International Journal of Applied and Natural Sciences (IJANS)
ISSN(P): 2319-4014; ISSN(E): 2319-4022
Vol. 7, Issue 5, Aug - Sep 2018; 123-130

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

PREDICTION OF SATURATED HYDRAULIC CONDUCTIVITY OF SEMI-ARID RED AND LATERITIC LOWLAND PADDY SOILS USING MEASURED SOIL PROPERTIES

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ABSTRACT

A saturated hydraulic conductivity of the semi-arid red and lateritic lowland paddy soils was assessed on the measured soil variables using modern statistical tools such as correlation matrix, multiple regression equations and principal component analysis (PCA). Multiple regression equations and PCA indicated the sand fraction as the key indicator in predicting a large variation of the saturated hydraulic conductivity of the soils. However, organic carbon, bulk density, particle density, electrical conductivity, cation exchange capacity, water holding capacity, porosity, and soil pH had significant contribution in explaining the variability of the saturated hydraulic conductivity. Model using minimum data set (MDS) as independent variables were , however, less predictive than PCA where organic carbon could function as the sole indicator in predicting the variance of the saturated hydraulic conductivity of soils. These unorthodox techniques may provide an alternative way of estimating the saturated hydraulic conductivity indirectly from the easily measured basic soil properties.

KEYWORDS: *Saturated Hydraulic Conductivity, Red and Lateritic Soil, Regression, Principal Component Analysis, Minimum Data Set*

Article History

Received:* *27 Aug 2018* | *Revised:* *31 Aug 2018* | *Accepted:* *08 Sep 2018

INTRODUCTION

The saturated hydraulic conductivity (Ks) is an important soil physical property which represents the ability of the soil to transmit water through its voids. The knowledge of Ks is indispensable for irrigation and drainage planning, crop and groundwater modeling, and regulation of risks of pollutant impacts on surface waters and groundwater (Patil *et al.,* 2016). It has a prominent role in groundwater recharge, soil water storage in the potential root zone and its availability for plant uptake and growth (Wijaya *et al.,* 2010). The soil components such as texture, macro- and microstructure, aggregation, compaction, grain size, distribution of pore sizes and pore geometry, bulk density, organic carbon content, exchangeable cations, clay minerals, vegetation types, land cover and land management also strongly influence the soil hydraulic properties (Fikry, 1990; Paramasivam, 1995; Mathan and Mahendra, 1993; Ndiaye *et al*., 2007; Wang *et al*., 2012). The different land use and land cover systems greatly control the infiltration rate and hydraulic conductivity of soils mainly by way of improvement of soil physical, chemical and biological environment of soil (Newaj *et al.*, 2007). Many direct methods have been developed over time for measurement of saturated hydraulic conductivity in the laboratory and field conditions (Klute and Dirksen, 1986). However, these practices are time-consuming, expensive and laborious and often fail to represent in a wide range of circumstances and for all soil types (Saikia and Singh, 2003; Zhang *et al.*, 2007). Since soil hydraulic properties have large spatial and temporal variability, many indirect methods have been proposed to estimate the saturated hydraulic conductivity from easily measured soil properties (Wösten and van Genuchten, 1988; Patil *et al.,* 2009). The recent development of statistical analysis methods for prediction of saturated hydraulic conductivity is considered to be an excellent tool which is intended to translate laboratory measured soil values into soil hydraulic properties. In these approaches, the correlation matrix, multiple regression equations and the principal component analysis (PCA) for data reduction were used to select the most appropriate soil indicators from the list of large datasets. These provisions proved to be good predictive indicators for unknown soil hydraulic characteristics (Aimrun, 2009). The aim of the present study was to predict the saturated hydraulic conductivity of semi-arid red and lateritic lowland paddy soils using modern statistical methods from routinely measured soil properties.

MATERIALS AND METHODS

The experimental site belonging to the semi-arid red and lateritic agro-climatic zone of West Bengal, India is located between 22.43^o and 23.84^o N latitude and 87.06^o and 87.86^0 E longitude. The average altitude ranges from 18.5 to 23.4 m above mean sea level. Physiographically the region is primarily characterized by undulating and rolling topography with numerous mounds and valley. The climate is humid sub-tropical with a very hot summer and a cold winter. The temperature ranges between 25.5 and 41.5 ^{0}C during summer and 12.7 to 18.3 ^{0}C during winter. The annual precipitation varies from 1100 mm to 1300 mm. Based on Soil Taxonomy, the soils of the area is classified as fine-loamy, mixed, hyperthermic Haplustalfs. Paddy is the principal crop of the area. The other major crops are wheat, mustard, pulses, and vegetables.

