of study

Fig.2a. Trends in soil water potential for irrigated and non-irrigated conditions @ DOY 15

Fig.2b. Trends in soil water potential for irrigated and non-irrigated conditions @ DOY 45

Fig. 3. Crop evapotranspiration calculated from soil water balance as affected by irrigation regimes during pepper growth.

Fig. 4. Relations of thermal time with Cg/ETa, ETa/ETo and CWSI (1-ETa/ETo) during pepper growth

Fig. 5a. Time trends in capillary upflux (Cg), Cg/ETa and 1-ETa/ETo for weekly irrigation

Fig. 5b. Time trends in capillary upflux (Cg), Cg/ETa and 1-ETa/ETo for fortnight irrigation

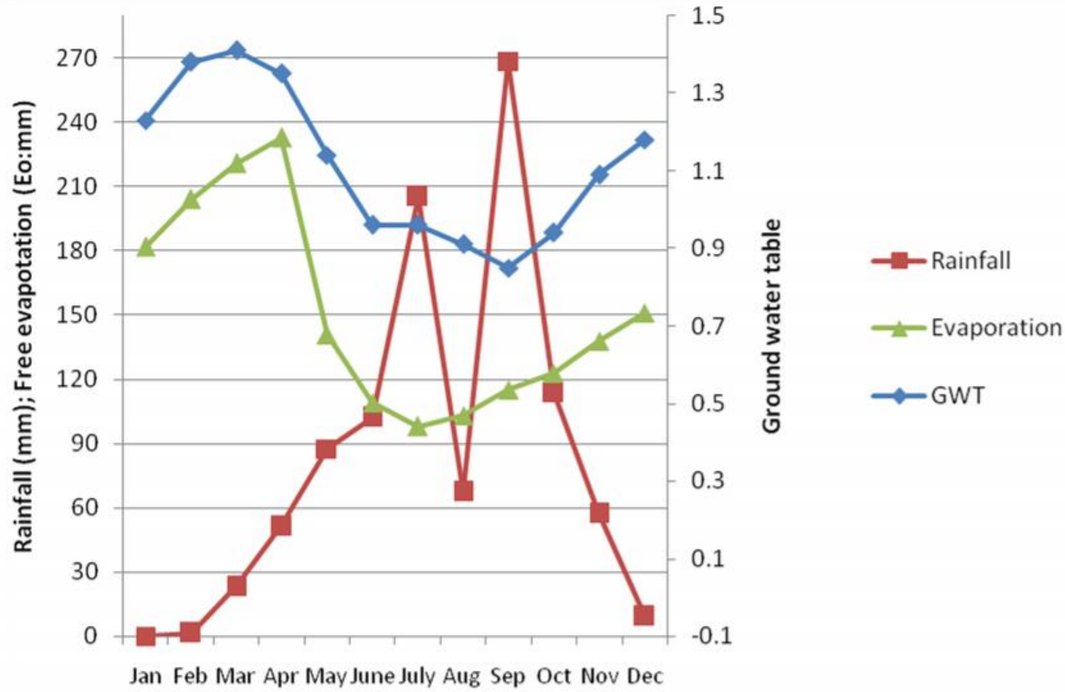

Fig. 1.Yearly trends of ground water table, rainfall and open water evaporation at site of study

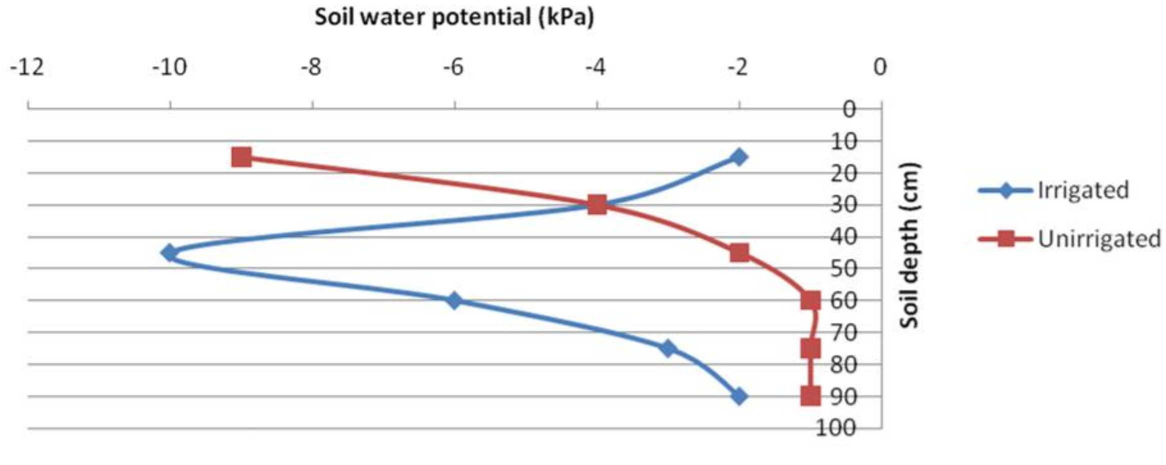

Fig. 2a. Trends in soil water potential (kPa) for irigated and non irrigated soil conditions @ DOY 15

