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EVALUATION OF A SIMULATION MODEL FOR PREDICTING SOIL-WATER CHARACTERISTICS OF SELECTED AGRICULTURAL FIELDS

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ABSTRACT

The ability of the Soil Water Characteristics-Hydraulic Properties Calculator (SWC-HPC) model in predicting soil-water characteristics of agricultural fields in Zaria, Nigeria, was tested and reported in this study. The goal was to establish the predictability and reliability of the model, and hence, its use in determining water characteristics of soils in the study area. Forty soil samples collected from four irrigation sites were used in the evaluation. The soils particle size distribution (specifically, percent clay and sand) and organic matter contents were inputted into the model to simulate soil moisture status at saturation, field capacity and wilting point, soil bulk density and saturated hydraulic conductivity. The model outputs were statistically compared with observed parameters from laboratory tests using root mean square error (RMSE), coefficient of variation (CV), modeling efficiency (EF) and coefficient of residual mass (CRM). The model accurately simulated the observed bulk densities of the soil tested, satisfactorily simulated soil moisture content at field capacity, and moderately simulated moisture content at saturation and wilting point. The model however, poorly simulated saturated hydraulic conductivity of the soils tested. The SWC-HPC may therefore be used only to simulate soil bulk densities and moisture status at saturation, field capacity and wilting point in the study locations.

Keywords: Simulation, SWC-HPC model, Field capacity, wilting point, bulk density, saturated hydraulic conductivity

1.0 INTRODUCTION

Soil-water characteristics refer to the relationship between soil and the moisture present in it. This relationship is commonly represented with a curve, referred to as soil-water characteristics curve (SWCC); and it shows the moisture contents of the soil at different suctions. The moisture content defines the amount of water contained within the soil pores. In soil science, the term volumetric water content, O, is commonly used for moisture content, while in geotechnical engineering practice, the term gravimetric water content, *w*, which is the ratio of the mass of water to the mass of solid, is used. Another term commonly used to indicate the percentage of voids that are filled with water is degree of saturation, *S*. The suction, also referred to as soil water potential, is related to the pressure that will be exerted to remove moisture from the soil. It may be expressed either as matric suction (also known as capillary pressure) or total suction (matric suction plus osmotic suction). Soil suction may range from zero kilo-Pascal (kPa) for moisture content at saturation (when all soil pores are filled with water) to about 1,000,000 kPa at zero moisture content (all soil pores are filled with air) (Fredlund, *et al.*, 1994).

In agriculture, the soil moisture content between two points on the SWCC is of great importance to crop growth and development. These points are air entry point and residual moisture content point. The air entry point on the SWCC (i.e. the bubbling pressure point) is the matric suction where air starts to enter the large pores in the soil (Fredlund and Xing, 1994). The moisture content at this point is commonly referred to as field capacity (FC). The residual moisture content point on the SWCC is the moisture content where a larger suction (= 1,500 kPa) is required to remove water from the soil. The moisture content at this point is known as permanent wilting point (PWP). The moisture content of the soil between the FC and PWP is referred to as Available water (AW). This is the water available for plant to take up for its metabolic activities. Information on the AW of soils are required in planning irrigation scheduling for crops, design of irrigation systems, drainage systems and other soil and water management strategies.

The importance of AW and SWCC in the science and engineering of soil and water conservation has encouraged the continuous search for quick and easier means of quantifying their parameters. Studies have shown that soil-water characteristic (soil water retention and hydraulic conductivity) is very much related to soil physical properties, which include soil particle size distribution, bulk density, porosity, organic matter content, among others (Salter and Williams, 1965; Gupta and Larson, 1979; Rawls *et al.*, 1982; Williams *et al.*, 1983; Fredlund and Rahardjo, 1993; Rawls *et al.*, 1998). Over the years, soil-water characteristics are determined through laboratory procedures carried out on collected soil samples. These procedures are cumbersome, time and energy consuming and expensive. In view of these difficulties, concerted efforts are being made by soil scientists to develop predictive relationships between soil-water characteristics and physical properties of soils. Such relationships, referred to as Pedotransfer functions (PTF) (Bouman and van Lanen, 1987; Tietje and Tapkenhinrichs, 1993; Bell and van Keulen, 1995) are predictive functions of soil properties that are readily available, easily, routinely, or cheaply measured.

