Spatial analysis of soil hydraulic properties of an alfisol in Akure, Southwestern Nigeria

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Abstract: The knowledge of soil hydraulic properties and processes leads to better predictions of both agricultural and environment impact. The objectives of this research are to determine, predict and compare the relationship between measured and estimated soil hydraulic properties and also spatially characterize these properties using geostatistics. Mini disc infiltrometer at a suction rate of 2 cm per second was used for the determination of soil hydraulic properties at different points of an alfisol in Nigeria. Soil samples (100, 200 and 300 mm depths) were also analyzed to determine soil bulk density (BD), total porosity (PT) and water holding capacity (WHC). The coefficients of variation (CV) of the textural classes indicate a non-considerable variability of the sand (CV=6%), silt (CV=20%) and clay (CV=3%) contents. From the statistical and spatial analysis for the different parameters, the variability of hydraulic conductivity (48%>33%>31%), cumulative infiltration (40%>26%>23%), soil water sorptivity (19%>11%>8%), followed the trend upper soil layer (0–100 mm) > middle (100–200 mm) > lower (200–300 mm) soil layers. Hydraulic conductivity and infiltration were more pronounced in soils with higher organic matter content (OMC) and PT. Pedotransfer models (PTF) for prediction of hydraulic conductivity (K), soil water sorptivity (Sw) and cumulative infiltration (I) from basic soil properties such as OMC, PT were developed and validated using multiple-linear regression method. K, Sw and I predicted by the PTF models were significant for the upper and middle soil layers respectively (r = 0.812 and 0.670; 0.825 and 0.670, and 0.820 and 0.670). Contour and wireframe representation were used to spatially analyze the soil hydraulic properties across the field. These contour and 3D surface plots are useful for establishing farm operating conditions, especially in water, fertilizers or pesticides management.

Keywords: sorptivity, cumulative infiltration, hydraulic conductivity, soil water movement, total porosity

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1 Introduction

Soil scientists have been concerned about spatial variation of soil properties for many years (Sepaskhah et al., 2005). The variability in soil properties in any landscape is an inherent natural phenomenon conditioned by geological and pedological settings even within short distances (Warrick et al., 1986). Spatial variability of these soil properties has appreciable effects on the infiltration process and its related parameters (Vogelmann et al., 2010). In agricultural lands, variability of soil texture, soil structure and other physical and chemical properties has been reported (Olorunfemi and Fasinmirin, 2011). Different studies have exhibited different spatial correlation structures for soil hydraulic properties such as saturated/unsaturated hydraulic conductivity, saturated and residual soil water content, sorptivity, and pore-size distribution parameter (Mohanty et al., 1994). The characterization of the spatial variability of soil attributes is essential to achieve a better understanding of complex relations between soil properties and environmental factors (Goovaerts, 1998). Also, useful estimates of attributes at unsampled locations, leading to better recommendations for the application of water, plant nutrients, fertilizers or pesticides can be achieved from the modeling of spatial dependence between soil data (Goovaerts, 1998).

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Hydraulic properties depend on the intrinsic permeability of the material and on the degree of saturation (the initial water content) (Chong and Green, 1979), the type of soil, porosity and the configuration of the soil pores (Olorunfemi and Fasinmirin, 2011). Soil infiltration is directly related to structural stability (Tisdall and Adem, 1986), bulk density (Patel and Singh, 1981) and pore structure (Ankeny et al., 1990). The infiltration process is a component in the overall unsaturated redistribution process that results in soil moisture availability for use by vegetation transpiration, evaporation, chemical transport and groundwater recharge (Houser, 2003). Measurement of hydraulic properties is very challenging considering that the parameters can differ over several orders of magnitude across the spectrum of sediments and rock types (Brassington, 1988). These properties vary widely in space (spatial variability) due to the fact that they depends on soil texture and structure (Bagarello and Sgroi, 2007) which is a function of the land use pattern and also vary in time (temporal variability) due to land use, dynamics of plant canopy and roots, tillage operations, activity of soil organisms (Fuentes et al., 2004). Since hydraulic properties are determined essentially at points in the field, a large number of determinations are required to assess the magnitude and structure of the variation within the selected area (e.g., Logsdon and Jaynes, 1996). Therefore, large numbers of measurement of hydraulic properties have to be repeated at different times for understanding and modeling hydrological phenomena at the field scale (Bagarello and Sgroi, 2007).

The assessment of the hydraulic properties of soil, such as hydraulic conductivity (K), infiltration (I) and soil water sorptivity (Sw) is an important component for the interpretation of the soil physical characteristics, and for the agricultural management practices (Green et al., 2003) and for useful estimates of attributes at unsampled locations. The non-availability of these hydraulic properties for most soils is the hindrance to be overcome for general application of numerical models (Simunek et al., 1998). Goovaerts (1997); Webster and Oliver (2001) and Moradi et al. (2012) have all extensively used geostatistics to quantify the spatial pattern of soil physico-chemical and environmental variables. Spatial analysis has been used to predict soil properties to better understand their spatial variability pattern over small to large spatial scale on the field (Lark, 2002). The study is being carried out to spatially analyze soil infiltration and hydraulic conductivity using geostatistics to be able to design field-specific applications like variable rate irrigation, seed rate, and fertilizer rate and predict attributes of soils of similar geological substrate, type and climatic conditions.

The study aimed to characterize the spatial variability of the soil infiltration, soil water sorptivity and unsaturated hydraulic conductivity of an alfisol and establishes correlations between different soil parameters in Akure, South Western Nigeria.

2 Materials and methods

2.1 Area description

The research was conducted between June and September, 2014 at the Research and Training Farm of the Federal University of Technology, Akure, Ondo State, Nigeria (7°14’ N and 5°08’ E, 351 m above the sea level). Akure lies in the rain forest zone of Nigeria with a mean annual rainfall of between 1300-1600 mm and with an average temperature of 27°C. The relative humidity ranges between 85% and 100% during the rainy season and less than 60% during the dry season period. Akure has a land area of about 2,303 km^2 and is situated in the western upland area within the humid region of Nigeria (Fasinmirin and Adesigbin, 2012). Other hill-like structures which are less prominent rise only a few hundred meters above the general elevation (Fasinminrin and Konyeha, 2009). The pattern of rainfall is bimodal, the first peak occurring in June-July, and the second in September with a little dry spell in August. The soil of the site is predominantly sandy clay loam and belongs to the Alfisol (Soil Survey Staff, 1999). Alfisols are a soil order in USDA soil taxonomy (Soil Survey Staff, 1999). Alfisols are a form in semiarid to humid areas, typically under a hardwood forest cover. They have a clay enriched subsoil and relatively high native fertility. Because of their productivity and abundance, the Alfisols represent one of the more important soil orders for food and fiber production (Soil Survey Staff, 1999).

2.2 Field experimentation and soil sampling

Field experiments were conducted in 77 plots to determine the unsaturated hydraulic conductivity, soil water sorptivity and cumulative infiltration (Figure 1). In this study, soil samples were collected from 0 to 300 mm depth in 77 sampled points using soil cores with 60 × 100 m plot (6 × 10 m grid) over a field measuring 0.4 × 0.7 km^2. Three soil layers were selected which are upper soil layer (0-100 mm), middle soil layer (100-200 mm) and lower soil layer (200-300 mm). The samples were packed in plastic bags, and transferred to the laboratory. The samples were allowed to dry in the open air until reaching friability. Soil physical properties such as bulk density, total porosity and water holding capacity were also determined.

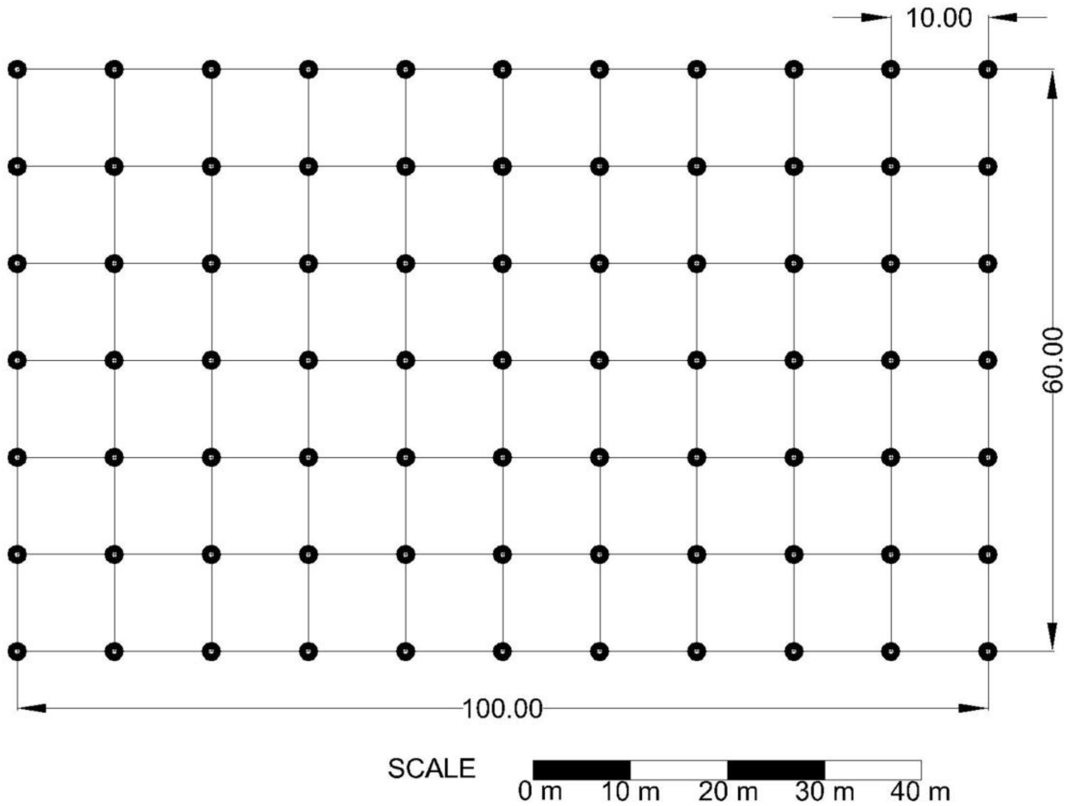


Figure 1 Experimental layout of the field experiment

2.2.1 Mini disk infitrometer

The minidisk infiltrometer (model S; *Decagon Devices*, Pullman, WA, USA) is a hand-held field instrument for assessing soil infiltration capacity. It was used to measure the soil unsaturated hydraulic conductivity, water sorptivity and cumulative infiltration of the experimental field. The infiltrometer has two chambers: upper and lower chambers. The upper chamber (or bubble chamber) controls the suction. The lower chamber contains a volume of water that infiltrates into the soil at a rate determined by the suction selected in the bubble chamber. Suction rate of 2 cm per seconds was chosen at different points on the field for the infiltration measurement. The suction rate was chosen to better accommodate the measurement of infiltration for the soil type of the experimental area (Decagon Devices, 2011).

