UPFLOW model prediction of capillary rise into root zone soil moisture for shallow water table soils of Obio Akpa river floodplain in the Niger-Delta environment, Nigeria

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Abstract: UPFLOW model was used to provide assessments of capillary rise into root zone soil moisture in shallow water table soils of Obio Akpa river floodplain using drum-culture lysimeters. A soil moisture depletion experiment was undertaken through the use of drums with bases intact and drums with bases removed and sunk in the field at different depths during the dry period with no rainfall and no irrigation. UPFLOW model was validated by comparing simulated capillary soil moisture values from a falling water table with gravimetrically observed data from 0 – 500, 500-1000 and, 1000-1500 mm water table depth in sandy loam and sandy clay soils. Simulated runs mimic the observed fluctuations and trend of capillary rise to the root zone. The statistical pointers of simulation performance showed that good interrelation exists between observed and simulated values for both sandy loam and sandy clay soils respectively. The index of agreement (0.9989 and 0.9948) shows a good performance of the model for both sandy loam and sandy clay soils respectively. Model efficiency value of about 99.75% and 99.48% for both the sandy loam and sandy clay soils, respectively indicates that the performance of UPFLOW model in simulating the capillary rise is satisfactory. Hence, UPFLOW can be used with confidence in simulating the capillary rise to the root zone in Obio Akpa, Nigeria.

Keywords: UPFLOW, capillary rise, shallow water table, floodplain, Obio Akpa, Nigeria

Citation: Udom, I. J., and S. A. Nta. 2020. UPFLOW model prediction of capillary rise into root zone soil moisture for shallow water table soils of Obio Akpa river floodplain in the Niger-Delta environment, Nigeria. Agricultural Engineering International: CIGR Journal, 22 (2):21-31.

1 Introduction

There is no doubt as to the fact that shallow groundwater plays an important role in agricultural water supplies in Nigeria, especially in floodplain terrains, where shallow groundwater supply is easily tapped as an important source of soil moisture that makes rain-fed and flood based farming system more reliable and can supply a substantial amount of water for irrigation management (Lockington and Parlange, 2004; Hillel, 2004).

Where no recharge through irrigation or rainfall takes place, the difference in potential between the unsaturated zone and the water table induces the rise of moisture (capillary rise) upward through the soil from the groundwater to the root zone. Where such conditions exist, the need for irrigation water can decrease and flexibility is imposed on irrigation water management both in terms of timing and in regulating the amount of water to be applied

Received date: 2019-03-20 **Accepted date:** 2019-08-03

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and the excess water flowing to drain depending on the soil type, rooting depth, precipitation, irrigation water delivery and evapotranspiration.

When groundwater use by the crop is included in the irrigation water balance, the estimated rate at which water is depleted from stored soil moisture is reduced and the irrigation interval is increased, thus reducing the total number of irrigations and total required depth and cost of applied water (Shankar et al., 2012). A study by Ayars et al.(2008) has demonstrated the potential of capillary rise of meeting up to 50% of the crop requirement from shallow groundwater. Neglecting capillary rise can lead to over irrigation with consequent effects on soil and crop (Kroes et al., 2016).

Simple methods do not exist to calculate the input of capillary rise to crop root zone (Gao et al., 2017). Many researchers (Ochoa et al., 2009; Udom et al., 2013; Luo and Sophocleous, 2010; Evett et al., 2009; Hutma and Schoneman, 1996; and Gao et al., 2017) have shown in a field and lysimeters studies that crops will extract significant quantities of water from shallow groundwater. Darcy's Law can be used to estimate the capillary rise from the water table to the soil surface accordingly:

$$q = k\left(\frac{dh}{dz} - 1\right) \tag{1}$$

Where

q = vertical flow rate(capillary rise) per unit area (cm day^{-1})

k = hydraulic conductivity (mm day^{-1}),

h = hydraulic head (cm) and

z = distance from the soil surface to the bottom of the root zone.

Rearranging Equation 1 yields

$$\frac{dz}{dh} = -\frac{1}{1+\frac{q}{k}} \tag{2}$$

In order to estimate the (hydraulic) head distribution (i.e. The relationship between z and h for a certain k-relationship and a specified flow rate q), Equation 2 should be integrated. This yield:

$$\int_0^{C} dz = -\int_0^{h_p} \frac{dh}{1+\frac{q}{k}} \tag{3}$$

Where,

hp = pressure head, at the upper boundary condition (cm) and

C = the height of capillary rise for flow rate q (cm)

Capillary rise can also be assessed 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 (**Δ**S) in the crop root zone can therefore be obtained:

$$W = \Delta S - E + Li - Lo + C - Dp \tag{4}$$

Where,

W= precipitation (mm)

E= actual evaporation from soil surface (mm)

Li = lateral inflow (mm),

Lo = lateral outflow (mm),

C = capillary rise from the water table (mm),

Dp = deep percolation (mm) and

ΔS = changes in soil moisture storage (mm).