Quite a number of PTFs exist in literature. To facilitate their usage, the PTFs and their solution are now being employed in designing computer programs for rapid and on-the-desk predictions of SWCC. Among such computer simulation models include SOILPAR (Acutis and Donatelli, 2003), ROSETTA (Schaap, *et al*, 2001), and the Soil Water Characteristics-Hydraulic Properties Calculator (SWC-HPC) (Saxton and Willey, 2006). Before adoption of any simulation model for use in any locality, it is important to first evaluate the model's ability to represent the state variables it is intended to simulate for that locality. This is usually done by comparing the model simulated outputs with measured/observed state variables the model represents. In this study, the ability of SWC-HPC model in predicting the soil-water characteristics of some soils in Zaria, Nigeria, was evaluated. The specific objectives were to use SWC-HPC model to simulate the soil water characteristics of selected soils, and to compare the model output parameters with those obtained from the laboratory for the same soils. The goal was to establish the predictability and reliability of the model, and hence, its use in determining water characteristics of soils in the study area.

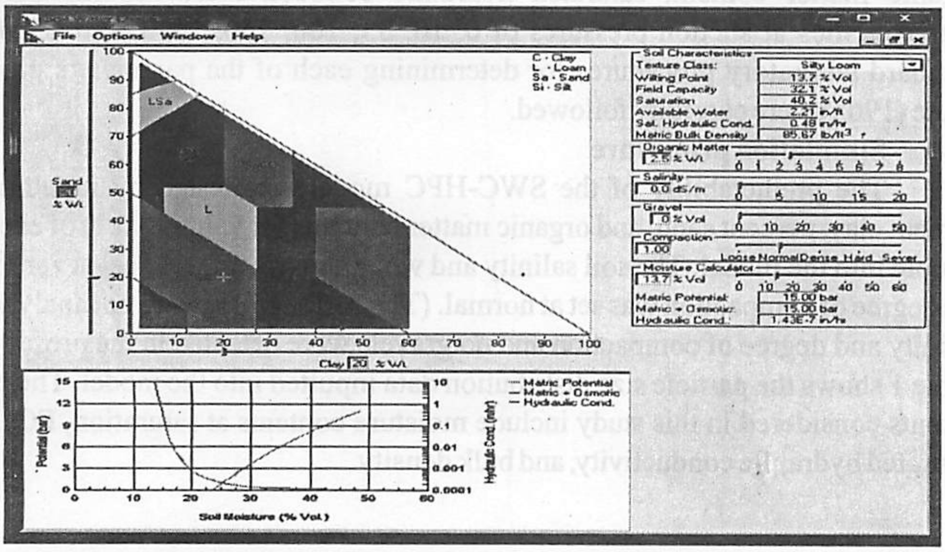
2.0 MATERIALS AND METHODS

2.1 Location of Study Area

The study was carried out in Zaria, Nigeria. Zaria lies on latitude 7°35'N, Longitude 11°11'E, and altitude 686 m above mean sea level, and is located within the Northern guinea savannah ecological zone. The climate can be described as semi-arid; with three distinct seasons: the hot dry season which spans from March to May; warm rainy season from June to early October; and the cool dry season which spans from November to February. The average relative humidity is 36.0 % during the dry season and 78.5 % during the wet season and the average minimum and maximum temperatures are 15.6°C and 38.5°C, respectively. The rainfall is monsoonal in origin averaging about 1150 mm per annum with a peak in August. The soils of the study area are classified as alfisols based on the USDA (1975) classification. The soils are reported as mantle of residue overlain by aeolian deposits, formed from loessial, loessial-colluvial and colluvial-alluvial parent materials (Aremu, 1980). The soils are deep (1.25-2.0 m) and have friable sandy clay to clay loam textures, while the sub-horizon (20-40 cm) are well structured, which favour good agricultural production (Odunze, 1998).