The hydraulic conductivity of soil was calculated using the method of Zhang (1997). The method requires measuring cumulative infiltration (I) vs. time (t) and fitting the results with the infiltration function

$$I = C_1 t + C_2\sqrt{t} \quad (1)$$

Where C_1 (mm/hr) is an empirical constant related to hydraulic conductivity, and C_2 (mm/hr$^{1/2}$) is the soil sorptivity.

The hydraulic conductivity of the soil (K) was then computed using the relationship in Equation 2 (Decagon Devices, 2011):

$$K = \frac{C_1}{A} \quad (2)$$

Where C_1 is the slope of the curve of the cumulative infiltration vs. the square root of time, and A is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius (1.55 cm) of the infiltrometer disk.

2.2.2 Bulk density and porosity

Soil bulk density was determined using the method described by Blake and Hartge (1986). The soil samples were collected in segments at depths 0-100 mm, 100-200 mm, and 200-300 mm from all the plots in the experimental field using 100 mm tall and 50 mm inner diameter ring cylinders. The soil sample volume was established to be the same as the volume of the sampler holder. Based on the gravimetric soil core method, the soil samples were taken to the laboratory, oven-dried at 110 ℃, and weighed (Agbede and Ojeniyi, 2009).

The total porosity was calculated from BD and PD using the equation and relationship developed by Danielson and Sutherland (1986).

$$PT = 1 - \frac{BD}{PD} \quad (3)$$

Where: BD = Bulk density and PD = Particle density (= 2.65 Mg/m^3). The default value of 2.65 Mg/m^3 is used as a rule of thumb based on the average bulk density of rock with no pore space (Fasinmirin and Olorunfemi, 2013).

2.2.3 Soil physical and chemical properties

Samples were tested for physical properties (BD, PT, and soil particle size distribution) and chemical properties of the soil (OMC). The OMC was determined using the Walkley-Black wet oxidation procedure (Nelson and Sommers, 1996). Soil particle sizes were determined using the hydrometer method described in Agbede and Ojeniyi (2009). Textural classification was carried out using the USDA classification system (Soil Survey Staff, 1999). The BD will be obtained by the gravimetric soil core method described by Blake and Hertage (1986). WHC was determined following the method described by Ibitoye (2006).

2.3 Data analysis

The slope of the curve of the cumulative infiltration vs. the square root of time was determined using a Basic Microsoft Excel spreadsheet macro created by Decagon (Decagon Devices, 2011). Descriptive statistics such as minimum and maximum value, averages, standard deviation (StDev), coefficient of variation (CV), skewness and kurtosis were calculated. The spatial variability (contour map and 3D wireframe) of soil properties, particularly hydraulic conductivity, soil water sorptivity and cumulative infiltration, were generated using Minitab 17 statistical software (Minitab Inc., Philadelphia, PA, USA) and Surfer 11 (Golden Software, Golden, CO, USA), respectively. The contour plot shows the variation of the data of the experimental field while the wireframe representation shows the operating conditions in which x–, y–, and z–axes represent longitude, latitude, and elevation. A one-way ANOVA was performed to compare soil properties for the different soil depths using Tukey mean comparison test using 5% of significance ($p \leq 0.05$). Due to the non normality of the K, Sw and I data distribution at the upper soil layer, the Box-Cox transformation procedure for correcting non normality in data was used to select the optimal transformation. The best transformation in a practical sense would be to use the rounded estimate of for K, Sw and I data (Minitab, 2013). Regression and correlation analyses were used to test the relationship between dependence of unsaturated K, Sw and I on BD, PT and OMC. To evaluate PTF performance, predicted

K, Sw and I values were statistically compared to those measured by the mini disk infiltrometer (MDI).

3 Results and discussion

3.1 Physical and chemical properties of experimental field

3.1.1 Soil textural classification

The soils of the experimental site were predominantly Sandy Clay Loam according to USDA soil textural classification (Soil Survey Staff, 1999). The descriptive statistics of particle size distribution of the site indicate that the soils generally have an average sand content of 51.13% ± 3.20% (Table 1). The CV of the sand fractions is 6%. The silt content is 18.33% ± 3.67% on average, with the larger CV (20%). The average clay content is 30.53% ± 1.03%, having a CV of 3%. The CV of the textural classes indicates a non-considerable variability.

Table 1 Descriptive statistics of particle size distribution of the experimental site

Statistics/Variables	Sand, %	Clay, %	Silt, %
Min	48.8	29.2	12
Max	56.8	31.2	22
Mean	51.13	30.53	18.33
Median	49.8	31.2	20
StDev	3.20	1.03	3.67
CV	6.00	3.00	20.0
Skewness	1.35	-0.97	-1.24
Kurtosis	1.24	-1.88	0.86

3.1.2 Soil physico-chemical properties of experimental field

Bulk density increased significantly with depth from about 1.32 Mg/m^3 to 1.53 Mg/m^3 in the top 100 mm depth to 1.61 Mg/m^3 in the 300 mm depth ($p \leq 0.001$) (Table 2). As expected, mean PT (0.46>0.45>0.43 m^3/m^3) also significantly decreased with soil depth ($p \leq 0.001$) (Table 2). The general trend of increase in BD observed in the soil layers is in conformation with Vereecken et al. (1989) and Adeyemo and Agele (2011). The increase down the soil profile is probably due to changes in soil texture, gravel content, and structure (Landsberg et al., 2003) but also because of biological activity on surface soils with high organic matter content which decreases across the soil profile (Doerr et al., 2000). This is also expected because of the overburden weight of soil above the depth of measurement (Sands et al., 1979). Total porosity as expected showed inverse relationship to the bulk density of the experimental site (Table 2). This observation agrees with the works of Vogelmann et al. (2010) and Olorunfemi and Fasinmirin (2012). Meanwhile, values for the BD at the experimental field are similar to those reported by Adekiya et al. (2011), and Fasinmirin and Olorunfemi (2013). There was no significant difference in the mean values of WHC down the soil layers but there was a slight increase in the mean WHC with depth (Table 2). The maximum value of 54.26% was observed in the upper soil layer. WHC of any soil is predominantly dependent on it texture and structure, and the OMC. The soil water storage capacity knowledge is an important water management tool since it allows the determination of how much water to apply at one time and how long to wait between each irrigation schedule. Mean values of OMC among upper (Mean=1.77%), middle (Mean=1.39%) and lower (Mean=1.05%) soil layers were statiscally significant ($F(2, 117) = 23.03$, $p \leq 0.001$) which may be due to the decline in microbial activities down the soil.

Skewness coefficients of BD demonstrate that depths (100 and 300 mm) are asymmetrically distributed whereas skewness coefficient for 200 mm depth with values 0.60 showed that the distribution is moderately skewed and can also be seen in the frequency distribution curves (Figure 2, first column). Meanwhile, kurtosis coefficients for all the depths indicate a platykurtic behavior in their distribution. Skewness coefficients of the PT at depths 100, 200 and 300 mm with values –0.23, –0.49 and –0.41 showed that the distribution is approximately symmetric (Figure 2, second column). The values of the coefficient of Kurtosis for the different soil layers also indicated a platykurtic behavior in their distribution characterized by negative values as obtained in 100, 200 and 300 mm with values –0.48, –0.42 and –0.28. The distributions of the average WHC of the study area at 100 and 300 mm are approximately symmetric while a moderately skewed distribution occurred at 200 mm depth (Figure 2, fourth column). Skewness and kurtosis reveal the direction of variation of the data set. It also informs about the normality of the data set. Shapiro–Wilk normality test and frequency distribution curves (Figure 2) indicate that the soil physic-chemical properties at upper, middle and lower soil layers (100, 200 and 300 mm) shows that there is not enough evidence to suggest that the data do not follow a normal distribution at $p<0.05$ except for total porosity at the middle soil layer with very slight deviation from normality.