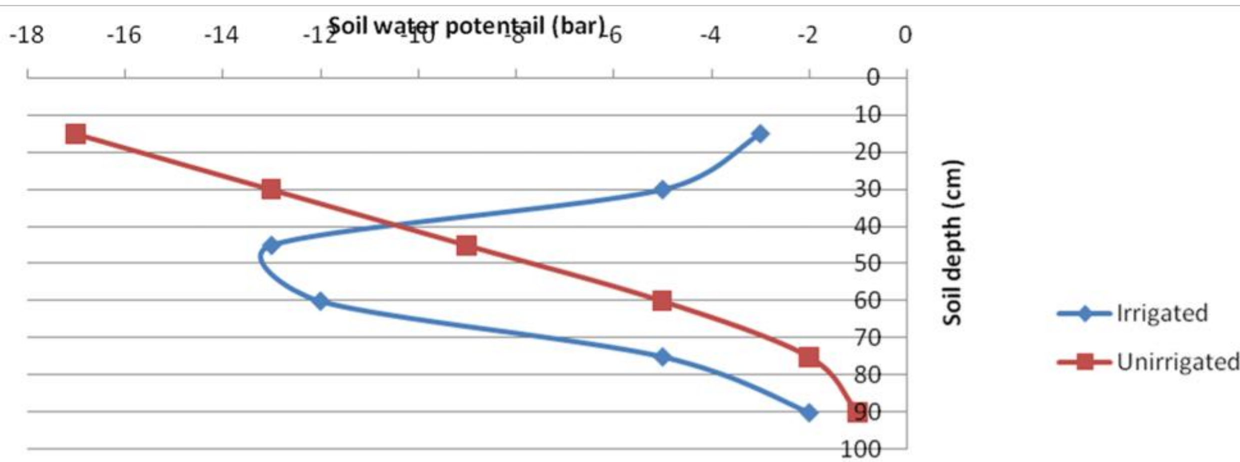

Fig. 2b. Trends in soil water potential (kPa) for irigated and non irrigated soil conditions @ DOY 45

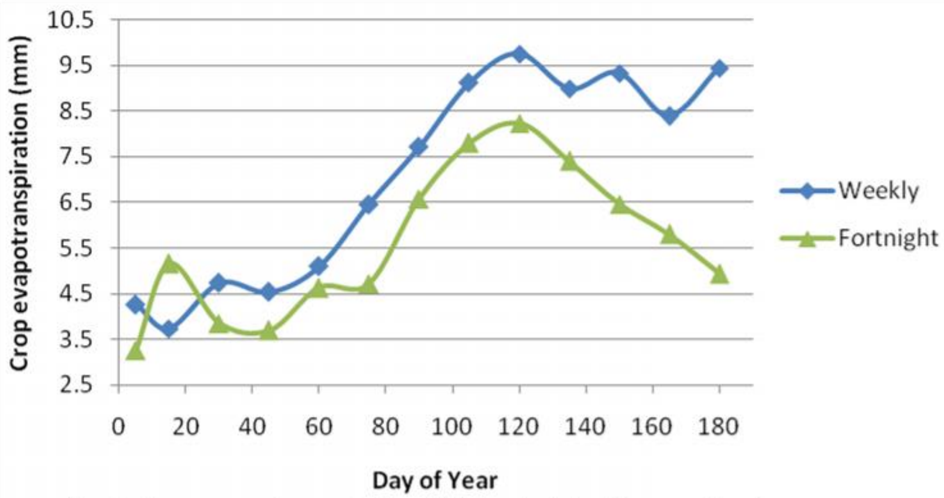

Fig. 3. Crop evapotranspiration (ETa) calculated from soil water balance as affected by irigation regimes during pepper growth

