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Evaluation of water table dynamics for sustainable cultivation in wetlands

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Abstract. Sustainable management of wetlands for cultivation calls for a thorough knowledge of factors that influence wetlands hydrodynamics. The use of the geographical information system led to an accurate assessment and prediction of water dynamics in wetlands. Rainfall, evapotranspiration and field elevation are major factors of importance influencing water table changes and soil moisture in wetlands. A survey of a non-tidal wetland in south western Nigeria showed that the mean depth to water table ranged between 0 cm (ground surface) and 92 cm (maximum depth). A total of 686.0 and 852.6 mm of rainfall and potential evapotranspiration, respectively, were recorded with the period of low water table. The impacts of these factors on the depth to water table among the observation wells were found to be significant at $p < 0.05$. Sustainable cultivation of wetlands is feasible during the period with potential evapotranspiration > rainfall because there is movement of moisture from the saturated to the unsaturated soil zones. Variation in available moisture across the field was influenced by field elevation and groundwater fluxes from saturated to unsaturated zone. Even though there may be no water table recharge during the period of agricultural drought, the soil available moisture was found to be high (ranging between 0.20 and 0.50 m^3m^{-3}) and sufficient for crop water supply without supplemental irrigation in the non-tidal wetland.

Keywords: water table, wetlands, potential evapotranspiration, soil moisture

INTRODUCTION

Cultivation of wetlands has received global attention in the quest to increase crop production and to enhance rural livelihood. Wetlands are attractive to farmers because cultivation can be extended beyond the rainy season. Wetlands and valley bottoms have also been reported to have relatively high fertility (Oluwatosin *et al*., 2005). The physical potential of inland valleys and cultivable wetlands in Sub-Saharan Africa were estimated at 135 mln ha while 1.3% of this potential is actually cultivated (FAO, 1998). In a review of conservation and cultivation of wetlands in Southern Africa, a shift is observed from outright restriction on cultivation to sustainable and regulated development of wetlands for agricultural purposes in places like Zambia, Zimbabwe and Mozambique (Karen and Isiah, 2001).

Kevin (2003) and Mann and Wetzel (2000) observed that precipitation remains one of the factors that most influence the hydrodynamics of wetlands. In wetlands, capillary fringe may extend into the root zone of the crops and vegetation. This is one of the major advantages of wetland cultivation for crop production (Ridder and Bonstra, 2006). There is vertical flux from the saturated into the unsaturated zone, from where moisture is removed by evaporation or to meet crop water requirement. The rate of rise, and the subsequent evaporation at the surface, decrease as the depth to the water table increases (Ridder and Bonstra, 2006; Winter and Rosenberry, 1995).

Chen and Qi (2004) observed that most studies of water exchange between the unsaturated zone and the atmosphere have focused on understanding soil moisture variations and their effects on atmospheric boundary layer processes affecting weather and climate. However, the influence of this variation on the available water for sustainable wetland cultivation is not often considered. In earlier studies, efforts have been directed towards conservation of wetlands and this has not encouraged research on agricultural uses of wetlands. Sustainable cultivation of wetlands, however, has become imperative in different parts of the world and in reality forms a part of strategy to mitigate food insecurity in developing nations. This study was designed to evaluate the relationships between depth to water table (*DWT*), potential evapotranspiration (*PET*), rainfall (*P*) and soil available water in a tropical humid wetland with a view to achieve sustainable cultivation.

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MATERIALS AND METHODS

The wetlands of South-Western Nigeria belong to the category of narrow headwater inland valleys (Andriesse, 1995) which are distinct from the inland basin and river flood plain wetlands. The valley bottoms are generally flat floored and relatively shallow. They are called 'dambos' in East and Central Africa, 'fadamas' in Northern Nigeria and Chad, and 'akuro' in South-Western Nigeria (Oluwatosin *et al.*, 2005). This study site was located on Fadama site at Omi Adio (7°23'47" N, 3°45'01" E), a suburb of Ibadan (Fig. 1). The study area is a peri-urban wetland serving as flood plain to Omi stream. The climate of the study area is tropical humid characterized by high humidity, temperature and precipitation. The average mean rainfall for the past 20 years is 1 414.85 mm with CV of 21.7%. The raining season is usually between March and November with a short period of drought in August.

The study area is overlying a Precambrian/Upper Cambrian Basement Complex consisting of older granites, gneisses, quatzites schists rocks, which are mostly metamorphic in origin. The soils of the valley bottoms are sediments of these rocks and were classified as Eutric Fluvisols (FAO) and Aeric Tropic Fluvaquent (USDA) by Oluwatosin *et al.* (2005).