Table 2 Descriptive statistics of bulk density (BD), total porosity (PT), water holding capacity (WHC) and organic matter content (OMC) of the experimental field

Variables/Statistics	BD, Mg/m^3			PT, m^3/m^3			WHC, %			OMC, %		
Depths, mm	100	200	300	100	200	300	100	200	300	100	200	300
Min.	1.32	1.38	1.42	0.42	0.41	0.39	31.7	28.94	34.8	0.85	0.67	0.42
Max.	1.53	1.57	1.61	0.5	0.48	0.47	54.26	53.72	54	2.94	2.18	1.97
Mean	1.42	1.46	1.50	0.46	0.45	0.43	43.27	44.10	46.09	1.77	1.39	1.05
Median	1.42	1.45	1.50	0.47	0.45	0.44	43.62	44.95	46.38	1.74	1.31	0.96
StDev	0.06	0.05	0.05	0.02	0.02	0.02	5.66	5.83	5.27	0.58	0.45	0.37
CV	0.04	0.04	0.03	0.05	0.04	0.04	0.13	0.13	0.11	0.33	0.33	0.35
Skewness	0.27	0.60	0.38	-0.23	-0.49	-0.41	-0.13	-0.53	-0.47	0.21	0.23	0.50
Kurtosis	-0.59	-0.24	-0.52	-0.48	-0.42	-0.28	-0.64	-0.14	-0.24	-0.68	-0.91	-0.06
Shapiro-Wilk p-value	0.31	0.05	0.29	0.09	0.03	0.13	0.83	0.36	0.10	0.27	0.10	0.34

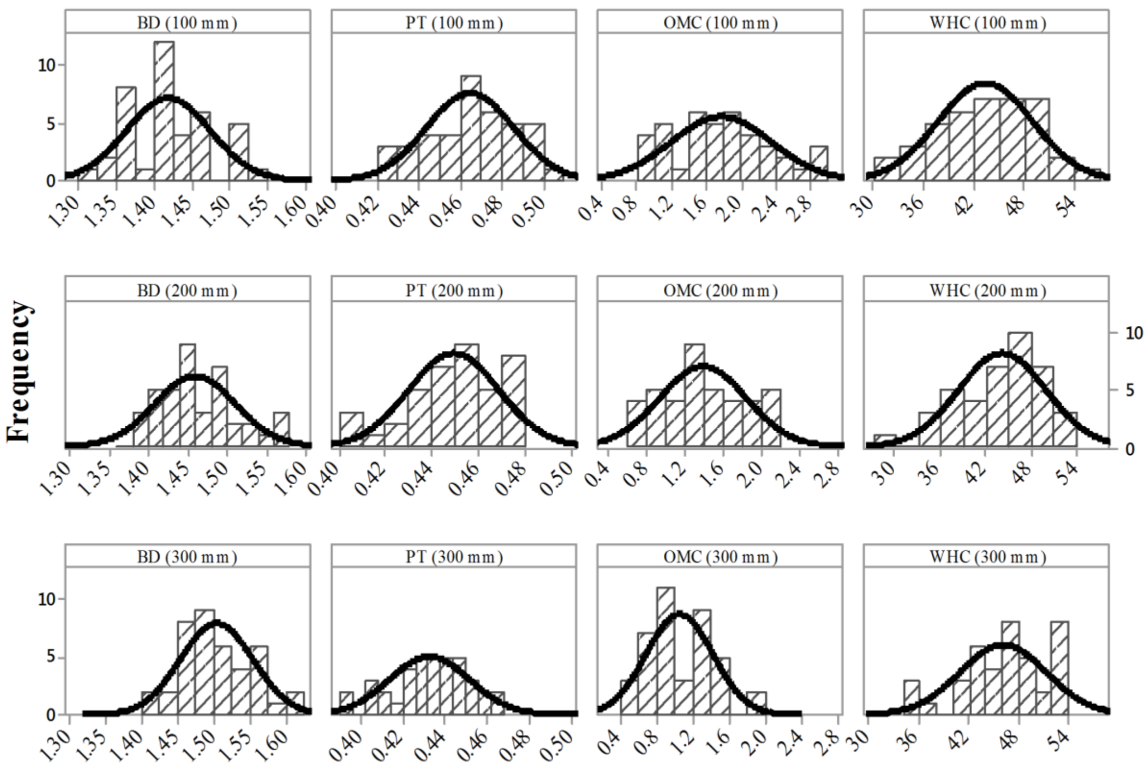


Figure 2 Histogram with normal curve of bulk density (Mg/m^3), total porosity (m^3/m^3), water holding capacity (%) and soil organic matter (%) of the experimental field at 100, 200 and 300 mm depths respectively

3.2 Spatial correlation and dependence of soil properties

At the upper soil layer, K and I correlated positively with OMC (r=0.748) and negatively with BD (r=–0.713) at $p \le 0.01$ in the upper soil layers. Similarly K and I display postive relationship with OMC (r=0.489) but correlated negatively with BD (r=–0.666) in middle soil layer ($p \le 0.01$) but showed no significant correlation with both OMC and BD in the lower layer of the experimental field ($p > 0.05$). Such correlations have been observed in other studies leading to the development of pedotransfer models (Fasinmirin and Olorunfemi, 2011; Olorunfemi, 2014). Likewise, increased in soil OMC increases the PT (r=0.633; r=0.501) and decreases the BD (r=-0.633; r =-0.501) at the upper and middle layer respectively ($p \le 0.01$). This conform with the fact that OMC stabilizes and holds soil particles together as aggregates, helping soil to resist compaction and promotings water infiltration and hydraulic conductivity (FAO, 2005).

Correlation analysis revealed that dry BD and OMC accounted for the spatial variability of unsaturated K, Sw and I (Figure 3). Increase in BD and a decrease in total pore space, significantly influences soil hydraulic properties (pore size distribution, water retention and hydraulic conductivity) (Lujan, 2003). Generally a soil with larger pores has a greater hydraulic conductivity than a soil with smaller pores (Hallet, 2007). Logsdon and Jaynes (1996) stated that unsaturated K variability reflected the evolution in micropores with tillage. They attributed this phenomenon to the influence of macropores, which were unstable due to tillage, shrink-swell phenomena, and root activities (Das Gupta et al., 2006). Changes in BD result in changes of porosity, pore-size distribution, pore continuity, infiltration rate, water retention and soil temperature (Mapa et al., 1986). Generally, K was more pronounced in soils with higher OMC in conformation according to Fasinmirin and Olorunfemi (2012). The contour plot (Figure 3a) shows that the highest K values were found at the lower right hand corner with an average BD less than 1.35 mg/m^3 and near an average OMC of 2.8% while the least K values were found at the upper left hand side with an average BD of 1.45 mg/m^3 and above. Also, the highest Sw and I were found at the lower right hand corner while the least values were found at the upper left hand side of the plot (Figure 3b). This shows that increasing BD lowers the soil pores and in consequence reduces the soil K in that part of the experimental field. Different studies have exhibited different spatial correlation structures for soil hydraulic properties such as saturated/unsaturated K, Sw, and pore-size distribution parameter (Mohanty et al., 1994). All of these earlier studies indicated the importance and the need for proper characterization of the spatial variability of soil parameters. Increase in K and I is due primarily to more and better connected soil pores as influnced by the soil OMC while the increase in BD either from soil compaction effect of tillage equipments or overburden stress caused reduction in water infiltration.

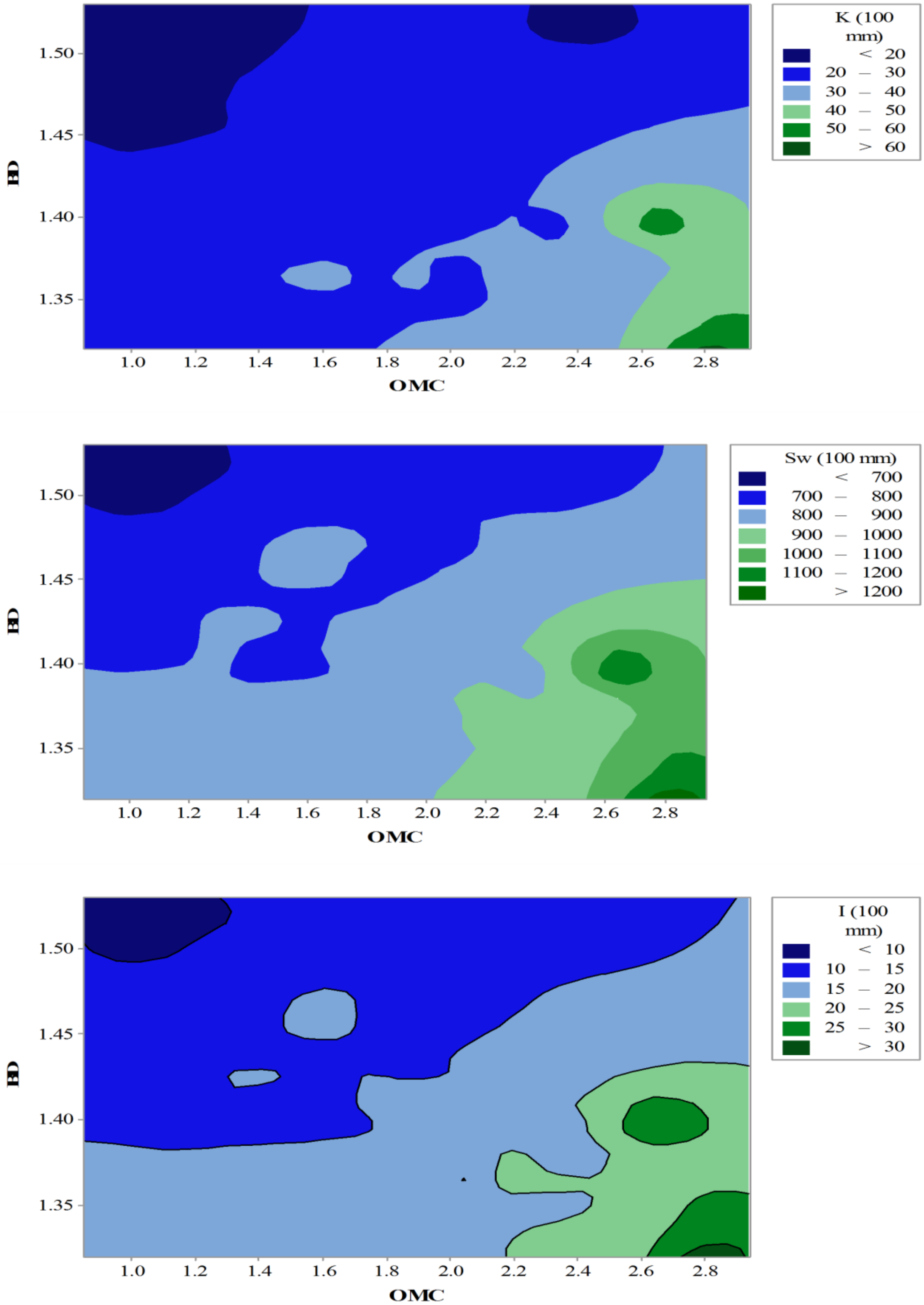


Figure 3 Contour plots of (a) hydraulic conductivity, (b) soil water sorptivity and (c) cumulative Infiltration vs. bulk density and organic matter content at the upper soil surface

3.3 Prediction of soil hydraulic properties using pedotransfer models

Pedotransfer models to predict soil hydraulic properties were developed regarding the results of correlation analysis. The existence of significant correlation between soil hydraulic and physico-chemical properties influenced the regression equations in terms of which predictor variables were included in the regression model. Models for unsaturated K, Sw and cumulative I were obtained using Regression Model (Table 3). Fitting regression models is a versatile tool for investigating relationships between a response variable and both categorical and continuous predictor variables. Pedotransfer models were obtained from the combination of PT and OMC. Comparison of measured vs predicted values of K and Sw is presented in Figures 4 and 5 repectively. These models may be adequate enough to predict K, Sw and cumulative I after necessary steps of model calibration, evaluation and testing are carried out. Several authors (Pachepsky et al., 1996; De Macedo et al., 2002; Gülser et al., 2007) have successfully predicted soil hydraulic properties through pedotransfer models. The knowledge of these soil hydraulic properties and processes leads to better predictions of both agricultural and environment processes.