For soils under the influence of shallow water tables, Equation 4 can be rewritten in the form (Agele et al., 2015):

$$E = W + I + Cg - Dp - Rs \pm \Delta S \tag{5}$$

Where,

E = evaporation from soil surface (mm),

W = precipitation (mm),

I = irrigation water applied (mm),

D_p = deep percolation (mm),

R_s = surface runoff (mm),

C_g = water table contribution (mm) and

ΔS = changes in soil water storage (mm).

During crop growth in the rainless dry months and when there is no irrigation for soils under the influence of shallow water tables, W, D_p, and R_s components of the water balance equation in Equation 5 could be assumed zero. If the soil is not cultivated, Equations 4 and 5 can then be simplified to account for the capillary rise in the form:

$$Cg = E \pm \Delta S \tag{6}$$

But, if the soil is cultivated, the water will be intercepted by the roots proliferating in the different layers of the soil such that Equation 6 becomes,

$$Cg = \Delta S \quad (7)$$

As an alternative of calculating capillary rise manually, computer programs might be used. Programs exist based on steady-state (Welling, 1991) and non-steady-state (Kroes et al., 1999), but data requirements are quite broad and they require great proficiency. Alternatively and much easier, UPFLOW (Raes and Deproost, 2003) may be used. UPFLOW is a simple software tool specifically developed to calculate the amount of water that will move upward from the water table to that point in the root zone where it is completely extracted by plant roots. The calculation procedure estimates the zone where the water is extracted by considering the root extraction rate. If the soil is not cultivated, the water will be transported to the soil surface where it evaporates (Raes, 2009).

Many floodplains in Akwa Ibom State, Nigeria, with humid tropical climate are used for dry season vegetable production under irrigation on soils with shallow groundwater. UPFLOW has been successfully used to estimate the capillary rise from shallow groundwater (1-1.15 m) to the root zone (0.4-0.6 m) of horticultural crops in loamy sand and sandy loam soils in Belgium that has a temperate maritime climate (Raes and Deproost, 2003).

The objective of this study is to validate UPFLOW model for estimation of capillary rise for the purpose of irrigation water management in the shallow water table soils of Obio Akpa river floodplain in the Niger-Delta environment of Nigeria, a humid tropical country.

2 Materials and methods

2.1 Description of Obio Akpa floodplain

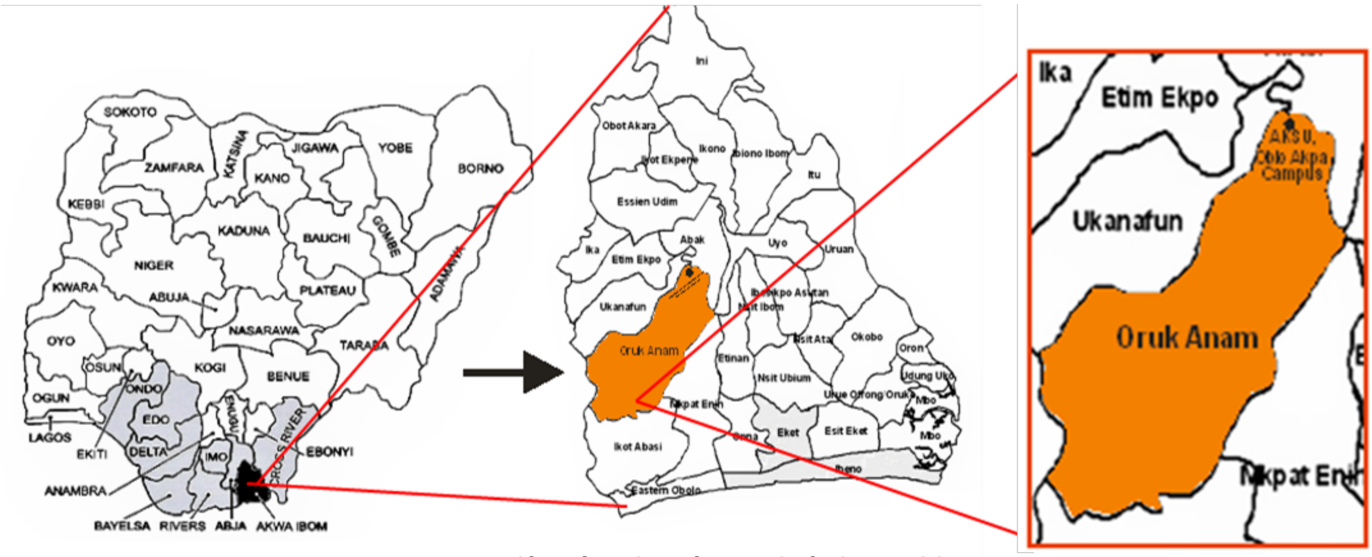
The study area for the validation of UPFLOW is Obio Akpa river floodplain bordering Akwa Ibom State University (AKSU), Obio Akpa campus, Nigeria.