Observation wells were installed in a grid with effective soil depths ranging from 180 to 200 cm. The observation wells were manually dug using a bucket auger. PVC pipes (5.1 cm diameter) with perforations and screens were installed at each observation point (Ridder, 2006). The water table depths were recorded every two weeks between December, 2007 and June, 2008 using a manual water table sounding apparatus equipped with measuring tape (Eijkelkamp, Giesbeek, The Netherlands).

Soil moisture sampling was evaluated by dividing the field into 4 quadrants (Fig. 1). Samples were taken for moisture determination at two depths (1 and 5 cm). The moisture analysis was carried out using the gravimetric method (McBride, 2002). At each depth, samples for gravimetric moisture were composite of five (5) random samples taken in each quadrant. Soil moisture sampling corresponded to water table measurement day. Undisturbed soil cores were taken with cylindrical corers (5 cm – height and inner diameter) at 0-20, 20-40 and 40-60 cm in each of the quadrants (Q1-Q4). Water retention characteristics between saturation and 10 kPa matric potential (-100 cm water) were determined using a tension plate apparatus (McBride, 2002). Pressure was also imposed between 10 and 1 500 kPa for the determination of available water capacity (AWC). Particle

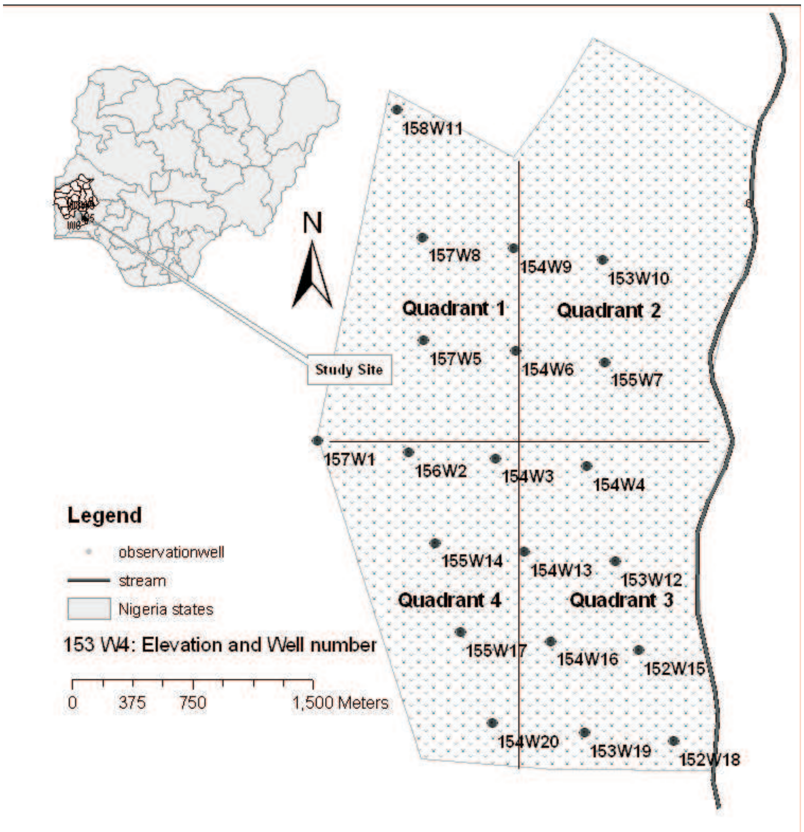

Fig. 1. Map of the field location showing the network of observation wells.

size analysis (PSA) of the Q1-Q4 soil was carried out using the pipette procedure (McBride, 2002), while the textural classification was based on the textural triangle (USDA Soil Survey). The rainfall during the period and other meteorological data were monitored from the Institute of Agricultural Research and Training Station (less than 2 km from the field).

With the aid of CROPWAT 4.3 model, the daily potential evapotranspiration (*PET*) for the field was computed and total *PET* was computed for the intervals between water table measuring days, by addition of daily *PET* for days in-between readings. The *PET* computation was based on Penman-Monteith (Feddes and Lenselink, 2006):

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where: PET – reference evapotranspiration (mm day^{-1}), R_n – net radiation at the crop surface (MJ m^{-2} day^{-1}), G – soil heat flux density (MJ m^{-2} day^{-1}), T – mean daily air temperature at 2 m height (°C), u_2 – wind speed at 2 m height (m s^{-1}), e_s – saturation vapour pressure (kPa), e_a – actual vapour pressure (kPa), e_s - e_a – saturation vapour pressure deficit (kPa), Δ – slope vapour pressure curve (kPa °C^{-1}), γ – psychrometric constant (kPa °C^{-1}).

Hand held geographical positioning system (GPS) was used to obtain the geographical location of each well for proper georeferencing of the data. The depths to water table data were brought into ArcGIS 9.2 for spatial analysis. Triangulated irregular network (TIN) technique in ESRI ArcGIS 9.2 3D analyst extension was used to display the water table as a surface plot across the quadrants, while the field elevation model was made using the ordinary kriging method (Hengl, 2009). All data on depth to water table (*DWT*) were subjected to correlation analysis and analysis of variance (ANOVA) using SAS (2002).