Fifteen soil profile samples were collected from lowland positions at a depth of 0-15, 15-30 and 30-45 cm with three cropping systems (rice-vegetable, rice-mustard and rice-fallow) from the districts of Purulia, Birbhum, Bardhaman, Bankura and Medinipur under the studied area. The samples after collection were cleaned, air-dried in shade and ground to pass through a sieve with 2 mm size opening. Each soil profile layer under specific cropping system from five different districts was then thoroughly mixed up to make a composite sample representing the soil of that particular layer under specific cropping system. The same process was followed for another soil layer for each cropping system. Standard methods used for determination of the physical, hydro-physical and chemical properties of the soils were international pipette sampling method for particle size distribution (Piper, 1966), core method for bulk density and particle density, and saturation method for porosity (Black, 1965), potentiometric method for soil pH and saturated soil paste extraction for electrical conductivity (Jackson, 1973), ammonium acetate extraction method for cation exchange capacity (Schollenberger and Simon, 1945), wet digestion method for organic carbon (Walkley and Black, 1934). A saturated hydraulic conductivity of the soil samples was measured according to the constant head method (Fireman, 1944). This procedure allowed water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen was measured over a period of time. The saturated hydraulic conductivity (Ks) using constant head method was calculated by the equation: $\mathrm{Ks} = \frac{\mathrm{Q\Delta L}}{\mathrm{AT\Delta H}}$ where Q is the quantity of water discharged, ΔL is soil length, A is cross-sectional area of soil, T is total time of discharge and ΔH is the hydraulic head difference. Various statistical procedures were employed for analyzing the measured database. The Pearson correlations coefficients were used to determine the eligible dependent variables for inclusion in the Principal Component Analysis (PCA). In the regressive predictive models, the saturated hydraulic conductivity was used as the dependent variable and other soil factors as the independent variables. All the independent variables were allowed to enter into the models competitively and the sequence of entry depended upon their contribution to the models. The levels of significance at which variables entered and stayed into the models were set at $P \leq 0.05$. The estimated coefficient of determination (R^2) indicated the relative suitability of different variables in the prediction of saturated hydraulic conductivity. The PCA was used as a data reduction tool to select the most appropriate indicators for the study area from the list of indicators generated from the high correlation matrix. Principal components (PCs) are sets of indicators with high eigenvalues and factor loading. Only the PCs with eigenvalues >1 and those that explained at least 5% of the data variation were considered for indicator identification. The indicators receiving weighted loading values between the highest and 10% reduction of the highest weighted loading were selected for the minimum data sets (MDSs). The uncorrelated variables in any PC were also selected in MDSs. Total multivariate mean data of all variables for all three cropping systems measured at three different depths were further subjected to PCA technique for testing the selected highest loaded MDSs through multiple regression equation. All important predictors were verified for their significance by the coefficient of regression (R^2), adjusted R^2 and standard error of estimate (SE_{est}) values.

RESULTS AND DISCUSSIONS

Soil Properties

The mechanical composition of the lowland soils under paddy based cropping systems varied from 30.64 to 38.42% for sand, 30.55 to 35.74% for silt and 30.26 to 34.62% for clay (Table 1). The sand fraction was decreasing and silt and clay fractions were increasing with depth in all pedons excepting a few for clay. All soils were clay loam in texture and were moderately finer in the sub-surface horizons than in the surface horizon, indicating the occurrence of clay Illuviation under pedogenic as well as anthropogenic processes (Rudramurthy *et al.*, 2007). The bulk density (BD) and particle density (PD) of the soils were found to range between 1.28 and 1.43 Mg m^{-3} and 2.49 and 2.67 Mg m^{-3}, respectively. Irrespective of cropping systems, both values were increasing with increase in depth. These could be attributable to the higher sand fraction (Sahu and Mishra, 1997) and greater compactness and reduced organic matter content (Walia and Rao, 1997) in the surface layer than in sub-surface layers. Comparatively higher BD in surface soil than the soils underneath under paddy land use system was ascribed to the collapse of non-capillary pores as a result of puddling operation (Rudramurthy *et al.*, 2007).The soil porosity ranged between 21.57% and 26.32% and decreased with depth in all the pedons. This was related to the increased sand fraction in the surface soil causing increased non-capillary pore which resulted in the improved saturated hydraulic conductivity of the soils. Other plausible reasons might be the increase in bulk density and particle density ofthe soils down the profile (Rudramurthy *et al.*, 2007). The water holding capacity (WHC) of soils ranged from 30.54 to 35.87%. The value increased with increase in depth. This was probably due to higher amounts of finer silt and clay particles in the sub-soils as compared with the surface soil. The saturated hydraulic conductivity of the soils in all the pedons varied from 18.27 to 25.41 cm hr^{-1}. The value was found to decrease with increase in depth and magnitude of variation seemed to be closely related with the sand distribution pattern in the profile. Soil pH was strongly acidic to mildly acidic (5.50 and 6.22) and increased with increase in soil depth (Table 2)). The electrical conductivity (EC) of the soils varied from 0.27 to 0.38 dS m^{-1} and followed almost the same trend as soil pH. The organic carbon contents ranged from 4.0 to 5.6 g kg^{-1} and decreased with depth. Higher organic carbon in the surface soil as compared with sub-surface soils were possibly due to organic matter and crop residues addition followed by restricted leaching owing to soil puddling.The cation exchange capacity varying from 14.40 to 16.21 cmol kg^{-1} increased with increasing depth.