Table 3 Pedotransfer models for soil hydraulic properties at 100 and 200 mm depths respectively

1)	$\ln K_{100\ mm} = -2.33 + 0.3195\ OMC + 10.69\ PT$	0.812**
2)	$K_{200\ mm} = -73.3 + 3.18\ OMC + 200.5\ PT$	0.670**
3)	$-Sw_{100\ mm} \wedge -2 = 0.000008 + 0.000001\ OMC + 0.000012\ PT$	0.825**
4)	$Sw_{200\ mm} = -393 + 39\ OMC + 2458\ PT$	0.670**
5)	$-I_{100\ mm} \wedge -0.5 = -0.860 + 0.03148\ OMC + 1.166\ PT$	0.820**
6)	$I_{200\ mm} = -33.6 + 1.57\ OMC + 99\ PT$	0.670**

Note: **significant at 1% probability level

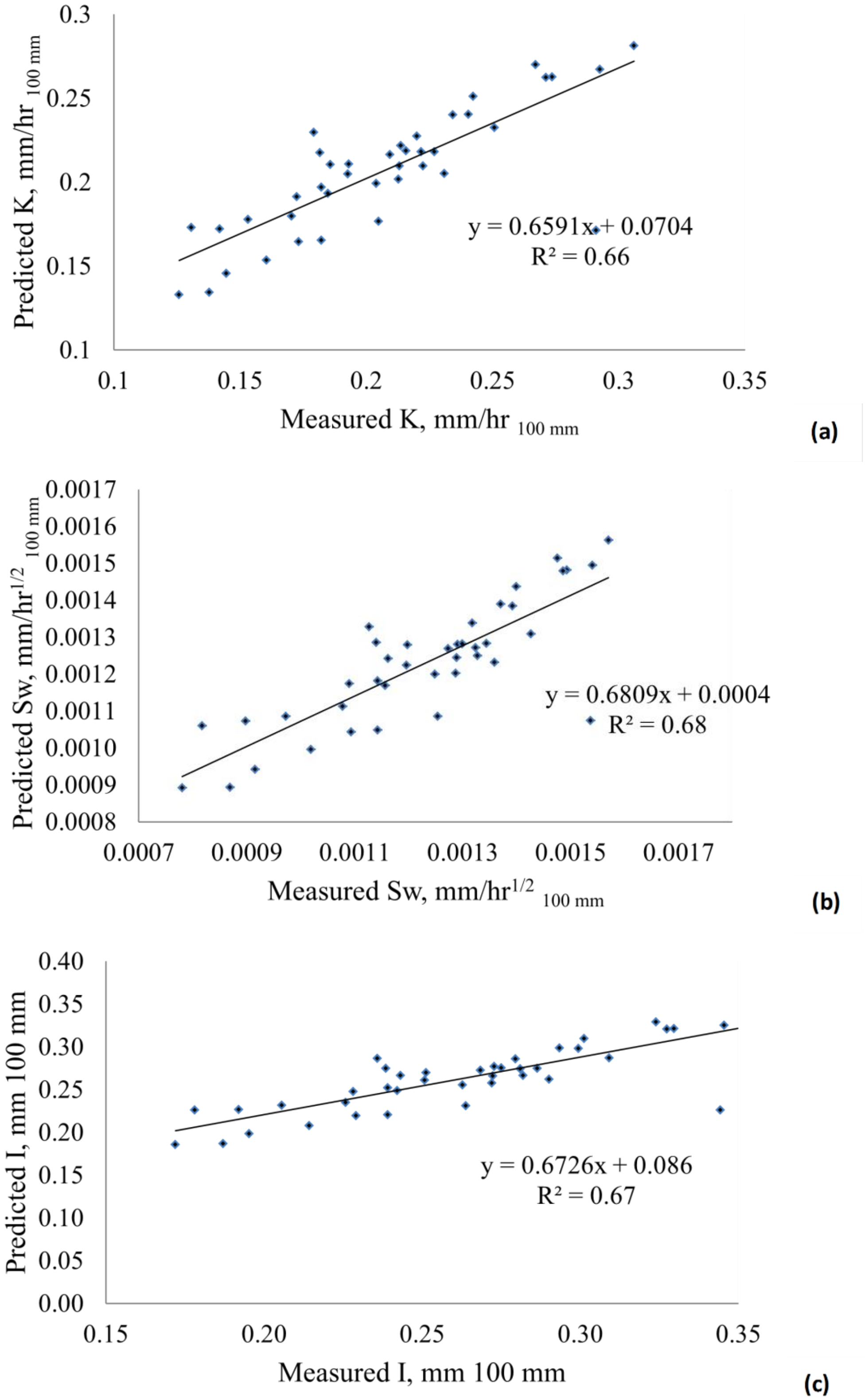


Figure 4 Relationships between measured (transformed response) and predicted soil hydraulic properties using pedotransfer function (a) models 1, (b) model 3 and (c) model 5

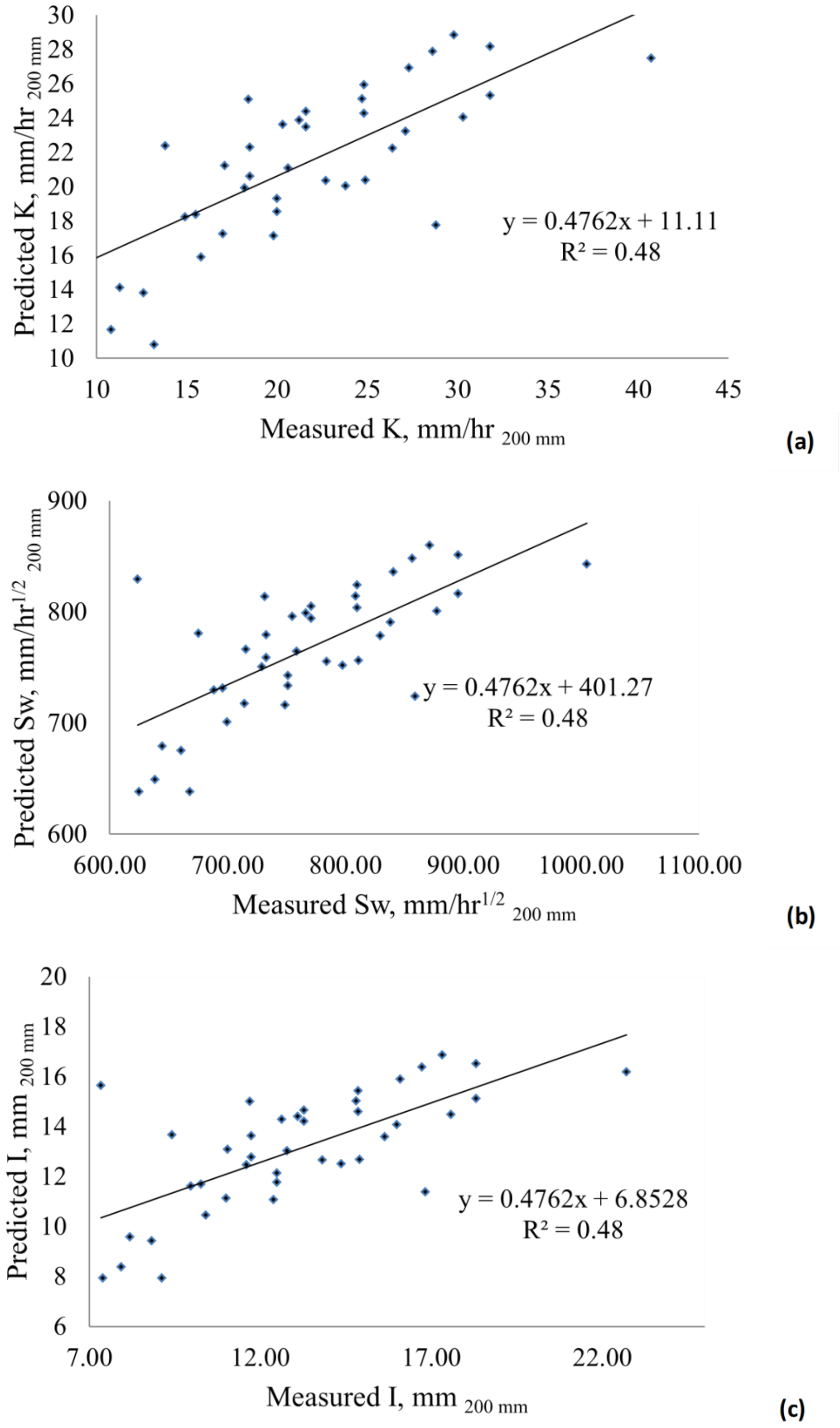


Figure 5 Relationships between measured and predicted soil hydraulic properties using pedotransfer function (a) models 2, (b) model 4 and (c) model 6

3.4 Hydraulic properties of the experimental field

The soil hydraulic properties data histogram with normal curve indicates that the data for the upper soil layer is bimodal (two lumps) while for the middle and lower soil layers, it is unimodal (one hump) (Figure 6). Skewness coefficient (Table 4) for the K, Sw and I data at the surface layer (100 mm depth) shows a highly skewed distribution and the data do not follow the normal curve as seen in the histogram (Figure 6). Further use of Shapiro–Wilk statistics with p = 0.002 shows that there is enough evidence to suggest that the data do not follow a normal distribution at 0.05 significant levels. Due to this observation, box–cox transformation procedure for correcting non-normality in data was used to select the optimal transformation values for the data. For the K, Sw and I data, the optimal values for λ are –0.15, –1.70 and –0.36 while the rounded values are 0.00, –0.20 and –0.50 respectively (Figure 7).