2.2 The Soil Water Characteristics-Hydraulic Properties Calculator model

The Soil Water Characteristic-Hydraulic Properties Calculator (SWC-HPC) model is a graphic computer program developed by Saxton and Willey (2006). It is used for estimation of hydrologic water holding and transmission characteristics of an agricultural soil horizon. The SWC-HPC is a component of the Soil-Plant-Water-Atmosphere (SPAW) hydrologic model (Saxton and Willey, 2006). However, it is also an independent program with its input and output variables. The major input variable required to run the SWC-HPC is particle size distribution, specifically percent sand and clay. Other input variables which are optional but are required to refine the output of the model and increase its predictability, are organic matter, salinity, gravel and degree of compaction. The input values are entered by using the slider bars for each variable from the ranges shown on the graphical soil texture triangle (Fig.1).



Soil Characteristics
Texture Class: Silty Loam
Wilting Point 13.7 % Vol
Field Capacity 32.1 % Vol
Saturation 40.2 % Vol
Available Water 2.21 in/ft
Sat. Hydraulic Cond. 0.48 in/hr
Matric Bulk Density 85.67 lb/ft³
Organic Matter 2.5 % Wt
Salinity 0.0 dS/m
Gravel 0 % Vol
Compaction 1.00
Moisture Calculator 13.7 % Vol
Matric Potential: 15.00 bar
Matric + Osmotic: 15.00 bar
Hydraulic Cond.: 1.43E-7 in/hr

Figure 1:Graphical input screen for the SWHPC model(Source: Saxtonand Willey, 2006)

The output variables of the SWC-HPC include percent volumetric moisture content at wilting point, field capacity and saturation. Other outputs of the model include available water (AW), saturated hydraulic conductivity, bulk density and textural class of the soil. The results are dynamically displayed in text and on a moisture tension and moisture conductivity graph as the inputs are varied. This provides rapid and visual display of the estimated water holding and transmission characteristics over a broad range of variables. According to Saxton and Rawls (2006), the soil water characteristic equations used in the development of SWC-HPC model are valid within a range of soil texture of approximately 0-60% clay content and 0-95 % sand content, bulk density of between 1.0 and 1.8 g/cm^3 and organic matter content not greater than 8%. The development of SWC-HPC and the relevant equations are given in detail by Saxton and Willey (2006) and Saxton et al. (1986).

2.3 Soil samples for model evaluation

The soil samples used in the study were obtained from four agricultural fields in Zaria. The fields include Institute for Agricultural Research Irrigation field, Galma Pilot Irrigation Project, Kubanni Irrigation Scheme, and Agricultural Engineering Department farmland. Ten soil samples were collected from the walls of two profile pits of 100 cm depth in each field. Five samples were taken from each pit at 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm depths using core samplers of 5 cm diameter. The samples were analyzed in the Soil Physics Laboratory of the Department of Soil Science, Ahmadu Bello University, Zaria. The analyses carried out include the particle size distributions, soil bulk densities, organic matter content, saturated hydraulic conductivities, and the moisture characteristics at suction pressures of 0, 10, 33, 100, 150, 1000, and 1500 kPa. Standard laboratory procedures for determining each of the parameters given by Klute (1965) were carefully followed.

2.4 Simulation procedure

The predictability of the SWC-HPC model was tested by inputting the percent clay, percent sand, and organic matter content (for values = 0.1) of each soil sample into the model. The soil salinity and weight of gravel were set at zero while the degree of compaction was set at normal. (The soil samples were not analyzed for salinity and degree of compaction and no gravels were detected in the profile pits). Table 1 shows the particle size distribution data inputted into the model. The model outputs considered in this study include moisture contents at saturation, FC, PWP, saturated hydraulic conductivity, and bulk density.