Correlation Matrix of Saturated Hydraulic Conductivity with Variables

A highly significant positive correlation was found between saturated hydraulic conductivity and sand particles (r=0.966**), porosity (r=0.642*), EC (r=0.876**) and OC (r=0.785**) and a strong negative correlation with silt (r=-0.845**), clay (r=-0.885**), BD (r=-0.815**), PD (r=-0.798**), WHC (r=-0.697*), pH (r=-0.857**) and CEC (r=-0.849**) of the soils (Table 3). This indicates that increasing sand content likely to increase the non-capillary pores in the soils which enhances the improved saturated hydraulic conductivity of soils. On the other hand, higher clay and silt contents in the soils are the impediment of the higher water transmission in the soil profile and thus the lower saturated hydraulic conductivity of the soils. These significantly correlated soil parameters were identified as the most eligible independent indicators for principal component analysis for predicting the saturated hydraulic conductivity of the soils.

Multiple Regressive Models for Saturated Hydraulic Conductivity of Soils

An analysis of the stepwise regressive models developed by using all the independent soil variables for predicting the saturated hydraulic conductivity showed that sand fraction alone could explain 93.4% of the total variation in the saturated hydraulic conductivity (Table 4). The second variable entered into the model was organic carbon which improved the R^2 to 0.957 and the third and fourth variables such as cation exchange capacity and bulk density further improved R^2 to 0.969 and 0.975, respectively. In other words, the inclusion of four independent soil variables could measure 97.5% of the variability in the saturated hydraulic conductivity of the soils. However, the sand fraction was found to be the key indicator among the four variables studied in the predictive models and largely regulates the saturated hydraulic conductivity of the soils.

Principal Component Analysis for Predicting Saturated Hydraulic Conductivity of Soils

The principal component analysis (PCA) irrespective of cropping systems and soil depths showed that different soil factors in each component have a differential contribution in predicting the variance of the saturated hydraulic conductivity of the soils (Table 5). The two principal components (PC) extracted whose eigenvalues >1 could account for 83.85% of total variance of saturated hydraulic conductivity. The first PC could explain 68.42% of the total variation in saturated hydraulic conductivity and sand, water holding capacity (WHC), porosity, electrical conductivity (EC) and organic carbon were highly positively loaded variables. The second PC could describe 15.43% of total variance, where sand, PD, pH, and EC were highly positively loaded variables. However, the indicators in the first component in PCA could explain the maximum variability of the saturated hydraulic conductivity of the lowland soils.

Minimum Data Set for Predicting Saturated Hydraulic Conductivity of Soils

The minimum data set (MDS) variables having eigenvalues more than one were selected based upon PCA technique and the resulted component matrix where from highly positively loaded variable organic carbon from the first component and particle density from the second component were selected as independent MDS variables (Table 5). A model regression equation was thus developed keeping saturated hydraulic conductivity (Ks) as dependent variable and MDSs as predictor or independent variables as Ks = -3.331 + 3.635 OC** where, $^{**}P<0.01$; R^2 = 0.616, Adjusted R^2 = 0.601, SE(est.) = 1.507. The predictive model for Ks using the MDS did not include particle density as the effective indicator and thus excluded from the model. Only organic carbon was found to be the most pronounced single indicator in predicting 61.6% of total variance of saturated hydraulic conductivity. However, the model using MDS variable was less predictive than the PCA. This is obvious because several other soil factors were assigned with PCA study which has their own contributory role in predicting the saturated hydraulic conductivity of the lowland soils.