The histogram (with normal frequency superimposed) of the hydraulic properties distribution (Figure 6) in the middle and lower layers shows that the distribution does not deviate too severely from normality. For the middle and lower layers, the K, Sw and I data distribution shows a right-skewed distribution (Figure 6 and Table 4). The distributions at 200 and 300 mm are approximately symmetric and moderately skewed respectively. Skewness coefficients for the middle and lower layers demonstrate that Sw is asymmetrically distributed showing positive skewness. Meanwhile, kurtosis coefficients for upper, middle and lower layers indicate a platykurtic behavior in their distribution characterized by positive values. The Shapiro wilk p –value shows there is no significant difference in the K, Sw and I data distribution for the middle and lower soil depths respectively.

All the soil layers showed medium variability (10%-100%) except Sw at the lower layer (CV = 8 %), with the upper layer having the largest variability. Higher spread of soil hydraulic properties were observed in the upper soil surface (100 mm) followed by the 200 mm (middle) and 300 mm (lower) soil layers.

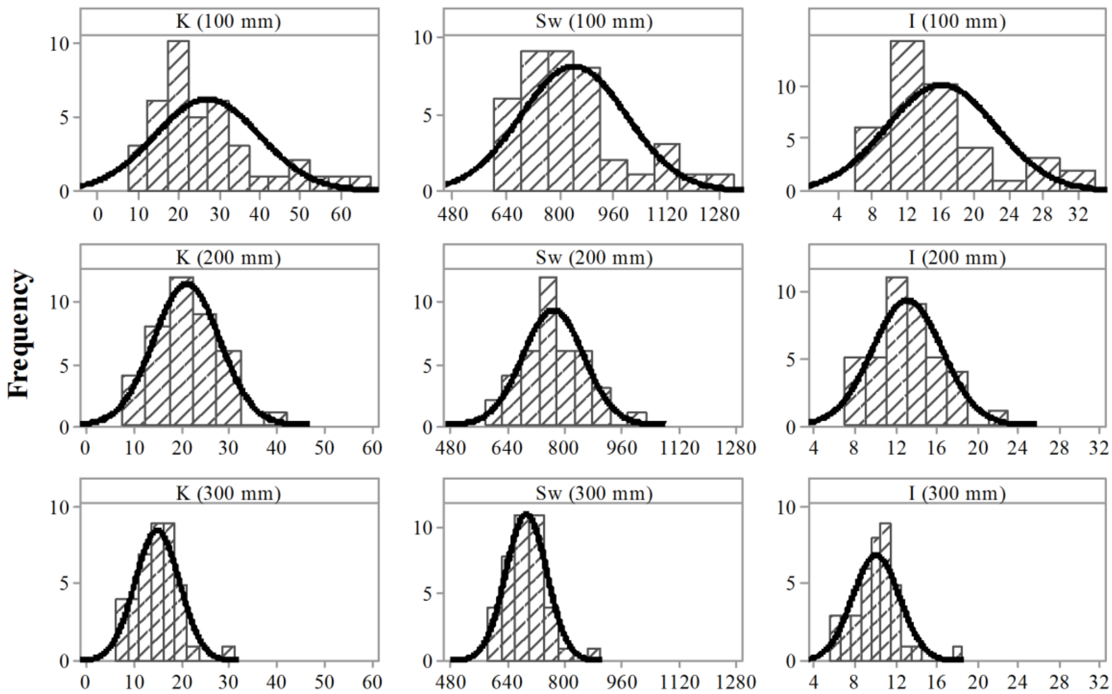
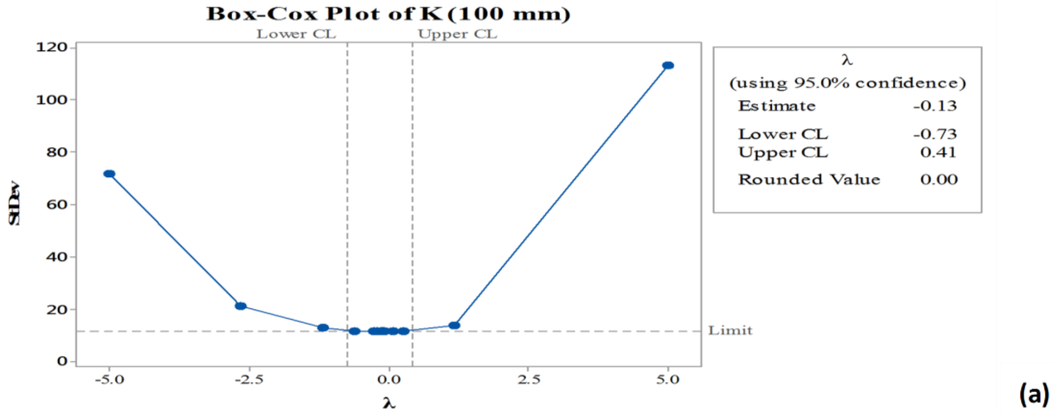
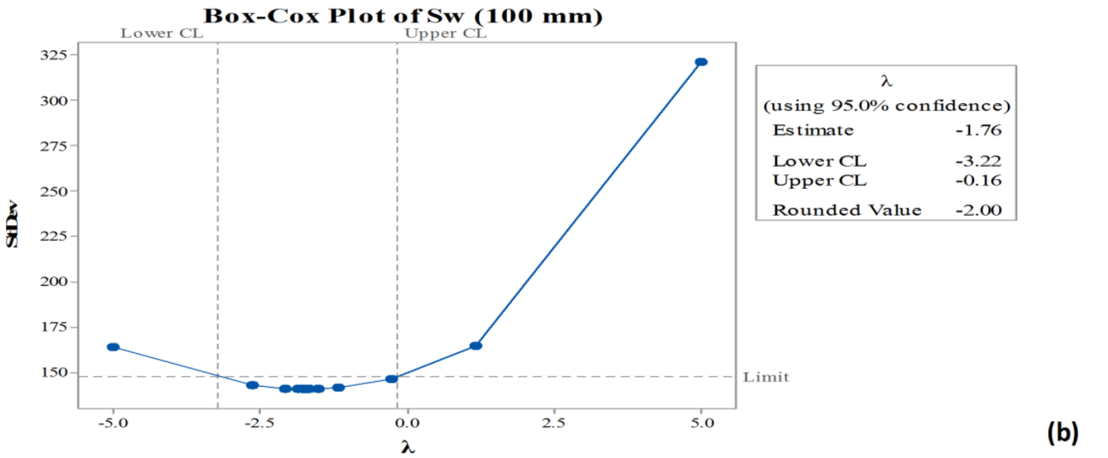


Figure 6 Histogram (with normal curve) of hydraulic conductivity, soil water sorptivity and cumulative infiltration at 100, 200 and 300 mm depths respectively

Table 4 Descriptive statistics of the hydraulic conductivity (K), soil water sorptivity (Sw) and cumulative infiltration (I) of the experimental field

Variables/Statistics	K, mm/hr			Sw, $mm/hr^{1/2}$			I, mm		
Depths, mm	100	200	300	100	200	300	100	200	300
Min.	10.67	9.60	6.80	636.90	623.70	589.37	7.88	7.35	5.97
Max.	63.18	40.70	31.00	1280.60	1005.00	886.06	33.81	22.71	17.92
Mean	27.23	21.21	15.00	839.78	766.01	689.95	16.05	13.08	10.02
Median	23.30	20.45	15.45	791.70	756.70	695.42	14.11	12.71	10.24
StDev	12.94	6.93	4.68	158.68	84.97	57.32	6.39	3.42	2.31
CV	48.00	33.00	31.00	19.00	11.00	8.00	40.00	26.00	23.00
Skewness	1.16	0.42	0.78	1.16	0.42	0.78	1.16	0.42	0.78
Kurtosis	0.92	0.21	2.32	0.92	0.21	2.32	0.92	0.20	2.32
Shapiro-Wilk p-value	0.002	0.570	0.068	0.002	0.570	0.068	0.002	0.568	0.068