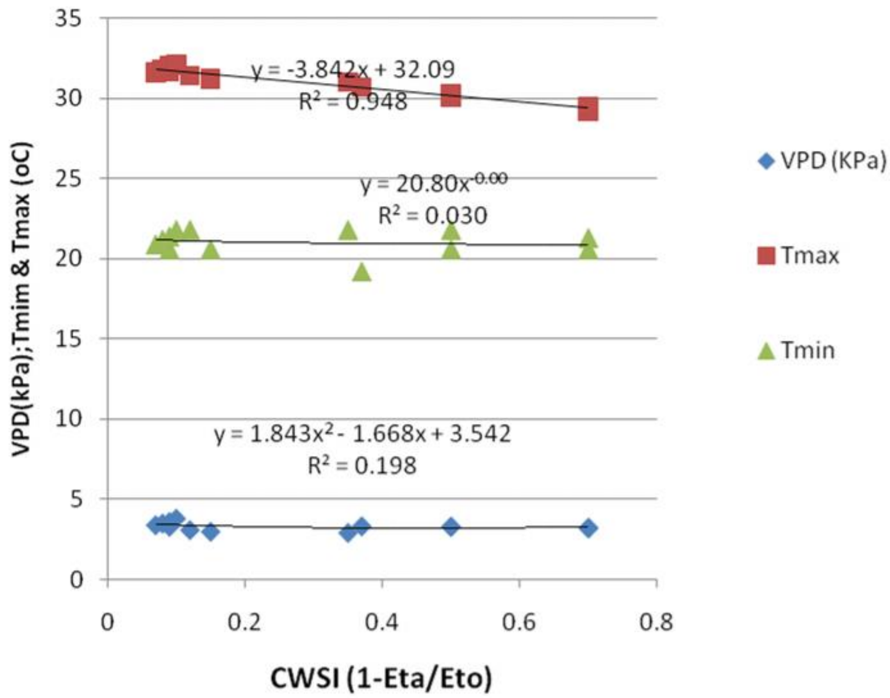

Fig. 4. Association of crop water stress index with weather factors

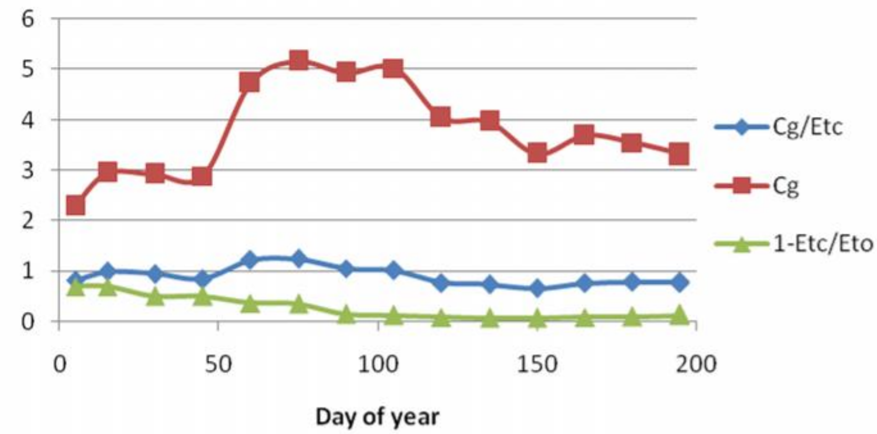

Fig. 5a. Trends in cappilary upflux (Cg) , Cg/ETc and 1-ETa/Eto (Weekly irrigation)

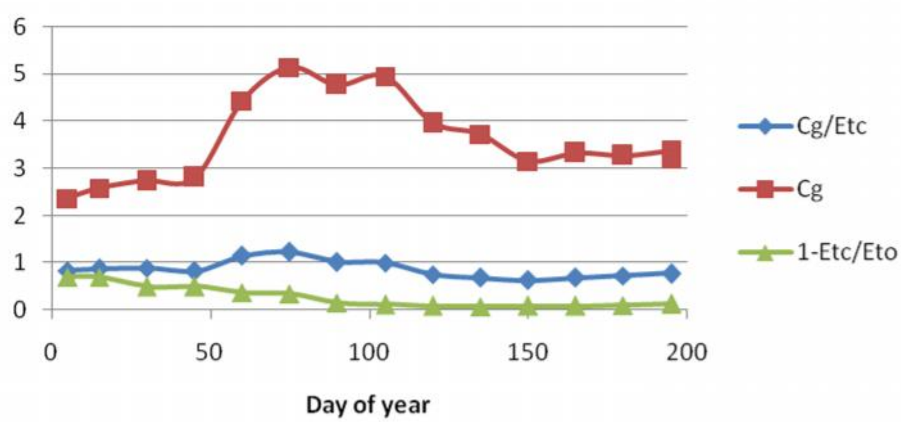

Fig. 5b. Trends in cappilary upflux (Cg) , Cg/ETc and 1-ETa/Eto (fortnight irrigation)