RESULTS AND DISCUSSIONS

A total of 686 mm of rainfall (P) was recorded during the study period (December, 2007 – June, 2008) while the total potential evapotranspiration (*PET*) was 852.6 mm. The difference between *P* and *PET* was negative for the first 140 days of the study (December – February) implying that the requirement of *PET* was not being met by *P* but from soil surface (Fig. 2).

During the first 100 days of the study, there was no precipitation for 75 days while the remaining days had less than 10 mm of rain. There was no recharge of the water table in the first 100 days. The depth of rain between 100th and 140th days was not sufficient to obliterate the effect of *PET* requirement. Therefore, there was loss of moisture from the land surface during this period. The difference between *P* and *PET* began to be positive from the 144th day, while recharge became steady as *P* began to exceed *PET*.

Table 1 gives a summary of the descriptive statistics of the observation wells. The depth to water table (*DWT*) varies between 0 cm, corresponding to water table at the surface, and 92 cm, observed maximum in W5. Figure 3 shows the changes in water table during the study period. The maps are the result of TIN analysis in ArcGIS 9.2. The *DWT* was grouped into 5 classes at 20 cm intervals. The maps revealed increasing depth to water table until the period of steady groundwater recharge. Between the 1st day (3rd December) and 81st day of study (26th February), a gradual increase in the depth to water table was recorded across the field. This is the period with high *PET* and <10 mm of rain. At about 105 days into the study, the least *DWT* was between 40 and 60 cm. This was at the border of the peak of dry season and the inception of wet season. Between 103 and 144 days into the water table study, increasing recharge of the water table results in decreasing *DWT*. From late April (beyond 144 days) the maximum depth to water table observed was no longer within 80-100 cm depth, but shifted to 60-80 cm. This

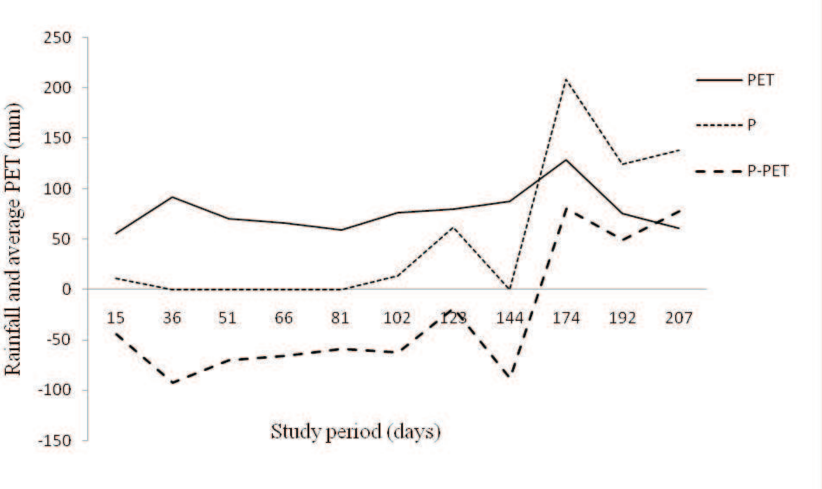

Fig. 2. Rainfall (*P*) and potential evapotranspiration (*PET*) for the study period.

T a b l e 1. Descriptive statistics of depth to water table (*DWT*) from the observation wells (W1-20) (number of observed data used in computation =12)

Parameters	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20
Mean *DWT*(cm)	47.3	31.9	44.7	34.0	78.5	26.8	35.1	75.8	47.3	58.8	59.9	15.6	28.0	30.6	12.4	29.1	32.0	10.2	19.1	32.0
Median *DWT* (cm)	51.5	34.0	41.5	32.0	78.0	26.5	31.5	76.0	47.0	65.5	63.5	14.5	28.5	28.0	11.0	29.0	32.5	5.0	15.5	28.5
SD	17.5	12.9	24.9	17.0	10.8	15.6	25.2	12.3	17.1	17.5	10.7	14.9	15.6	14.5	14.2	15.3	16.6	12.3	20.2	13.6
Variance	304.6	166.1	621.7	289.1	117.0	242.7	637.5	151.3	292.9	307.7	115.4	223.2	244.7	209.4	201.0	232.8	276.7	150.3	406.3	183.6
Range	53.0	42.0	80.0	56.0	33.0	45.0	74.0	38.0	59.0	61.0	34.0	47.0	44.0	40.0	43.0	47.0	50.0	35.0	58.0	49.0
Minimum	17.0	6.0	10.0	8.0	59.0	5.0	4.0	53.0	14.0	15.0	36.0	0.0	6.0	12.0	0.0	8.0	10.0	0.0	0.0	16.0
Maximum	70.0	48.0	90.0	64.0	92.0	50.0	78.0	91.0	73.0	76.0	70.0	47.0	50.0	52.0	43.0	55.0	60.0	35.0	58.0	65.0
CV(%)	0.37	0.40	0.56	0.50	0.14	0.58	0.72	0.16	0.36	0.30	0.18	0.96	0.56	0.47	1.14	0.52	0.52	1.21	1.06	0.42

W1 – observation well 1, CV– coefficient of variation, SD – standard deviation.

pattern confirmed the impact of rainfall on the recharge of wetlands, even though the water table depth is generally considered shallow across the entire field (<1.0 m).