Obio Akpa is located on the coastal plain of South-Eastern Nigeria between longitude 7°30'E and 8°20'E and latitudes 4°30'N and 5°30'N in Oruk Anam Local Government Area of Akwa Ibom State. The soils are deep porous, brown, well drained ferrallitic soils rich in free iron. They have low mineral reserve and therefore are very low in humus content and natural fertility. The soil at the Obio Akpa campus is with sandy loam surface (Udo and Mamman, 1993). Sandy clay soil was imported from the European Union assisted Small Scale Irrigation (EUSSI) project located in at the Obio Akpa river floodplain. The region has a dry season from November through March and a wet season from April through October when 90% of the average precipitation of 2500 mm is received. The mean monthly air temperature varies between 25°C in August and 27°C in February and a mean relative humidity of 68%. Wind direction varies predominantly between South and West and average wind speed varies between 23.5 ms^{-1} day^{-1} in November and 35.4 ms^{-1} day^{-1} in August (NIFOR, 2005).

A fluctuating, non-saline water table is the characteristic of this coastal plain area. The water table fluctuates between 0.3 m and 2 m below the surface during the peak of the dry season. This seasonal sub-irrigation provides a major portion of the total water required for cultivating vegetables on the floodplain.

2.2 UPFLOW model description

The model comes with default values put in place. A steady state condition is assumed, whereby the calculated flux is in equilibrium with the evaporative demand and the soil water conditions in the top soil. The model program contains various sets of soil water retention curves that are considered as representative for various classes and indicative values for root water extraction for a number of crops. The environmental conditions (Figure 1) are detailed in fields of the main menu by specifying: (i) the average evapotranspiration of the atmosphere during the period under consideration (ii) the average soil water content that is maintained in the top soil during that period (iii) the depth of groundwater below the soil surface (iv) the water extraction pattern of the plant roots (v) the thickness and characteristics of successive layers of the soil profile and (vi) the salt content of the water table.



Nigeria showing Akwa Ibom State Akwa Ibom State showing Oruk Anam LGA Oruk Anam LGA showing AKSU

Figure 1 Map of study area showing location of the Akwa Ibom State University (AKSU)