Table 1: Particle size distribution of soil samples used as input data into the model

Soil sample No	Clay %	Silt %	Sand %	Textural Class
1	17	34	49	Loam
2	15	28	57	Sandy loam
3	9	30	61	Sandy loam
4	11	40	49	Loam
5	9	34	57	Sandy loam
6	7	40	53	Sandy loam
7	7	34	59	Sandy loam
8	11	48	41	Loam
9	9	52	39	Silt Loam
10	9	50	41	Silt Loam
11	15	50	35	Silt Loam
12	21	40	39	Loam
13	19	44	37	Loam
14	21	42	37	Loam
15	15	52	33	Silt Loam
16	15	44	41	Loam
17	15	46	39	Loam
18	11	26	63	Sandy loam
19	9	28	63	Sandy loam
20	11	38	51	Loam
21	15	36	49	Loam
22	15	48	37	Loam
23	13	48	39	Loam
24	27	40	33	Loam
25	19	46	35	Loam
26	25	44	31	Loam
27	25	54	21	Silt Loam
28	21	40	39	Loam
29	15	44	41	Loam
30	23	50	27	Silt Loam
31	22	34	44	Silt Loam
32	30	30	40	Clay loam
33	26	30	44	Loam
34	20	30	50	Loam
35	28	28	44	Clay loam
36	26	28	46	Silty Clay Loam
37	14	40	46	Loam
38	20	36	44	Loam
39	24	30	46	Loam
40	22	16	62	Silty Clay Loam

2.5 Model evaluation procedure

The comparison between the model predicted values and the laboratory measured values was carried out using statistical indices like the root mean square error (RMSE), coefficient of variation (CV), modeling efficiency (EF) and coefficient of residual mass (CRM). These statistical indices were selected to adequately evaluate the model performance. The RMSE, CV, EF and CRM were given as (Mahdian and Gallichard, 1995; Krause *et al.,* 2005 and Antonopoulos, 1997):

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5} \tag{1}$$

$$CV = 100 * \frac{\left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5}}{O_m} \tag{2}$$

$$EF = 1 - \frac{\sum_{i-1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_m)^2} \tag{3}$$

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \tag{4}$$

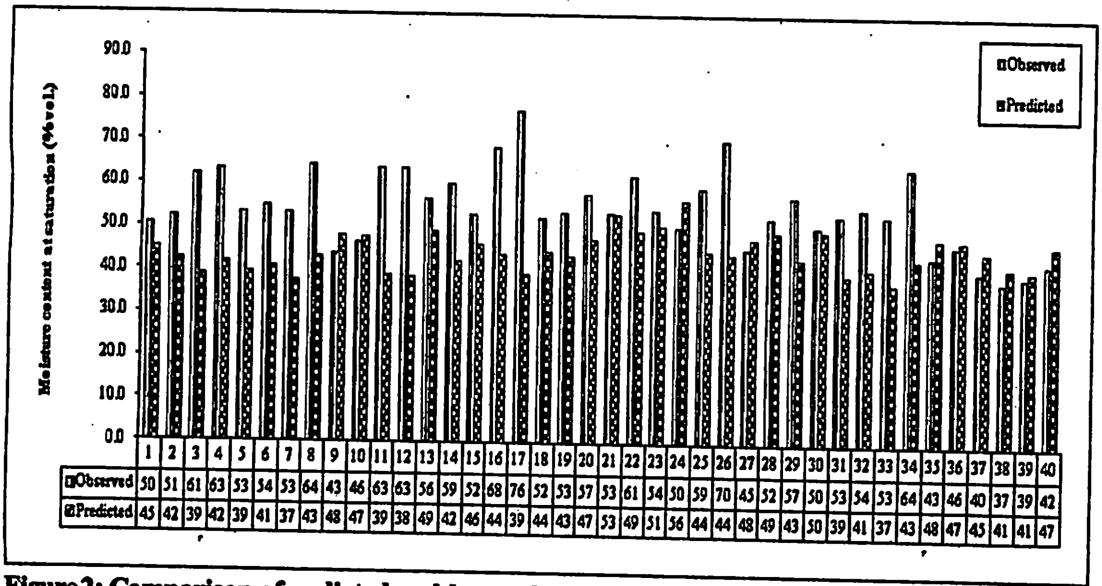
Where, P_i is model predicted values, O_i is observed values, O_m is mean of observed values, and 'n' is number of data.