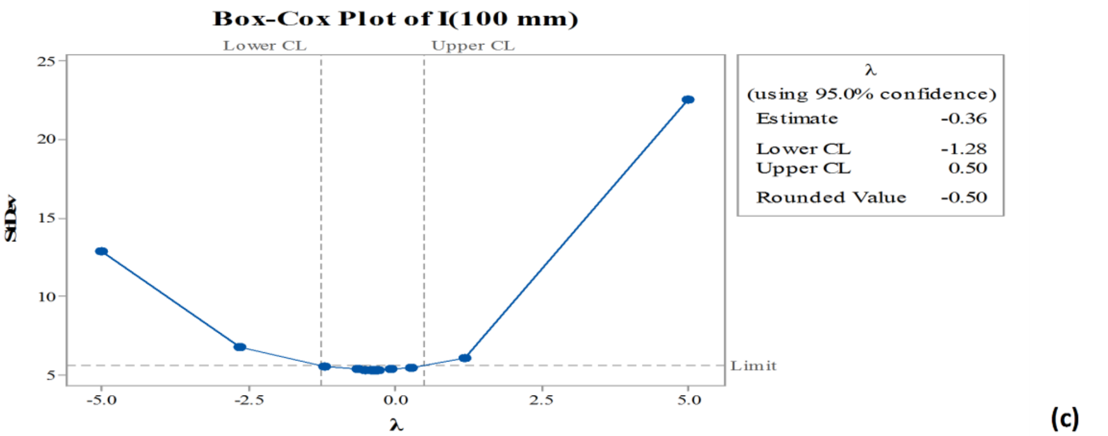


Figure 7 Box-Cox transformations of (a) hydraulic conductivity, (b) soil water sorptivity and (c) cumulative infiltration data at 100 mm soil layer showing the Confidence Limit (CL)

Hydraulic conductivity, soil water sorptivity and cumulative infiltration values are significantly different among the soil layers. The K, Sw and I data down the soil depths differs significantly among the three soil layers as is shown by the Tukey Confidence Intervals (CIs) for differences of means for between the depths for K, Sw and I respectively (Table 5 and Figure 8). In all cases, K, Sw and I data was significantly lower in the lower layer (300 mm) than in the middle layer (200 mm), and that of the middle layer (200 mm) was equally significantly lower than that of the upper layer (100 mm) respectively. Price et al. (2010) reported significant difference in the mean value of saturated K in their study. They discovered that the average K sat-L of the upper core was nearly twice as great as the lower core at p<0.001.

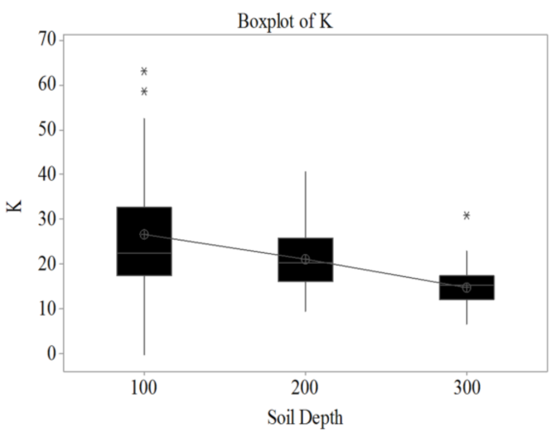
Table 5 Mean significant differences in soil properties between soil depths

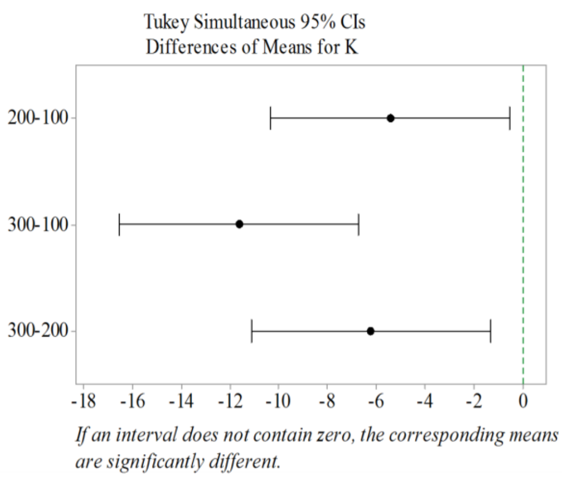
Properties	Significance of the difference between soil depth		
	Upper layer (100 mm)	Middle layer (200 mm)	Lower layer (300 mm)
K, mm/hr	26.63^{A}	21.21^{B}	15.00^{C}
Sw, mm/hr$^{1/2}$	839.80^{A}	766.00^{B}	689.95^{C}
I, mm	16.05^{A}	13.08^{B}	10.02^{C}

Note: Means that do not share a letter are significantly different

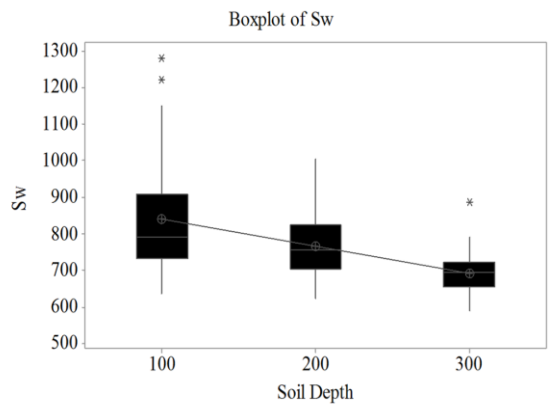
Boxplots and difference of means for K, Sw and I respectively reveal significant difference among soil depths (Figure 8). The boxplot indicates that K, Sw and I values at the upper layers (100 mm) had both the highest mean and the greatest variability while the lower layers (300 mm) values had the direct opposite with the least mean, median and variability. Hydraulic conductivity, soil water sorptivity and infiltration mean values and variability showed a decreasing trend in the order: upper>middle>lower soil layers respectively. The high mean values and greater variability at the top layer was due to greater and uneven soil loosening and variations in organic matter content caused by lack of uniformity in tillage management practices.

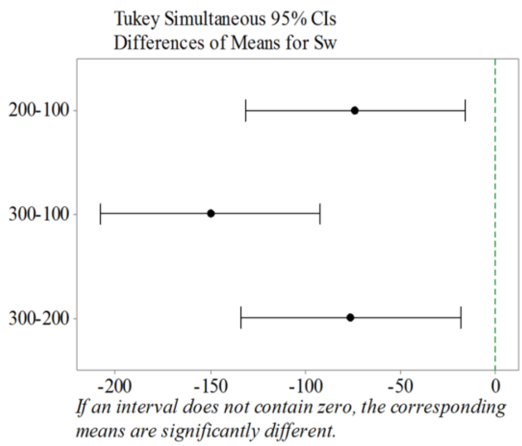
(a)





(b)





(c)

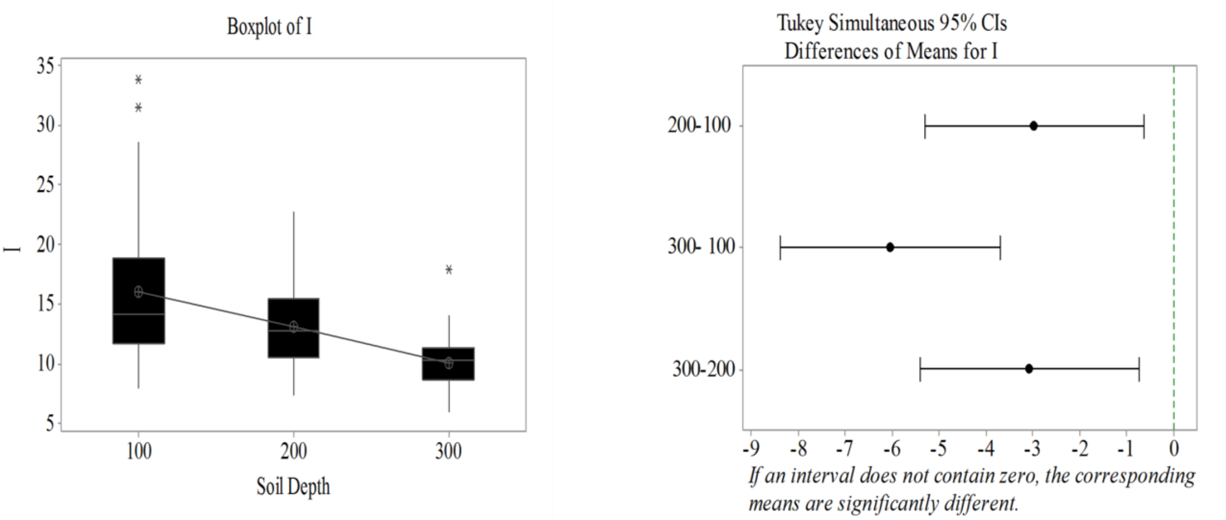


Figure 8 Boxplot (left) and Difference of means (right) of (a) Hydraulic conductivity/mm hr^{-1}, (b) Soil water sorptivity/mm hr$^{-1/2}$, and (c) Cumulative infiltration/mm of the experimental field versus soil depth ($p \leq 0.001$)

3.5 Application of contour spatial variability maps of hydraulic properties of the experimental field

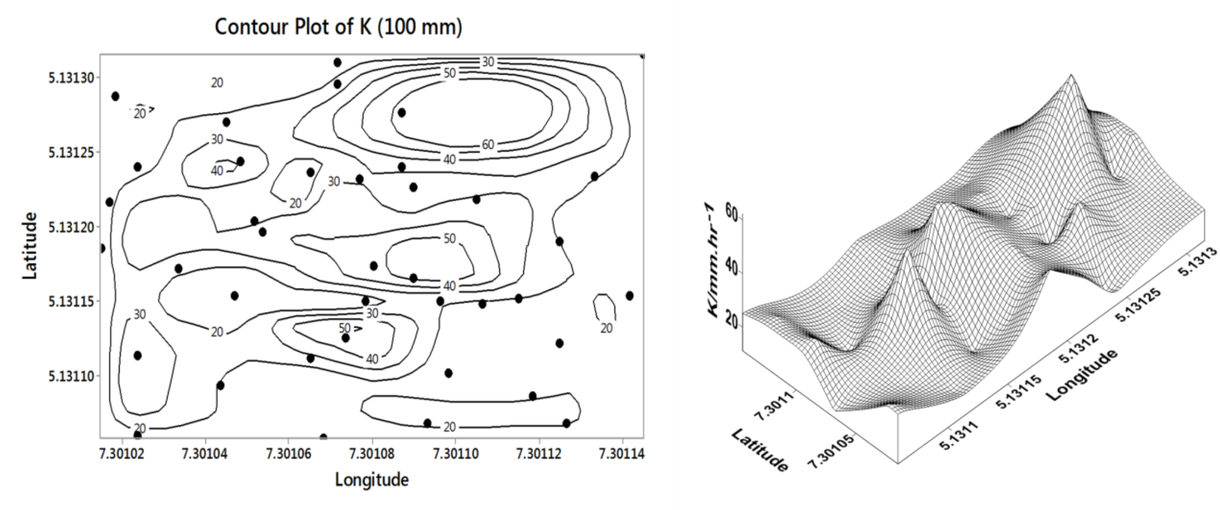
The contour plots and their corresponding wireframe representation show the spatial variation of K (Figure 9), Sw (Figure 10) and I (Figure 11) at upper (100 mm), middle (200 mm) and lower (300 mm) soil layers over the field. The contour plots clearly reveal a larger variability and spread of the hydraulic properties data in the upper, middle soil layers than in the lower soil layer. Osunbitan et al. (2005) and Zimmerman et al. (2007) performed similar studies and concluded that the higher values of unsaturated K and I are a consequence of soil tillage that causes an apparent increase in PT and decrease in BD. Since tillage effects decrease down the soil depth, definitely lower values and smaller variation is bound to be observed in the lower soil depth (Fasinmirin and Olorunfemi, 2012).