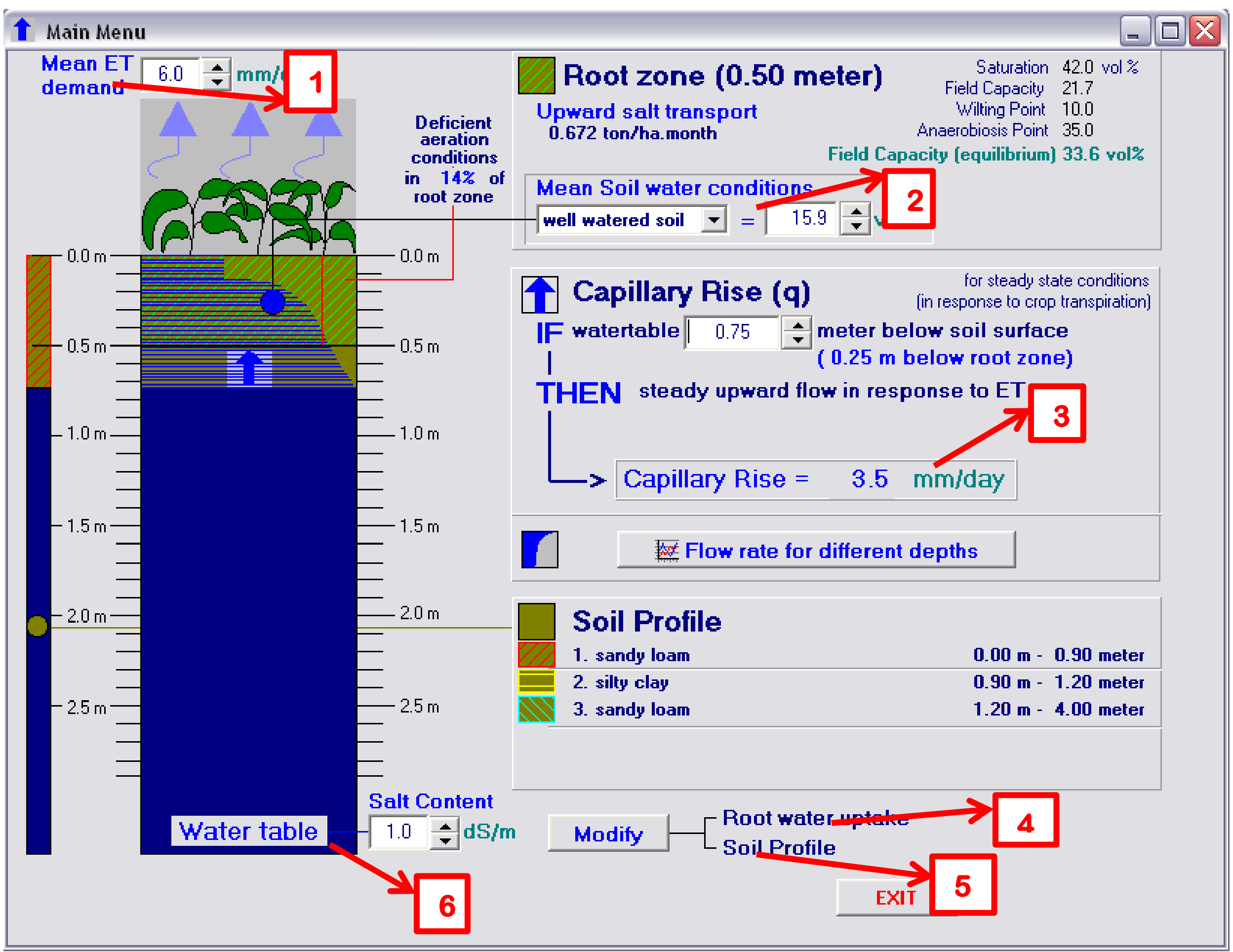


Figure 2 Input fields in main menu of UPFLOW (Raes et al., 2003)

Inputs may be altered either through the selection of options through the drop down menus or through reserved input fields (Figure 2), where the conditions that are valid in the environment during a particular period of time can be specified. By hitting the "calculate" button in the main menu, UPFLOW displays for the specified environmental conditions:

-Expected steady upward flow from the water table to the top soil (if any)

-Average soil water content expected in the top soil when no water flows in equilibrium with the water table.

-Amount of salt transported upward during the given period, when the water table contains salt.

- Degree of water logging in the root zone (if any).

- Graphical display of the soil water profile above the water table.

2.3 Experimental validation of UPFLOW

For model validation, lysimetric field experiments (Udom et al., 2013) were used to provide accurate water balances to determine the soil moisture changes during the period of the study and have been widely used to validate models (Kendy, 2003; Luo and Sophocleous, 2010; Xu et al., 2015). The experimental set up in the fields involved twelve non-weighing type (600 mm diameter, 1500 mm deep) drum culture lysimeters sunk in a 30 m × 20 m area of land at the Akwa Ibom State University Obio Akpa campus (Udom et al., 2013). Six drums with bottoms (bases) intact were designated as B, while six other drums with bottom removed were designated as BL. The twelve drums were divided into two sets for the experimental set up in the field. Each of the two sets of six drums comprised three drums with bottom intact and three drums with the bottom removed. They were designated as B (L1), BL (L1for the first set and B (L2), BL (L2) for the second set.

The twelve drums were buried in the field in three rows and four columns randomized set up (Figure 3) keeping the drums six meters apart from each other and from the boundaries of the plot respectively.