The RMSE is a measure of precision while the CV (expressed in %) is a measure of variability between predicted and observed data. The RMSE should tend towards zero as the measure of precision between the predicted and observed value increases. The CV for a model aims to describe the model fit in terms of the relative sizes of the squared residuals and outcome values The higher the CV, the greater the dispersion in the variable. The lower the CV, the smaller the residuals relative to the predicted value, and is suggestive of a good model fit. The modeling efficiency (EF) also referred to as the coefficient of Nash-Sutcliffe (Nash and Sutcliffe, 1970), is a measure of fit between predicted and measured data. It is similar to the coefficient of determination (R^2). Nash-Sutcliffe efficiencies can range from -8 to 1. An efficiency of 1 ($E = 1$) corresponds to a perfect match of predicted to the observed data. An efficiency of 0 ($E = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-8<E<0$) occurs when the residual variance (described by the numerator in Eq.3), is larger than the data variance (described by the denominator), and it implies that the observed mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate the model is (Nash and Sutcliffe, 1970). The coefficient of residual mass (CRM) is an indicator of the tendency of the model to either over or under predict measured values. A positive value of CRM indicates a tendency of underestimation while a negative value indicates a tendency of overestimation (Antonopoulos, 1997).

3.0 RESULTS AND DISCUSSION

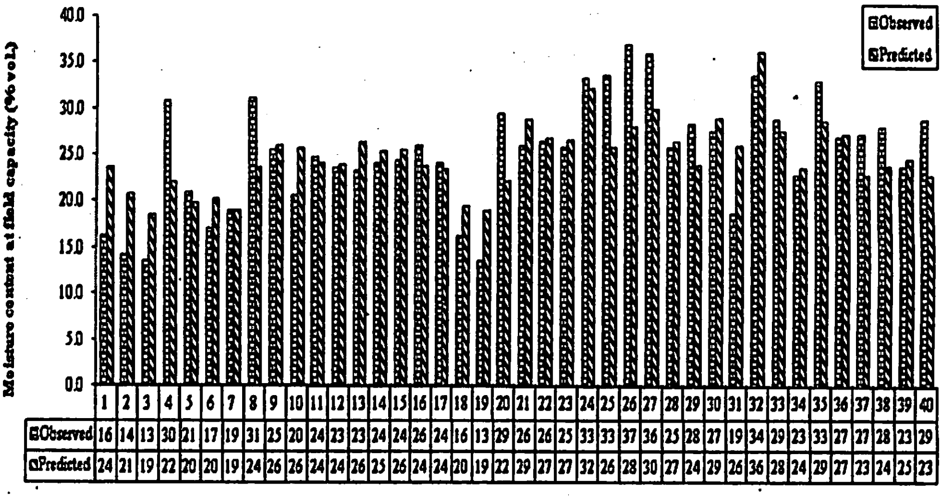
3.1 Predicted versus observed soil moisture contents at saturation, field capacity and wilting point

Figure 2 shows the predicted and observed volumetric soil moisture content at saturation. The predicted data ranged from 37.4% to 56.2 % with a mean value of 44.2%, while the observed data ranged from 37.9% to 76.8 % with a mean value of 54.3%. The mean error of bias between the predicted and observed values was -10.17 %. Figure 3 and 4 show the predicted and observed volumetric moisture content at field capacity (FC) and wilting point (WP), respectively. The predicted moisture content at FC ranged from 18.5% to 36.2%, with a mean value of 24.9%, while the observed data ranged from 13.6% to 37.0% and a mean value of 25.3%. The mean error of bias between the predicted and observed moisture content at FC was -0.44%. The predicted moisture content at WP ranged from 7.7% to 23.9%, with a mean value of 11.6%, while the observed data ranged from 4.6% to 22.2%, with a mean value of 10.1%. The mean error of bias between the predicted and observed moisture content at WP was 1.49%.