Influence of precipitation on *DWT* fluctuations has also been reported by Moorhead (2001) and Todd *et al.* (2006). Table 2, based on Pearson correlation, gives the correlation matrix of the observation wells relating the *DWT* among the wells. Higher correlation shows high spatial similarity, and this depicts similar water table characteristics. The correlation classification ranged between very strong and very weak correlations. The correlation coefficients across the observation wells show a good agreement with the patterns and classifications from the GIS TIN generated maps. The map gives a better visualization of groundwater profiles in the field. This makes the GIS maps a good decision making tool for wetland cultivation.

The analysis of variance of the *DWT* and days into the study as well as their interaction showed that there exists a significant difference between the means returned for each of the sources of variations. The differences in the mean returned by the different wells at different periods were statistically significant ($P<0.05$). The Duncan multiple range text (DMRT) partitioned the observation wells into 17 different classes. This shows high degree of variation in the water table pattern across the wetland. Mean *DWT* returned for well W5 (78.5) was significantly higher than those for all other wells. The mean class returned for W18 (10.17) was the least. W5 and W18 were located at the area with highest and lowest field elevation, respectively. W18 was also closer to the stream than other observation wells. Thus, the observed depth to water table could have also been influenced by the base flow.

The mean water table depths recorded for W2 (31.92 cm), W17 (32.0 cm) and W20 (32.0 cm) were not significantly different from one another; hence, they were clustered together by the DMRT in the 9th class. The different dates were partitioned into eleven independent and significant classes. Day 81st (26/2/08) was significantly higher than other days, closely followed by day 66th (12/2/08), which was significantly higher than any other days. The least mean water table depth was obtained on 25/6/08 (14.10 cm), closely followed by 10/6/08 (20.25 cm). This trend was in line with the direct proportionality relationship between climate and water table depth. Mitsch and Gosselink (1993) also reported that the hydro-period of wetlands varies statistically according to climate and antecedent conditions.

The changes in depth to water table were also found to respond to field elevation (Fig 4). Higher elevation sites consistently had deeper *DWT* relative to the observed *DWT* in areas with lower elevation. Field elevation influenced the water table characteristics in the direction of lower gradient. Although, the study site slope ranges from 1 to 5%, decreasing towards the Omi stream; this gentle slope contributed to the groundwater flow. The field elevation pattern, therefore,

Table 2. Correlation matrix of the depth to water table in the observation wells (W1-W20)

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20
W1																				
W2	0.876																			
W3	0.826	0.919																		
W4	0.810	0.960	0.932																	
W5	0.979	0.884	0.829	0.841																
W6	0.751	0.907	0.844	0.934	0.742															
W7	0.771	0.933	0.890	0.985	0.795	0.958														
W8	0.979	0.835	0.761	0.772	0.981	0.707	0.728													
W9	0.741	0.864	0.700	0.862	0.795	0.846	0.874	0.781												
W10	0.872	0.939	0.782	0.850	0.882	0.825	0.817	0.882	0.908											
W11	0.914	0.901	0.798	0.820	0.911	0.816	0.783	0.910	0.840	0.958										
W12	0.568	0.681	0.621	0.734	0.639	0.663	0.741	0.612	0.731	0.666	0.589									
W13	0.826	0.939	0.855	0.925	0.819	0.927	0.951	0.767	0.854	0.862	0.845	0.704								
W14	0.815	0.911	0.885	0.881	0.813	0.816	0.873	0.719	0.684	0.765	0.783	0.533	0.915							
W15	0.412	0.424	0.334	0.503	0.459	0.521	0.529	0.527	0.704	0.532	0.443	0.744	0.445	0.116						
W16	0.832	0.933	0.876	0.928	0.834	0.909	0.948	0.769	0.851	0.845	0.847	0.639	0.987	0.932	0.396					
W17	0.860	0.651	0.546	0.604	0.839	0.574	0.606	0.868	0.694	0.700	0.747	0.329	0.658	0.617	0.402	0.694				
W18	0.359	0.445	0.326	0.536	0.435	0.553	0.586	0.467	0.777	0.538	0.442	0.760	0.514	0.186	0.956	0.480	0.386			
W19	0.415	0.558	0.459	0.642	0.473	0.676	0.706	0.473	0.848	0.608	0.540	0.689	0.664	0.367	0.831	0.659	0.453	0.935		
W20	0.414	0.612	0.526	0.626	0.452	0.647	0.685	0.393	0.770	0.607	0.586	0.391	0.717	0.595	0.340	0.766	0.478	0.537	0.786	

W1 – observation well 1, correlation coefficients (>0.9 – very strong, 0.89-0.7 – strong, 0.74-0.60 – mild, 0.59-0.40 – weak, <0.39 – very weak correlation).