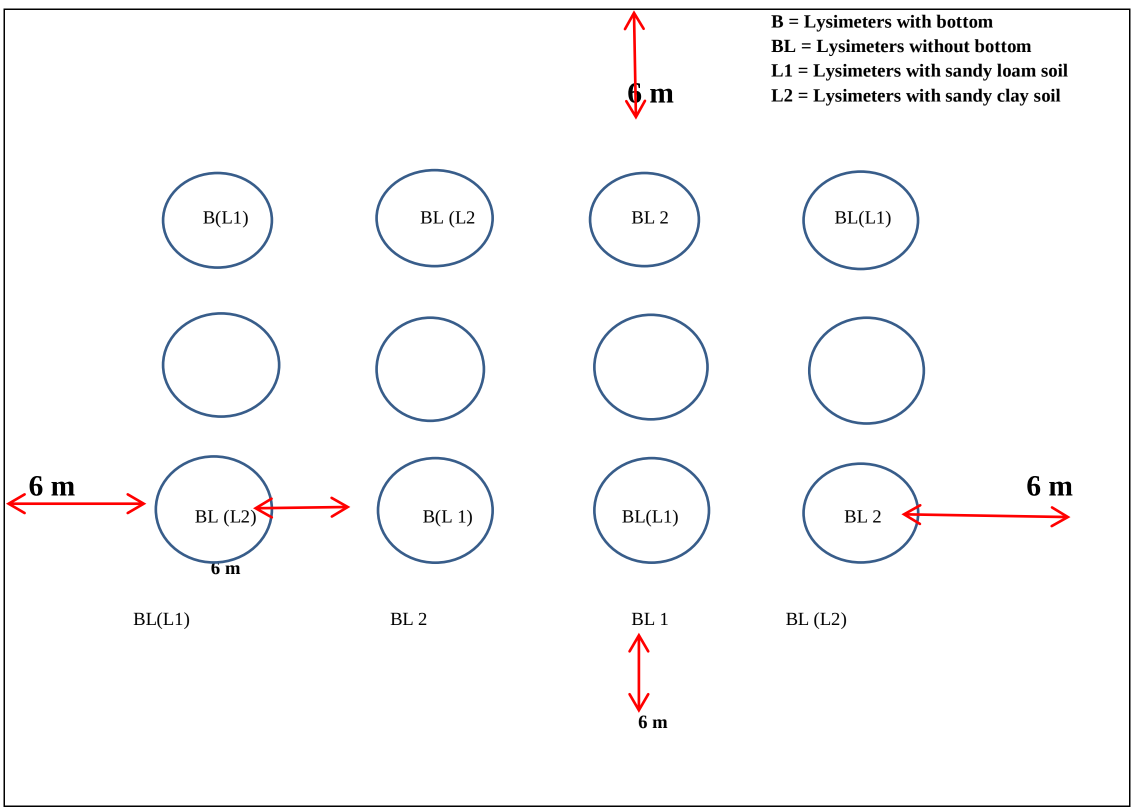


Figure 3 Experimental setup of lysimeters in the field

The drums were buried in the soil, keeping the top of the drums at ground level while the bottoms of the drums were sunk in the soil to gain access to a falling shallow water table. Measured amount of water was added to the lysimeter tanks to maintain the required depth to water level.

All the lysimeters were filled from the bottom with 20 cm layer of a mixture of stones, gravel and sand (Mackay and Younger, 2000) to provide ideal drainage. The remaining space on the first set of six drums, B(L1) and BL(L1),were filled with sandy loam soil while the other set of six drums, B(L2) and BL(L2), were filled with sandy clay soil imported from the EUSSI farm. The soils were compacted in 30 cm increments in the lysimeters. The depth to water table at the experimental site was accessed through a tube well drilled at a distance of 20 m from the center of the experimental plot. The datum from which water level in the well was measured was the top of the wall installation by the use of a Popper apparatus (Davidson, 2000). Measurement, which was continued daily throughout the experimental period, provided data for drawdown of the well from beginning to end of the experiment.

On the drums with bottoms, applied water, rainfall and stored soil moisture was the expected sources of water and there was no contribution from the groundwater (capillary rise). In the drums without bottoms there was no barrier for upward movement of water from the water table to the soil surface. Three different soil depths (0-500, 500-1000 and 1000-1500 mm) were studied with points of moisture measurement at 500, 1000 and 1500 mm. Three types of Tensiometers (500 mm and 1000 mm and 1500 mm long) were installed at the desired depths in the lysimeters to measure soil water potentials. The soil at the different depths were sampled and the Tensiometers were calibrated against the standard gravimetric method (Mackay and Younger, 2000) from soil samples taken from the top 700 mm, covering a broad range of soil moisture from wet to dry. Data obtained from these parallel measurements were used to obtain the soil water characteristic curve from which subsequent estimation of the moisture profile was based. Particle analysis (Evans et al., 1996) of the lysimeter soils showed that the sandy loam soil composed of 62% sand, 12% silt and 26% clay. The sandy clay soil composed of 53%, 5% and 42% sand, silt and clay respectively. These particle percentages were used as input to the Soil Texture Triangle Hydraulic Properties Calculator (Evans et al., 1996) to obtain values for the experimental soil hydraulic properties. Capillary rise was monitored as the water table fell during the dry season between 700 mm at the beginning of the study to 1550 mm at the end. The method of Saxton (1986) was used to determine bulk density of the lysimeters soils as 1.51 g cm^{-3} and 1.33 g cm^{-3} for the sandy loam and sandy clay soils respectively.

The entire experimental area, both in between and around the lysimeters was cropped with Waterleaf (*Talinum triangulare*). In the drums with bottom and those without bottom, the plants were grown in identical conditions and it was presumed that the total crop water requirement in both cases was similar in each soil type.

The difference in moisture content between the bottomed and bottomless drums represented the amount of water contributed by the water table through the capillary rise and retained in the soil profile.

2.4 Quantitative evaluation of UPFLOW

To validate UPFLOW model, the observed data from the research plots were used as input to the model. The model was run stepwise for different water-table conditions. The model simulated outputs were compared with the corresponding measured values. The ability of UPFLOW model to predict the capillary rise was evaluated quantitatively using the following statistics to indicate overall model performance (Ali and Abustan, 2014)

2.4.1 Bias or mean bias (*ME*)

$$ME = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \quad (8)$$

Where *P* and *O* are the predicted and observed values for the observation and *N* is the number of observations.