In the 100 mm contour map shown in Figure 9(a), the variation of the K data shows a south west-north east (SW-NE) trend. Lower values and little variation of K were found in the lower south western part of the experimental field while a peak contour value was observed at the north eastern part with a value of 60 mm/hr. In the 200 mm contour map (Figure 9(b)), careful observation of the map shows similar observation with the upper surface (100 mm) plot with peak contour of 40 mm/hr found at the north eastern part of the experimental field. Contour map showing the spatial variation of K in the 300 mm soil depth (Figure 9 (c)) generally shows less variability in comparison to the upper soil depths. Contour maps (Figure 10) indicated areas with high and low values of Sw in the upper, middle and lower soil layers in the experimental field. In the middle layer (Figure 10(b)), higher Sw values were found in the NE and SE parts of the map respectively. Figure 11 shows the distribution and the variation of I over the field. Cumulative infiltration (in mm of water) is the accumulated depth of water infiltrated into the soil during the period of each measurement (sampling point). Since these properties are determined essentially at points in the field, a large number of determinations are required to assess the magnitude and structure of the variation within the selected area (e.g., Logsdon and Jaynes, 1996).

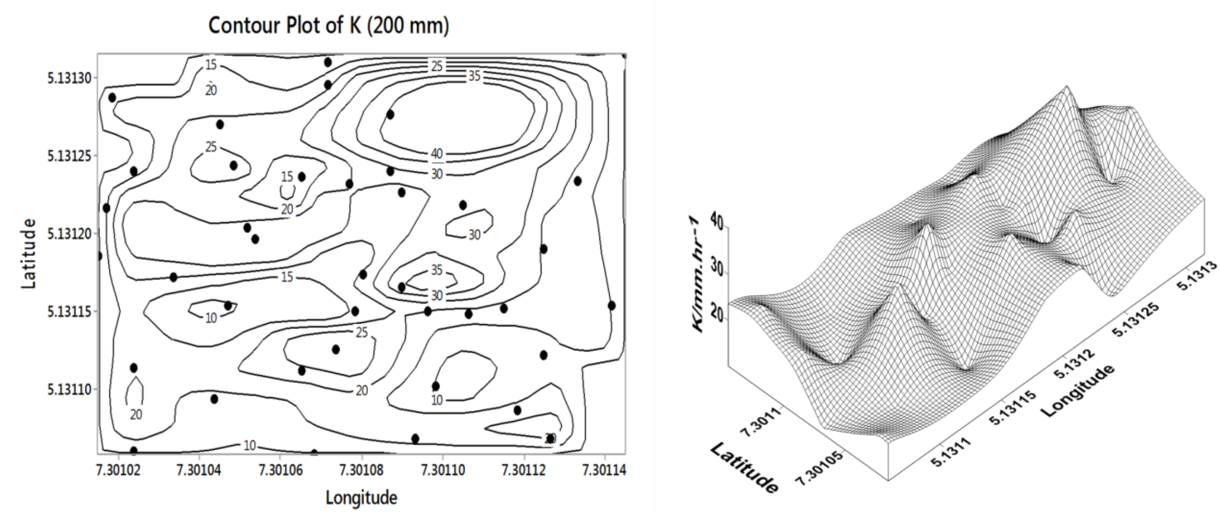
Figures 9, 10 and 11 show the wireframe representation of K, Sw and I which is the 3D surface plot in the 100, 200 and 300 mm soil layers. These 3D surface plots are useful for establishing operating conditions. Observation of the three dimensional plots of the upper soil layer revealed some crest toward the north eastern part of the field. The lower end dipped with some lower values. The 300 mm depth show more troughs with yet some lower values than the upper soil layers.

Consideration of the observed variability of experimental field is important in irrigation and water management system. In planning and designing an irrigation system, concern is primarily on the WHC of the soil, particularly in the root zone of the plant; with the water-intake rate of the soil (K and Sw); the accumulated depth of water infiltrated and with the amount of water that the crop uses. The impact of these hydraulic properties on soil moisture dynamics in the root-zone, plant water stress and vegetation water use has been reported in previous studies (Gwenzi, 2010; Gwenzi et al., 2011). Hydraulic properties data is very dependent on sampling position and varies so much even between close points as seen from the contour maps (Figures 9, 10 and 11). In agricultural lands, severe variability of soil hydraulic properties has been reported. Spatial variability of these soil properties has appreciable effects on irrigation process and groundwater recharge. In irrigation projects, low irrigation efficiencies might arise from spatial variation of soil hydraulic properties such as Sw that directly influence on infiltration equation (Sepaskhah et al., 2005). Applying a unique amount of water to every part of the field using the same infiltration equation may lead to deficit and/or over irrigation at different points (Sepaskhah et al., 2005). Therefore, assessment of the hydraulic properties of soil, such as K, I and Sw, is important for the interpretation of the physical characteristics of soil and the management of agricultural practices (Green et al., 2003). For instance, peak contour value of K observed at the north eastern part of the field with a value of 60 and 40 mm/h in the upper and middle soil layer, respectively, showing that the NE part of the field has higher infiltration rates, and definitely, high PT and probably low WHC. Therefore it is advisable that NE part of the field has its unique infiltration equation as rightly suggested by Sepaskhah et al. (2005). This will result in better farm water management by the achievement of high efficiency and uniformity of irrigation. Spatially analyzed soil I and K on the overall enable soil water management experts to be able to design field-specific applications like variable rate irrigation, seed and fertilizer rate.

(a)



(b)



(c)

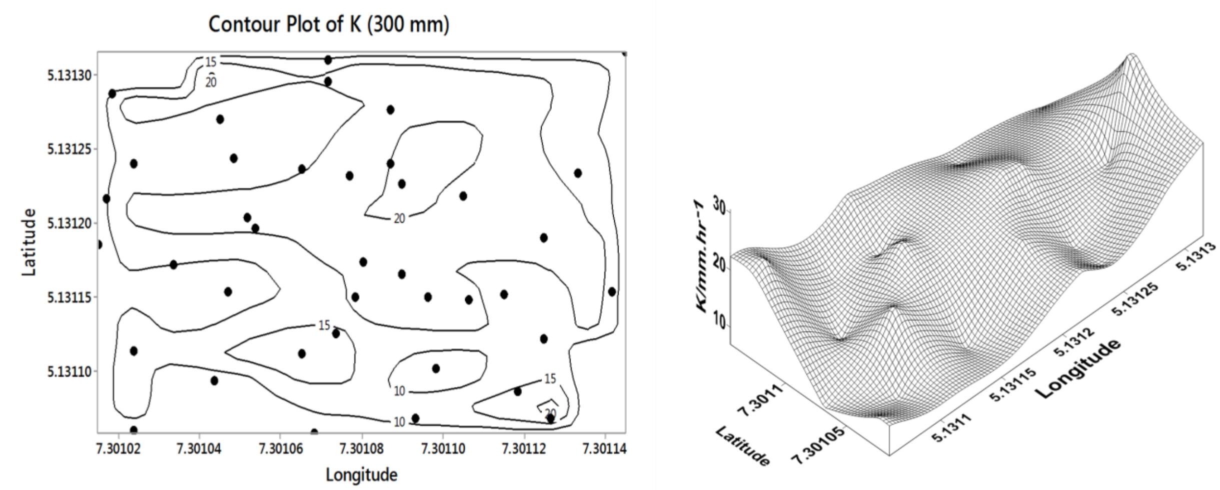
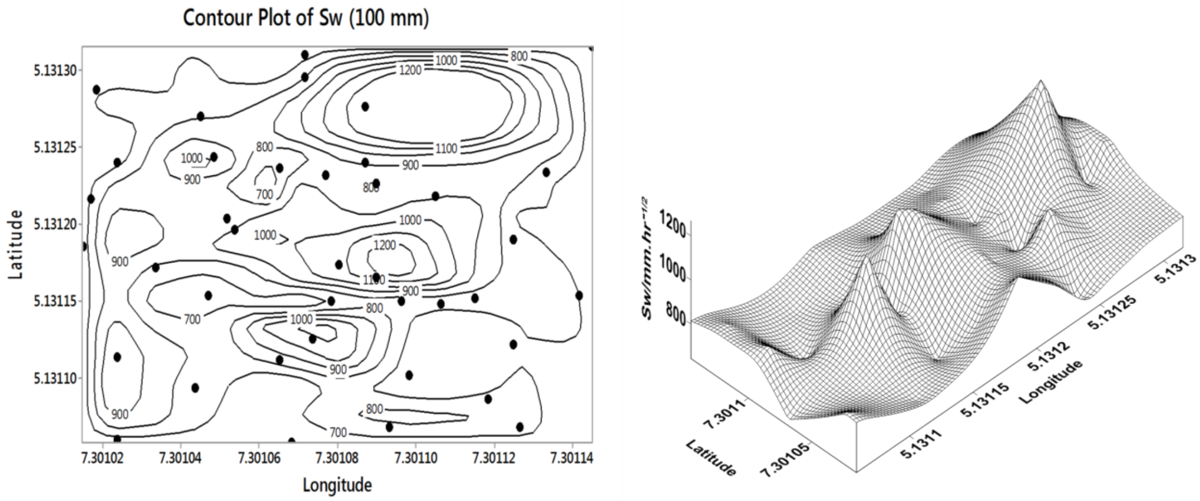
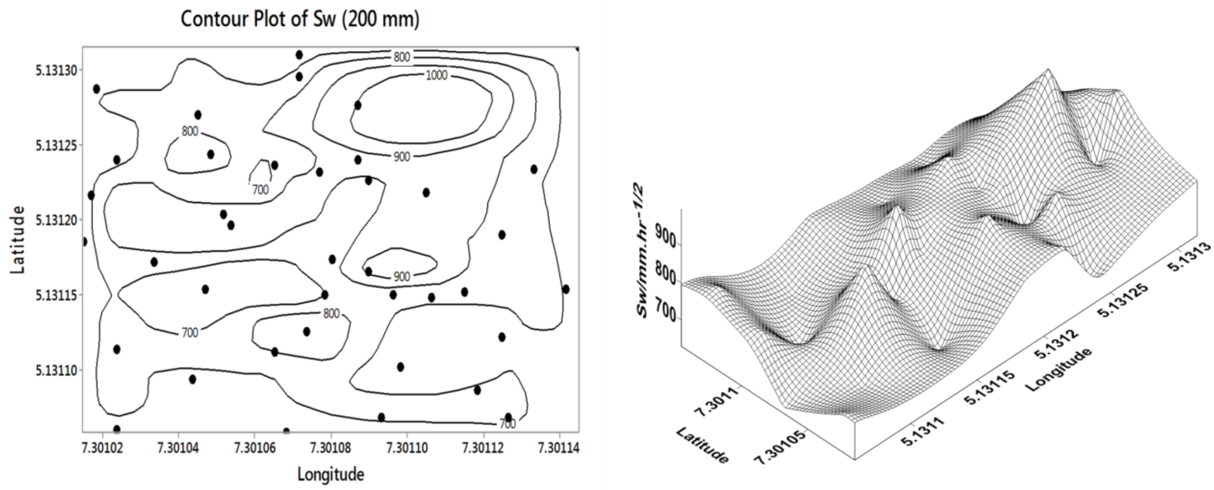