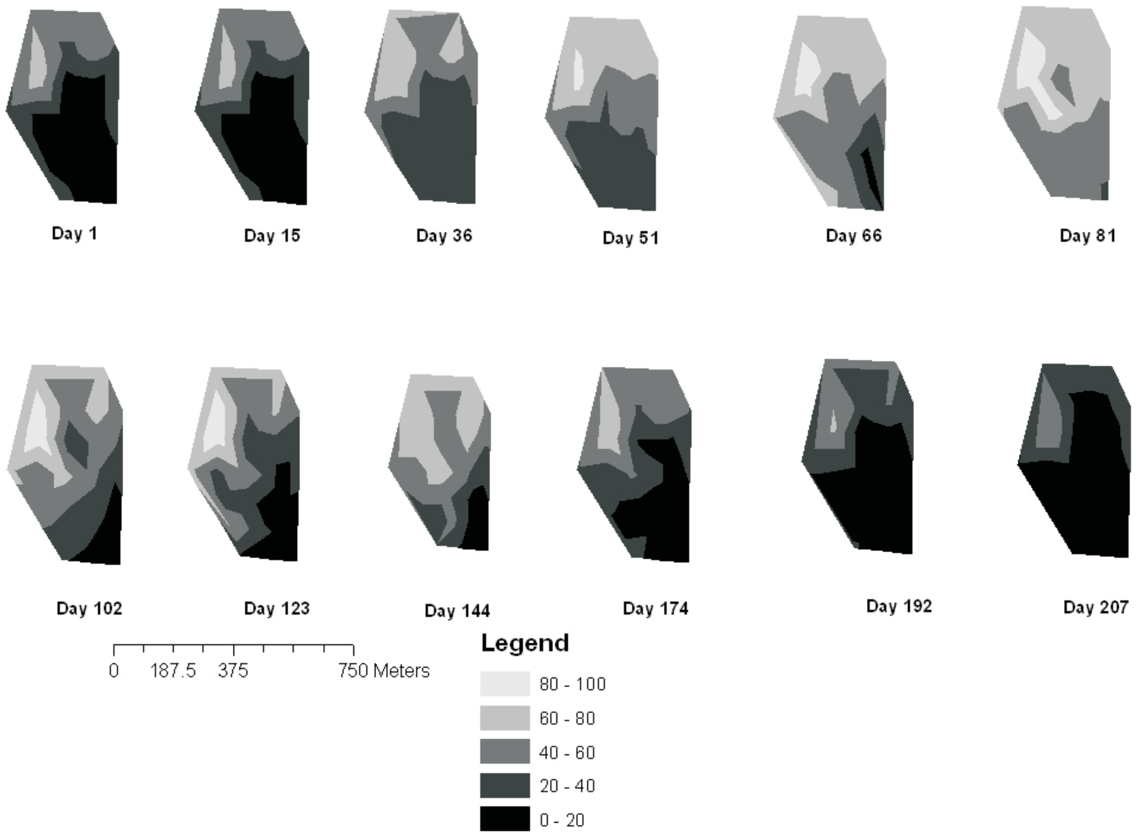

Fig. 3. Depth to water table changes during the study period.

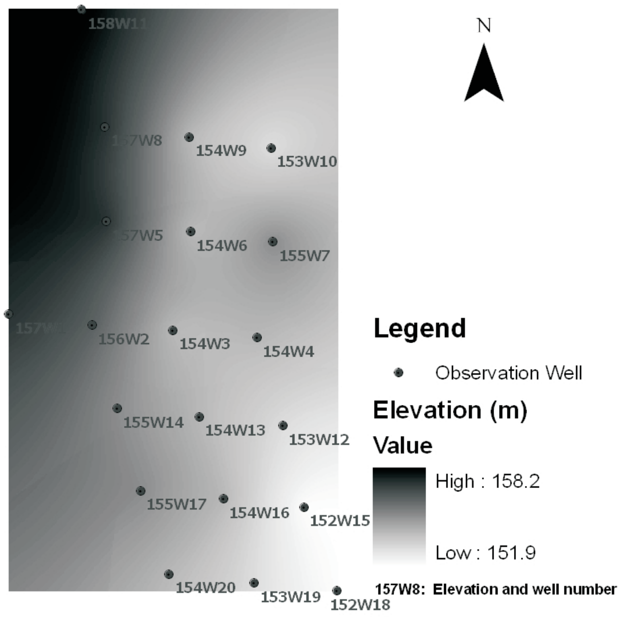

Fig. 4. Field elevation contour model and the observation wells.