2.4.2 Mean absolute bias or error (*MAE*) (Fox, 1981; Cob and Juste, 2004)

$$MAE = \frac{1}{N}\sum_{i=1}^{N}(|P_i - O_i|) \quad (9)$$

2.4.3 Root mean square error (*RMSE*)

It quantifies the dispersion between simulated and measured data.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \quad (10)$$

2.4.4 Relative error (RE):

$$E = \frac{RMSE}{\bar{O}} \times 100 \quad (11)$$

Where $\bar{O}$ is the mean of the observed value. Ideally, the value of ME, MAE, RMSE and RE should be zero.

2.4.5 Model efficiency

Model efficiency (*EF*) was calculated as:

$$EF = \frac{\sum(O-\bar{O})^2 - \sum(P-\bar{P})^2}{\sum(O-\bar{O})^2} \quad (12)$$

2.4.6 Index of Agreement (*IA*)

$$d = 1 - \frac{\sum_{i=1}^{N}(O-\bar{S})^2}{\sum_{i=1}^{N}(O' + S')^2} \quad , 0 \le d \le 1 \quad (13)$$

Where $O' = |O - \bar{O}|$, $S' = |S - \bar{S}|$, O is the observed value, S is the simulated value and $\bar{S}$ is the simulated mean. An ideal value of *EF* and d is unity.

3 Results and discussions

3.1 Estimation off capillary rise

The effects of different treatments on the estimation of capillary rise to the root zone of the Waterleaf crop under bottomed and bottomless conditions are presented in Tables 1 and 2 and in Figures 1 and 2.

Table 1 Capillary rise rate of sandy loam soil

Water table Depth (mm)	Treatments	Soil Moisture extraction pattern for different depths			Total (mm)	Observed capillary rise (mm day^{-1})	Simulated Capillary rise (mm day^{-1})
		Top Depth (0 - 500mm)	Middle Depth (500 - 1000mm)	Bottom Depth 1000 - 1500mm			
	BL	1.40	2.36	0.95	4.71		
700	B	0.44	0.56	0,41	1.41	3.30	3.6
	BL	0.93	1.55	0-60	3.08		
800	B	0.13	0.20	0.10	0.43	2.65	2.8
	BL	0.91	1.56	0.60	3.07		
850	B	0.09	0.16	0.14	0.38	2.69	2.5
	BL	0.85	1.41	0.52	2.78		
900	B	0.12	0.20	0,07	0.38	2.40	2.2
	BL	0.69	1.13	0.43	2.24		
1000	B	0.10	0.17	0.07	0.34	1.90	1.7
	BL	0.47	0.77	0.29	1.53		
1100	B	0.08	0.11	0.03	0.22	1.31	1.4
	BL	0.38	0.62	0.23	1.23		
1200	B	0.05	0.09	0.02	0.16	1.07	1.1
	BL	0.36	0.60	0.23	1.19		
1320	B	0.06	0.08	0.03	0.17	1.02	0.9
	BL	0.25	0.48	0.16	0.84		
1450	B	0.03	0.06	0.02	0.11	0.73	0.70
	BL	0.11	0.18	0.07	0.36		
1550	B	0.02	0.03	0.01	0.06	0.30	0.50

To observe the effect of the falling water table on the capillary rise to the root zone, the root zone was divided into three layers of 500 mm thickness. The greater part of the moisture uptake occurred in the root zone (500-1000 mm) region. This is where there is the maximum concentration of roots and hence highest moisture uptake by plants.

The groundwater flux at the root zone decreased with increase in water table depth. For a 30% increase in the water table depth, groundwater flux decreased by 42% and 50% in the sandy loam and sandy clay soils respectively. For 1500 mm water table depth, only 9% and 17%, of total flux at 700 mm, were contributed for the sandy loam and sandy clay soils respectively.

Table 2 Capillary rise rate of sandy loam soil

Water table Depth (mm)	Treatments	Soil Moisture extraction pattern for different depths			Total (mm)	Observed Capillary rise (mm day^{-1})	Simulated Capillary rise (mm day^{-1})
		Top Depth (0 - 500mm)	Middle Depth (500 - 1000mm)	Bottom Depth 1000 - 1500mm			
700	BL	0.94	1.59	0.80	3.33	0.78	0.84
	B	0.72	1.22	0.61	2.55		
800	BL	0.74	1.23	0.62	2.59	0.58	0.62
	B	0.60	0.94	0.47	2.01		
850	BL	0.62	1.05	0.51	2.18	0.48	0.74
	B	0.49	0.82	0.39	1.70		
900	BL	0.60	1.01	0.48	2.09	0.42	0.46
	B	0.56	0.67	0.44	1.67		
1000	BL	0.50	0.84	0.40	1.74	0.39	0.36
	B	0.39	0.66	0.30	1.35		
1100	BL	0.37	0.61	0.28	1.26	0.27	0.28
	B	0.29	0.48	0.22	0.99		
1200	BL	0.27	0.44	0.20	0.91	0.23	0.24
	B	0.20	0.33	0.15	0.68		
1320	BL	0.26	0.43	0.21	0.90	0.20	0.22
	B	0.21	0.34	0.15	0.70		
1450	BL	0.22	0.37	0.18	0.77	0.15	0.14
	B	0.18	0.30	0.14	0.62		
1550	BL	0.17	0.19	0.09	0.45	0.13	0.12
	B	0.09	0.15	0.07	0.32		