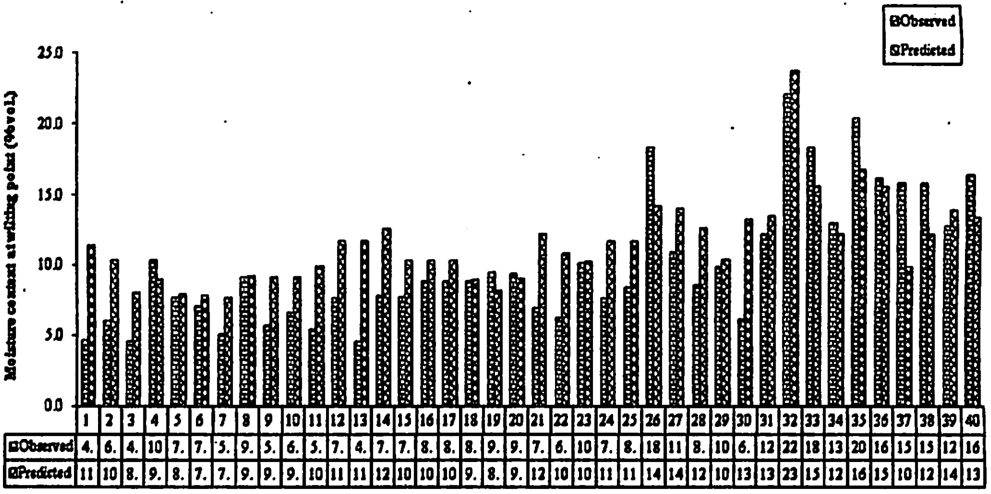
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
□Observed	50	51	61	63	53	54	53	64	43	46	63	63	56	59	52	68	76	52	53	57	53	61	54	50	59	70	45	52	57	50	53	54	53	64	43	46	40	37	39	42
▨Predicted	45	42	39	42	39	41	37	43	48	47	39	38	49	42	46	44	39	44	43	47	53	49	51	56	44	44	48	49	43	50	39	41	37	43	48	47	45	41	41	47

Figure2: Comparison of pedicted andobservedvolumetric soil moisture content at saturation



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
▨Observed	16	14	13	30	21	17	19	31	25	20	24	23	23	24	24	26	24	16	13	29	26	26	25	33	33	37	36	25	28	27	19	34	29	23	33	27	27	28	23	29
▨Predicted	24	21	19	22	20	20	19	24	26	26	24	24	26	25	26	24	24	20	19	22	29	27	27	32	26	28	30	27	24	29	26	36	28	24	29	27	23	24	25	23

Figure 3: Comparison of pedicted andobservedvolumetric soil moisture content at field capacity



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
▨Observed	4.	6.	4.	10	7.	7.	5.	9.	5.	6.	5.	7.	4.	7.	7.	8.	8.	8.	9.	9.	7.	6.	10	7.	8.	18	11	8.	10	6.	12	22	18	13	20	16	15	15	12	16
▨Predicted	11	10	8.	9.	8.	7.	7.	9.	9.	9.	10	11	11	12	10	10	10	9.	8.	9.	12	10	10	11	11	14	14	12	10	13	13	23	15	12	16	15	10	12	14	13

Figure4: Comparison of pedicted andobservedvolumetric soil moisture content at wilting point

Table 2 shows the statistical indices of the comparison between the model predicted and laboratory observed values of soil moisture status at saturation, field capacity and wilting point. The root mean square errors (RMSE) of the FC and WP data were lower than that of S, being 4.37 %, 3.45%, and 14.75%, respectively. RMSE should tend towards zero as the measure of precision between the predicted and measured data increases. The results imply that the degree of precision of the model predictions of moisture content at saturation were less than that of field capacity and wilting point. The coefficient of variability (CV) of the predicted and observed moisture contents at saturation, field capacity and wilting point can be said to be moderate based on Wilding (1985) classification. Wilding (1985) classified coefficient of variability of soil parameters of: <15 % as low, 15< CV< 30 % as moderate, and >30 % as high. The results indicate that the predicted moisture contents at wilting point were highly dispersed from observed data as compared to the other two parameters. The modelling efficiency which is a measure of the degree of fit or closeness of the predicted data to the observed values showed that the S and FC data had higher degree of fit than WP, being 0.85, 0.86 and 0.74, respectively. However, the coefficient of residual mass (CRM) revealed that the model under-predicted moisture content at field capacity by 0.02 (i.e., 2%) while it over-predicted moisture content at wilting point by 15 %. It also under-predicted moisture content at saturation by 19 %. The results imply that the SWC-HPC model satisfactorily predicted soil moisture status of the fields studied at field capacity and moderately at saturation and wilting point.