serves as a guide for farmers in the selection of wetlands for cultivation. Higher field elevation contributed to the depletion of water table because it increased hydraulic gradient which facilitated subsurface water flow. Therefore, entering the field for preparation and cultivation should be in the order of higher elevation followed by area with lower elevations. This will allow for the use of the residual moisture in the upper soil horizon at the beginning of the drought period while water table in the area of lower elevations continues to recede before cultivation becomes possible. Chen and Qi (2004) reported also that in a shallow groundwater regions, wetlands and lowlands or in river valleys, a high groundwater table and significant hydraulic gradient between saturated zone and the root zone lead to continuous supply of groundwater to the root zone.

Plants exert their absorptive force throughout the rooting depth and take water from wherever it is most readily available. Root depth varies from crop to crop, and from one root to another. This affects the pattern of water uptake. The typical water extraction pattern for more frequently irrigated field or field with high moisture could be 60-30-7-3% (Ayers and Westcot, 1994). This means that the crop will get 60% of its *ET* demand from the upper quarter of the root zone, 30% from the next quarter, 7 and 3% from the last two quarters, respectively. This implies that 90% of the needed water uptake will be expected to be drawn from the first 50% (30 cm) of the soil depth for crops with shallow roots (<60 cm). Therefore, the period when the *DWT* is less than 20 cm may not be suitable for cultivation of shallow rooted crops since waterlogging becomes a critical issue. With this criterion, the water table configuration in late December – through May shows substantial part of the field with depth to water table of >20 cm (Fig. 3) making the period most suitable for cropping activities, especially with no further possible groundwater recharge. Beyond these months, the field was almost completely inundated (*DWT* <10 cm), therefore, only hydrophylic crops such as sugar cane and lowland rice may be suitable for cultivation until the inception of dry season in late November. Surface drainage is the major strategy usually employed in management of wetlands water table for cultivation. Drainage in wetlands is often discouraged since it exposes the soil to subsidence (Braun and Kruijne, 2006). However, drainage could be avoided in non-tidal wetlands when the understanding of depth to water table flunctuations, field elevation, soil moisture characteristics and the profile of available area are considered as factors in determinining when to prepare the field, in the choice of crops and period of cultivation. The period of agricultural drought, when the *PET* exceeds the *P*, is the most appropriate for wetland cultivation. The residual moisture could be optimally used without supplemental irrigation.

The mean depth to water table was modelled using a linear regression model. The model expressed water table depth as a function of possible cultivation days:

$$y = f(x^n). \qquad (2)$$

Mean depth to water table can thus be related with the period of active farming activities for the wetland studied using:

$$y = -1.068x^2 + 12.51x + 13.96, \qquad (3)$$

y – mean depth to water table (cm), x – farming days.

The days (farming days) are from December, 1st till June 25th. Beyond these days, the entire field would have been submerged and intensive drainage would be needed.

The coefficient of determination R^2 is 0.90 while the sum of the residuals is 0. This implies that this model is a very close reflection of the field and possesses a high predictive ability (Fig. 5).

Zhang and Schilling (2006) modelled water table fluctuations in wetlands using Eq. (4), however both Eq. (3) and Eq. (4) are empirical models reflecting different conditions as:

$$d_t = d_0(1\text{-}e^{\alpha t}), \qquad (4)$$

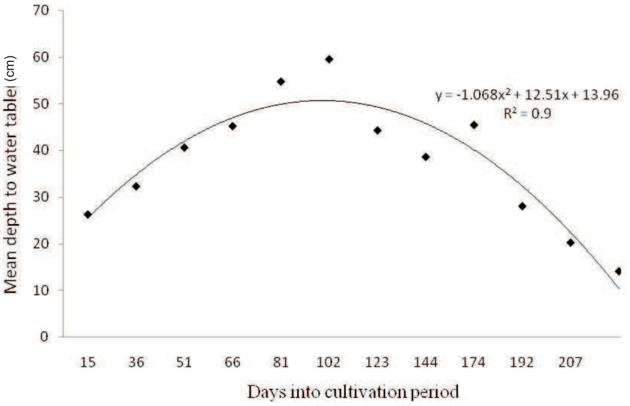

Fig. 5. Regression model of water table and dates.

where: d_t is the depth to water table, while d_0 is the asymptotic depth at which the water table becomes stable, α is the decline coefficient and t is the time. Equation (3), however, relates the farming dates (in days) to the mean water table, thus enabling farmers to have an idea of expected water table during the period of cultivation.