The difference in the capillary rise of the two soils is intimately related to the general physical nature of the soil and especially for its mechanical composition which influences its permeability. Permeability increases with the amount and size of pores. Small pores give more hydraulic resistance to flow than large pores. Thus, although the porosity of the sandy loam is less than that of the sandy clay, the much greater bonding in the clay makes the amount of water held in the soil at a given pressure to be more in the sandy clay than in the sandy loam. Differences in the hydraulic properties of the vertical soil profile also influence the vertical water flow. The depth of the groundwater directly influences the size of the gap that the capillary flux has to bridge to be able to reach the root zone. Luo and Sophocleuos (2010) had observed that up to 2500 mm depth of the groundwater table and for deeper depths, the groundwater contribution is almost negligible.

3.2 UPFLOW calibration

Calibration is a process of comparing predicted results with observed data and thereafter adjustments are made to the most sensitive parameters in the model. UPFLOW predictions of capillary rise of the specified conditions were compared with measured averages as indicated in Figures 4 and 5.

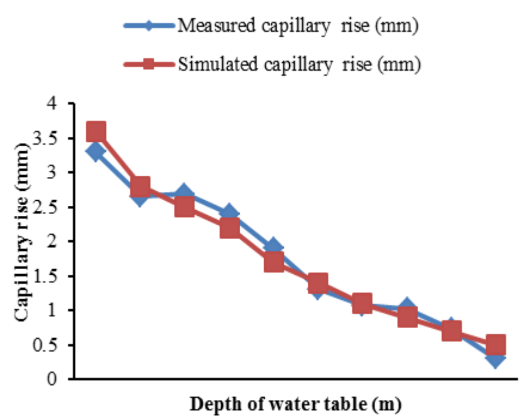


Figure 4 Comparison of predicted and observed

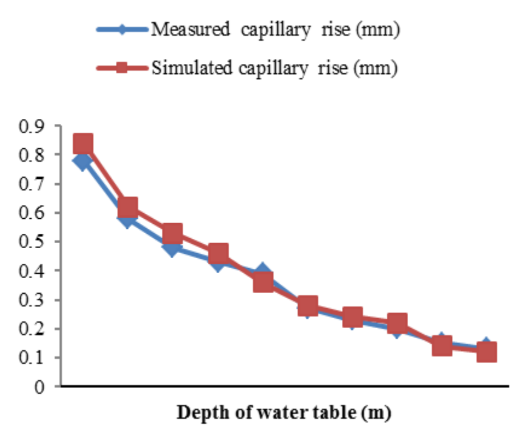


Figure 5 Comparison of predicted and observed capillary flux in sandy loam soil

There was an initial mismatch of measured and simulated values between 700 and 1100 mm water depth. While the field values underestimated the model in the 700 to 800 mm range of water table depth of the sandy loam soil, the underestimation continued up to 900 mm water depth in sandy clay soil. But, between 850 to 1000 mm, the field values overestimated the model predictions in the sandy loam soil, but underestimated the model in the sandy clay soil. This could have been due to possible deficient aeration of the root zone and hence reduced observed capillary rise. Low bulk density of imperfectly consolidated lysimeter soils and soil heterogeneity against assuming uniformity could also have been prime causes for the under estimation of the model predictions.

It is evident from Figures 4 and 5 that the UPFLOW model resembles the depletion patterns of the field condition of the Obio Akpa area from which the data for the study was based. It is clear that the simulated moisture conditions and the field data match closely. It reveals that the model can estimate actual capillary rise with reasonable accuracy. This reflects the suitability of the model for irrigation water management in the area.

Figures 6 and 7 present the distribution of simulated capillary flux against observed field values around the 1:1 line.