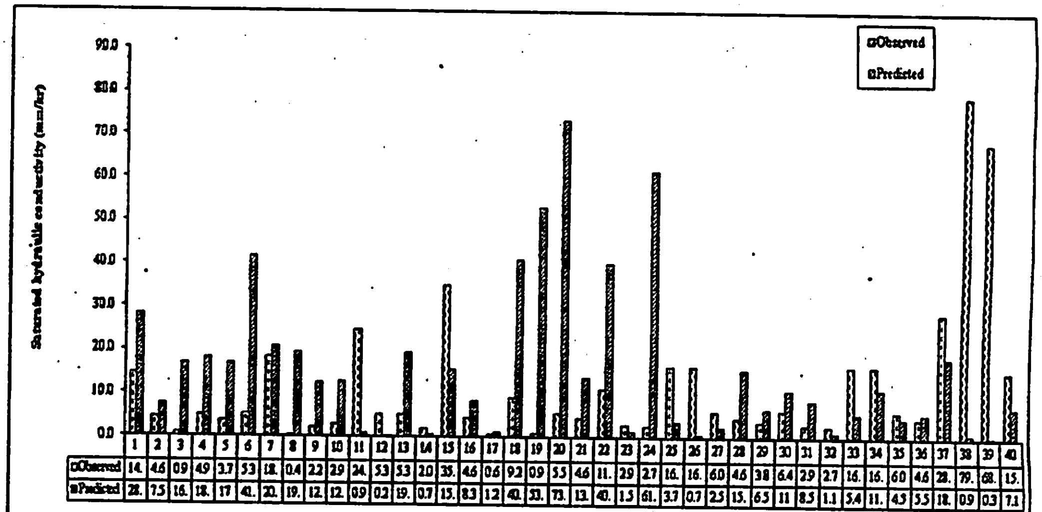
Table 2: Statistical indices of the comparison of predicted and observed soil moisture status at saturation, field capacity and wilting point for the study location

Statistical indices	Saturation	Field capacity	Wilting point
RMSE	14.76	4.37	3.45
CV (%)	27.12	17.25	34.32
EF	0.85	0.86	0.74
CRM	0.19	0.02	-0.15

3.2 Predicted versus observed saturated hydraulic conductivity and bulk density

Figures 5 and 6 show the predicted and observed values of saturated hydraulic conductivity and soil bulk density, respectively. The predicted saturated hydraulic conductivity ranged from 0.2 to 73.2 mm/hr with a mean value of 15.8 mm/hr, while the observed data ranged from 0.4 to 15.3 mm/hr with a mean value of 15.2 mm/hr. The mean error of bias between the predicted and observed data was 0.63 mm/hr. The model's predicted bulk density values ranged from 1.2 g/cm^3 to 1.61 g/cm^3 with a mean value of 1.45 g/cm^3 while the observed data ranged from 1.25 g/cm^3 to1.66 g/cm^3 with a mean value of 1.47 g/cm^3. The mean error of bias between the predicted and observed moisture bulk density was -0.01 g/cm^3.