Considering the spatial moisture distribution across the field, it was observed that Quadrant1 (Q1), which correspond to the area with the highest elevation (Figs 1 and 4), had the lowest moisture profile throughout the period of study. Q3 and Q4 were closest to Omi stream, while their soil textures were sandy loam and loamy soil, respectively. Q1 was sandy clay loam at the 0-20 cm and loamy at 20-60 cm, whereas Q2 is sandy loam at the three depths. Q1 and Q2 were on higher elevation 155-158 m (Fig. 1). Q3 and Q4 gave higher mositure level at the two depths of sampling throughout the study period. Figure 6a and b show the moisture characteristics during the period at 10 and 50 cm depth respectively. At both depths, soil moisture was much higher in Q2, Q3 and Q4 which are areas with lower field elevation. Two factors were probably responsible for this moisture gradient. The subsurface flow facilitated by the hydraulic gradient and the influence of seepage from the stream (Kevin, 2003). The analysis of the available water reveals that even at very high pressure head, the moisture content still ranged between 0.25-0.50 $m^3 m^{-3}$ in Q3 at the three soil layers (0-20, 20-40 and 40-60 cm) (Fig. 7c). The soil layers showed very similar relationships in their available water under pressure. In Q1, which is at the highest elevation, moisture characteristics from saturation (0 kPa) and permanent wilting point (PWP) (1 500 kPa) in the 40-60 cm depth ranged between 0.30-0.40 m^3m^{-3}, although the moisture levels in the 0-20 and 20-40 cm depths were much lower (Fig. 7a). Q2 and Q4, which were sandy loam and loamy soil at the 0-60 cm depth, were similar in their response to tension at 20-40 cm with low available moisture content (Fig. 7b, d).

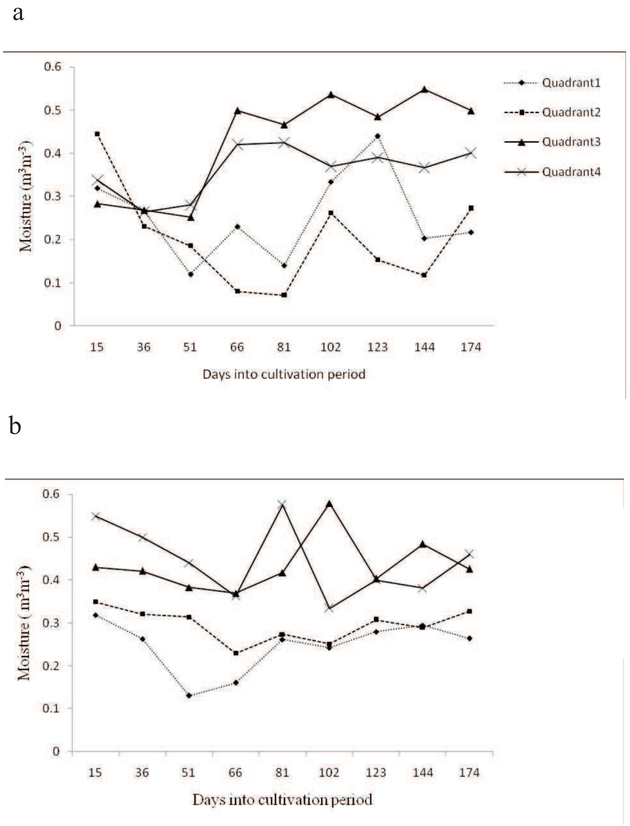

Fig. 6. Mean moisture distribution at: a – 10 cm, b – 50 cm for the quadrants.

However, in comparison, Q2 still had higher moisture distribution than Q4 at 20-40 cm. The moisture distribution from saturation to PWP in 0-20 and 40-60 cm layers ranged between 0.28 and 0.35 m^3 m^{-3}(Fig. 7b) in Q2, and a higher range was observed in Q4 (0.28-0.4 m^3 m^{-3}) (Fig. 7d).

The spatial hetereogeneity of moisture was very high as a result of soil properties, topography, and depth to water table. Chen and Qi (2004) documented a similar observation when he found a high degree of inconsistency in moisture characteristics in lowlands, wetlands and river valleys. Three major moisture regimes were observed in non-tidal wetlands. Firstly, there are areas with low *DWT* (0-20 cm) throughout the period of agricultural drought with high soil moisture at the 0-60 cm soil depth. This area would have the problem of waterlogging throughout the possible cultivation period except where surface drainage is employed. Secondly, there are areas where *DWT* ranges between 20 and 60 cm with decreasing water table as the number of days into cultivation period increases. There was adequate soil moisture in the 0-60 cm soil depth throughout the possible cultivation period. Such areas do not need drainage since the root zones were not waterlogged. There are other areas with deep water table, *DWT* >80 cm. Loss of soil moisture is easily noteceable in the 0-20 cm depth. Adequate moisture was observed in the 30-40 cm depth, and this may make cultivation