Figure 9 Spatial variation (left) and wireframe representation (right) of hydraulic conductivity at (a) 100, (b) 200 and (c) 300 mm depths of the experimental site

(a)



(b)



(c)

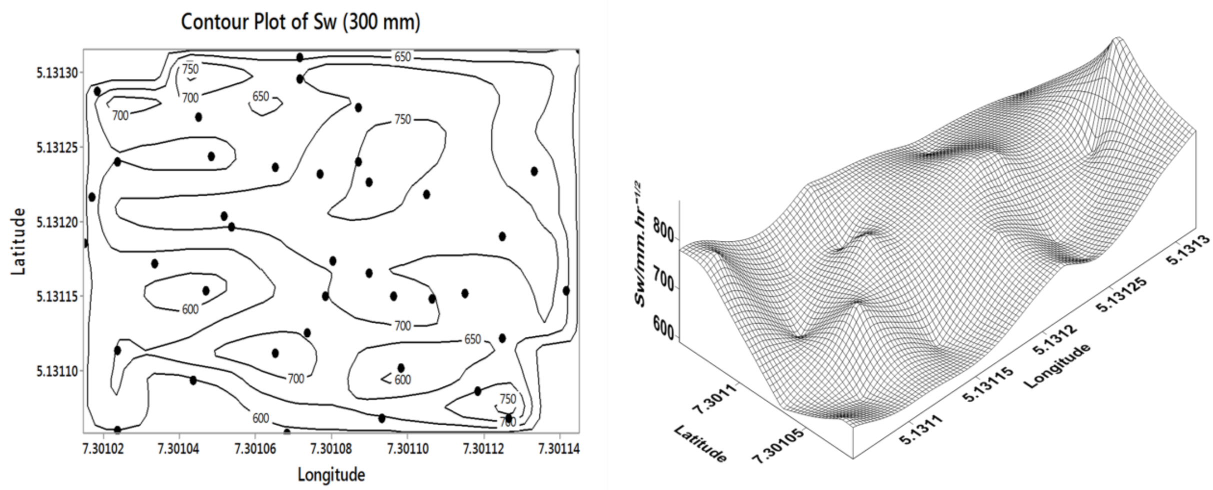


Figure 10 Spatial variation (left) and wireframe representation (right) of soil water sorptivity at (a) 100, (b) 200, and (c) 300 mm depths of the experimental site

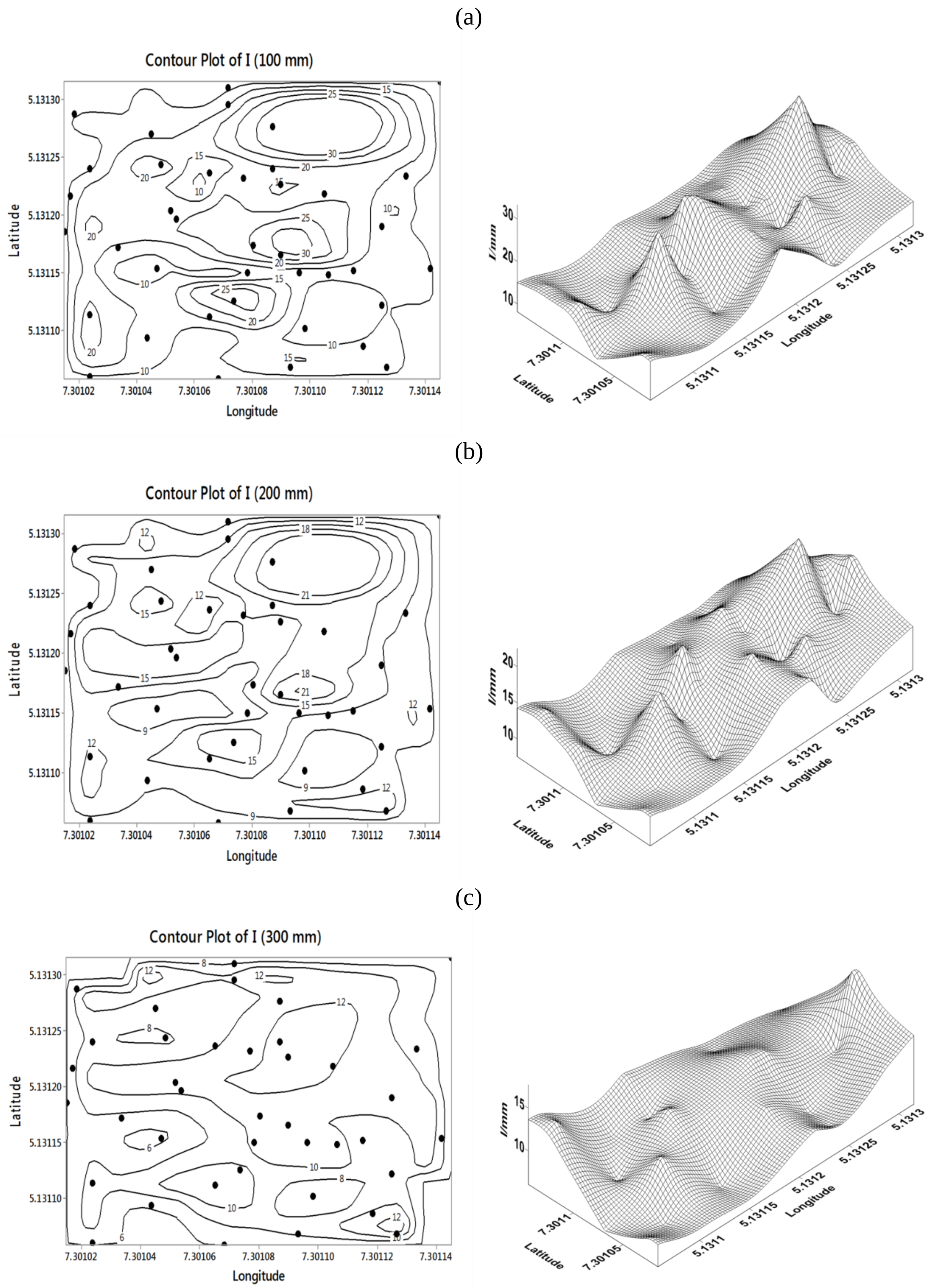


Figure 11 Spatial variation (left) and wireframe representation of cumulative infiltration (right) at (a) 100, (b) 200, and (c) 300 mm depths of the experimental site

4 Conclusions

In this research, we studied the spatial variability of hydraulic conductivity, soil water sorptivity and cumulative infiltration of an alfisol soil in Akure, Southwestern Nigeria. The statistical and geostatistical analysis revealed spatial variability in soil physical and hydraulic properties among soil depths and across the field. Greater and uneven soil loosening and variations in organic matter content caused by lack of uniformity in tillage management practices resulted in high mean values and greater variability of hydraulic properties at the top soil layer. Correlation analysis revealed that BD and OMC accounted for the spatial variability of unsaturated K, Sw and I indicating the importance and the need for proper characterization of the spatial variability of soil parameters. The knowledge of these soil hydraulic properties and processes leads to better predictions of both agricultural and environment processes. Consideration of the observed variability of experimental field is important in irrigation and water management system. Therefore, it is concluded that by applying spatial analysis, one can obtain better insight on the infiltration equation for different parts of the irrigation field and proposes valuable water resources management systems. This will result in better farm water management by the achievement of high efficiency and uniformity of irrigation.

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