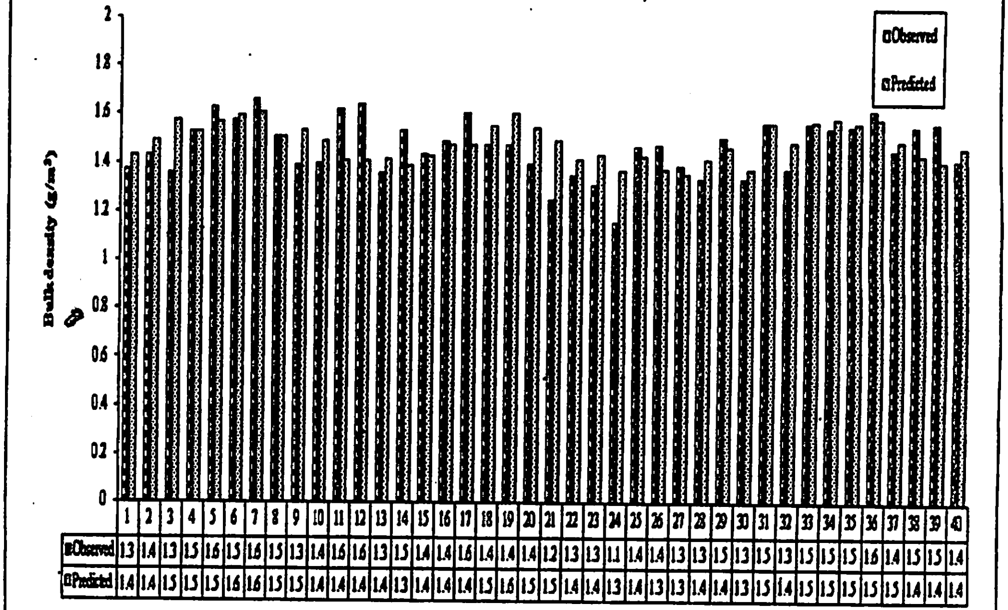
Table 3 shows further statistical indices of the comparison between predicted and observed values of saturated hydraulic conductivity and bulk density. The level of precision between predicted and observed values of saturated hydraulic conductivity was very low; the CV was over 100 % and the modelling efficiency was less than zero (-0.65). Modelling efficiency less than zero means that the mean of the observed data is a better predictor than the model. This implies that the SWC-HPC model poorly predicted the saturated hydraulic conductivity of the field studied. However, the model was found to accurately predict the soil bulk densities.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
□Observed	14.	4.6	0.9	4.9	3.7	5.3	18.	0.4	2.2	2.9	24.	5.3	5.3	2.0	35.	4.6	0.6	9.2	0.9	5.5
▨Predicted	28.	7.5	16.	18.	17	41.	20.	19.	12.	12.	0.9	0.2	19.	0.7	15.	8.3	1.2	40.	53.	73.

	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
□Observed	4.6	11.	2.9	2.7	16.	16.	6.0	4.6	3.8	6.4	2.9	2.7	16.	16.	6.0	4.6	28.	79.	68.	15.
▨Predicted	13.	40.	1.5	61.	3.7	0.7	2.5	15.	6.5	11	8.5	1.1	5.4	11.	4.3	5.5	18.	0.9	0.3	7.1

Figure5: Comparison of predicted and labatory observed saturated hydraulic conductivity



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
▨Observed	1.3	1.4	1.3	1.5	1.6	1.5	1.6	1.5	1.3	1.4	1.6	1.6	1.3	1.5	1.4	1.4	1.6	1.4	1.4	1.4
□Predicted	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.5	1.5	1.4	1.4	1.4	1.4	1.3	1.4	1.4	1.4	1.5	1.6	1.5

	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
▨Observed	1.2	1.3	1.3	1.1	1.4	1.4	1.3	1.3	1.5	1.3	1.5	1.3	1.5	1.5	1.5	1.6	1.4	1.5	1.5	1.4
□Predicted	1.5	1.4	1.4	1.3	1.4	1.3	1.3	1.4	1.4	1.3	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4

Figure 6: Comparison of predicted and laboratory observed soil bulk density

The RMSE was 0.08, while the level of dispersion between predicted and observed data measured by the CV was only about 6 %. The modelling efficiency was very high (EF= 0.98) and the magnitude of under-prediction indicated by the CRM was less than 1 %.

Table 3: Statistical indices of the comparison of predicted and observed saturated hydraulic conductivity and bulk density

Statistical indices	Saturated hydraulic conductivity	Bulk density
RMSE	35.21	0.08
CV (%)	232.91	5.75
EF	-0.65	0.98
CRM	-0.04	0.003

4.0 CONCLUSIONS

The performance of Soil Water Characteristics-Hydraulic Properties Calculator (SWC-HPC) model in predicting soil water characteristics from particle size distribution was evaluated for soils from selected sites in Zaria, Nigeria. The model was found to accurately simulate bulk densities of the soils tested, satisfactorily simulated soil moisture content at field capacity, moderately simulated moisture contents at saturation and wilting point, and poorly simulated saturated hydraulic conductivity. These levels of performances may be improved upon if information on the salinity and degree of compaction of the soils is available. The SWC-HPC may be use to simulate soil bulk densities and moisture status at saturation, field capacity and wilting point in the study locations.

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