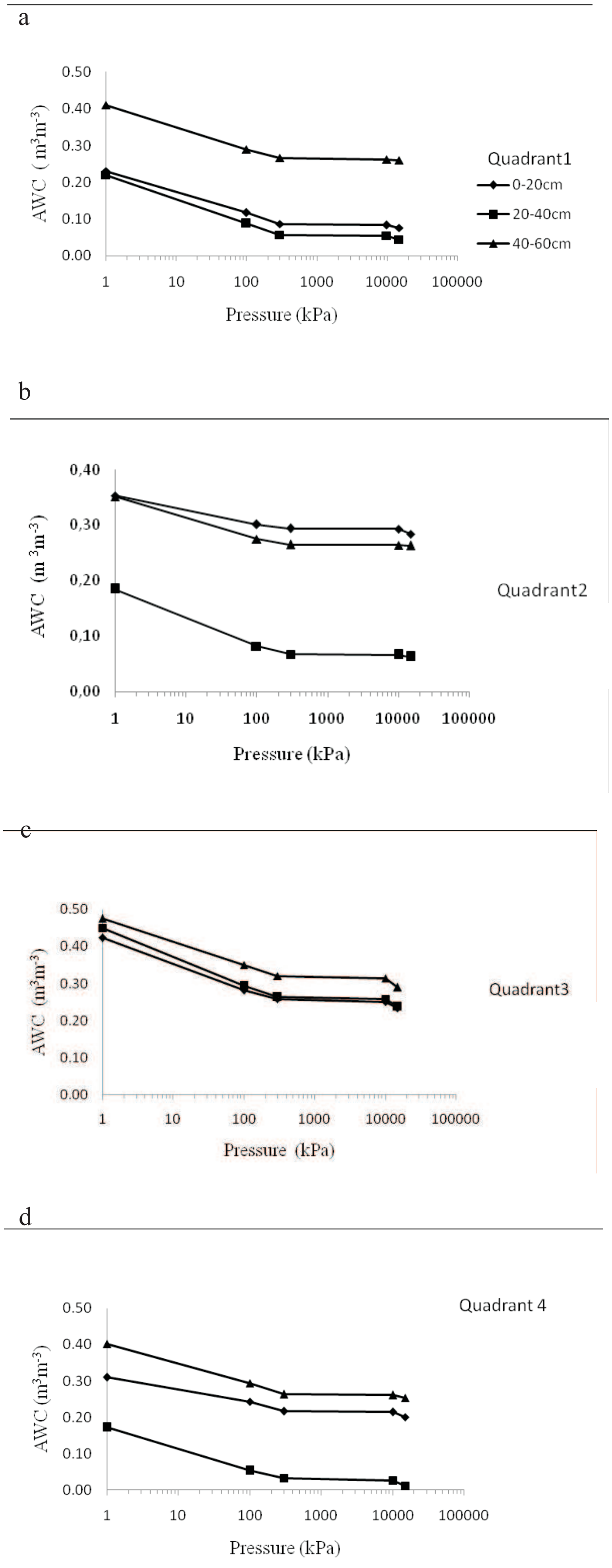

Fig. 7. Pressure and available water characteristics (AWC) at: a – Quadrant 1, b – Quadrant 2, c – Quadrant 3, d – Quadrant 4.

possible if the preparation and planting commences before the *DWT* receeds deeper. This is the case with areas with high elevation. The deeper the water table, the more inadequate the soil available water becomes for crop cultivation. However, for a larger period of this study (January-May, 2008), *DWT* of 20-60 cm was the most prominent and the field presented adequate available water to meet crop water requirements. The adequacy of the available water between saturation and permanent wilting point has to be ascertained during the period when *PET* exceeds *P*. This is similar to the findings of McCarthy *et al.* (2000). The knowledge of those two extremes is very crucial as part of preliminary field survey in wetlands to be used for cultivation.

CONCLUSIONS

1. Wetlands, inland valleys and lowland floodplains have great potentials for crop production either directly or with some form of land use management. Cultivation of wetlands is possible without drainage which usually may create hydrological imbalance in the system.

2. In non-tidal wetlands or inland valleys, cultivation can be safely practiced in periods when rainfall has subsided. In the field studied, the period when *PET>P* was found to be most suitable for wetland cultivation. This period allows for the use of residual soil moisture and soil available water without any need for installation of a drainage structure. The problem of root zone water-logging may not arise because of prevailing water table recession.

3. Farmers can commence planting operations when the water table is 20-30 cm. The risk of root zone water-logging is minimal at this water table depth.

4. Soil available water was found to be adequate throughout the study period because of moisture replenishment of the unsaturated zone from the saturated zone. However, areas with higher elevations are susceptible to early soil moisture inadequacy.

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