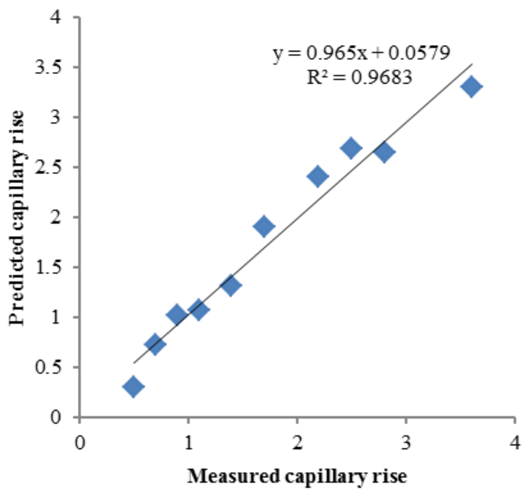


Figure 6 Correlation of observed and simulated capillary rise in sandy clay soil

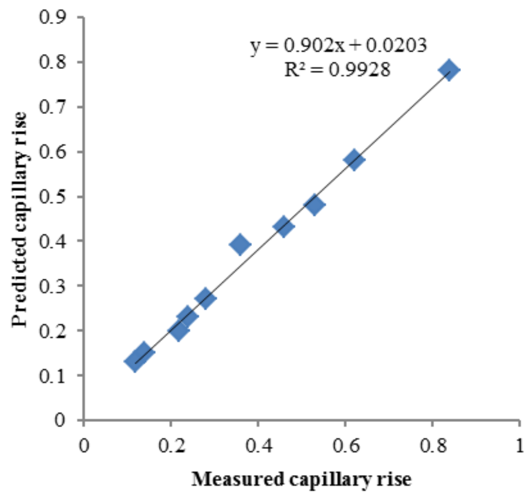


Figure 7 Correlation of observed and simulated capillary rise in sandy loam soil

The data points lie around the 1:1 line, which means that the model output is reliable and reasonable.

3.3 Statistical indicators of UPFLOW model performance

Statistical indicators of model performance are presented in Table 3.

Table 3 Statistical indicators of model performance

Soil Type	R^2	r	Mean bias error (mm)	Mean absolute bias (mm)	Root Mean Square Error (mm)	Relative Error (%)	Model efficiency (%)	Index of Agreement
Sandy loam	0.9683	0.9840	0.03	0.15	0.54	31.16	99.75	0.9989
Sandy clay	0.9928	0.9964	0.04	0.48	0.12	6.76	99.48	0.9948

The statistical pointers of simulation performance summarized in Table 3 has shown that the rate of coefficient of determination (R^2 = 0.9683, 0.9928) implies that a good interrelation occurs amongst observed and simulated values for both sandy loam and sandy clay soils respectively. The rate of mean bias or error (*ME*) is equal to

0.03 and 0.04 mm for both sandy loam and sandy clay soils respectively. A positive value of *ME* indicates overestimation and vice-versa. The mean absolute bias or error and root mean square error were 0.15 and 0.48 mm and 0.54 and 0.12 mm, respectively for both sandy loam and sandy clay soils. The mean absolute bias or error is an indicator of overall bias in the model estimate. The extent of root mean square error (*RMSE*) is also a convenient parameter of model performance. In a perfect condition, the values of relative error (*RE*) and the model efficiency (*EF*) will be 0% and 100%, respectively. So the *RE* value of about 31.16% and 6.76% and *EF* value of about 99.75% and 99.48% indicates that the performance of UPFLOW model in simulating actual upward flow or capillary rise is satisfactory for both the sandy loam and sandy clay soils respectively. The limit of index of agreement (*d*) value is from 0 to 1. A higher value indicates a better agreement between the simulated and observed values. In this study the value of d (0.9989 and 0.9948) shows a good performance of the model for both sandy loam and sandy clay soils respectively.

Some discrepancies are observed in graphical display, and the statistical parameters are also deviated from the ideal value. These may be due to inherent assumptions in the model principle, and also in the field data. For example, the model assumes the steady state condition, that is, the flow does not change with time. But in reality, this may not be true (as the flux varies with the change in moisture level and atmospheric demand). Considering the above statistical parameters and graphical comparison, it can be said that the overall performance of the UPFLOW model in simulating actual upward flux from waterleaf field under variable water-table condition is satisfactory.

4 Conclusion

Assessment of predicted and measured capillary rise values for different water table depths indicates that the UPFLOW model can estimate actual capillary rise with reasonable accuracy.

Considering the graphical display and statistical parameters, it can be strongly suggested that the UPFLOW model could be used with confidence in estimating capillary rise to the root zone under shallow water table condition in Obio Akpa floodplain and similar environments under variable water-table condition. Perfect match between model predictions and measured values could be obtained with a well aerated, properly consolidated soil and hence reliable data.

Application of simulation model such as UPFLOW in quantifying the magnitude of capillary flux under different field situations can help to suggest appropriate irrigation management practices to exploit shallow water-table efficiently, and thus reduce the frequency of irrigation and save energy. This study can also be extended to different agro-climatic zones under different field crops.

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