CONCLUSIONS

The statistical tools such as multiple regression equation and principal component analysis (PCA) indicated that sand fraction was identified as the key indicator in predicting a large variation of the saturated hydraulic conductivity of the soils. However, variables like organic carbon, BD, PD, EC, CEC, WHC, porosity, and pH had a contributory role in explaining the variance of the saturated hydraulic conductivity. Model using MDS as independent variables was less predictive than PCA where organic carbon could function as the sole indicator in assessing the saturated hydraulic conductivity of the soils studied.

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APPENDICES

Table 1: Physical and Hydro-Physical Properties of Soils for Different Cropping Systems

Cropping System	Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural Class	BD (Mg m^{-3})	PD (Mg m^{-3})	Porosity (%)	WHC (%)	HC (cm hr^{-1})
Rice-Vegetable	0-15	37.29	32.45	30.26	Clay loam	1.34	2.49	25.64	30.54	25.31
	15-30	34.89	33.26	31.85	Clay loam	1.36	2.52	23.42	32.25	23.23
	30-45	30.64	35.74	33.62	Clay loam	1.42	2.56	22.35	35.85	19.41
	SEm(±)	0.21	0.05	0.22	-	0.002	0.003	0.07	0.06	0.04
	CD (*P*=0.05)	0.84	0.20	0.90	-	0.01	0.013	0.28	0.23	0.17
Rice-Mustard	0-15	38.42	30.55	31.03	Clay loam	1.28	2.50	26.32	31.67	25.41
	15-30	34.31	32.42	33.27	Clay loam	1.35	2.54	25.14	33.65	22.26
	30-45	30.64	34.74	34.62	Clay loam	1.43	2.57	23.74	34.29	18.27
	SEm(±)	0.44	0.06	0.39	-	0.02	0.01	0.40	0.20	0.07
	CD (*P*=0.05)	1.78	0.25	1.59	-	0.08	0.05	1.63	0.81	0.27

Rice -Fallow	0-15	37.00	32.45	30.26	Clay loam	1.32	2.62	24.54	32.86	24.65
	15-30	34.57	32.26	33.17	Clay loam	1.35	2.63	23.86	33.21	22.45
	30-45	35.97	32.40	31.62	Clay loam	1.40	2.67	21.57	35.87	23.00
	SEm(±)	0.34	0.07	0.25	-	0.01	0.01	0.27	0.38	0.08
	CD (*P*=0.05)	1.39	NS	1.02	-	0.03	0.04	1.08	1.54	0.31

NS: Non-significant

Table 2: Chemical Properties of Soils for Different Cropping Systems

Cropping System	Soil Depth (cm)	pH (1:2.5)	Electrical Conductivity (dS m^{-1})	Organic C (g kg^{-1})	Cation Exchange capacity (cmol kg^{-1})
Rice-Vegetable	0-15	5.50	0.28	5.80	14.40
	15-30	5.60	0.31	5.50	15.50
	30-45	5.80	0.33	4.70	15.90
	SEm(±)	0.09	0.005	0.05	0.05
	CD (*P*=0.05)	-	0.02	0.21	0.21
Rice-Mustard	0-15	5.50	0.27	5.70	14.50
	15-30	5.70	0.32	5.50	15.70
	30-45	5.90	0.35	4.60	16.30
	SEm(±)	0.002	0.01	0.05	0.13
	CD (*P*=0.05)	0.01	0.03	0.21	0.51
Rice-Fallow	0-15	5.50	0.31	5.90	14.90
	15-30	5.80	0.34	5.40	15.70
	30-45	6.22	0.38	4.59	16.21
	SEm(±)	0.01	0.005	0.10	0.18
	CD (*P*=0.05)	0.36	0.02	0.39	0.71

Table 3: Correlation Coefficient (r) of Saturated Hydraulic Conductivity with Soil Variables

Variable	'R' Value
Sand	0.966**
Silt	-0.845**
Clay	-0.885**
Bulk density (BD)	-0.815**
Particle density (PD)	-0.798**
Water holding capacity (WHC)	-0.697*
Porosity	0.642*
pH	-0.857**
Electrical conductivity (EC)	0.876**
Organic carbon (OC)	0.785**
Cation exchange capacity (CEC)	-0.849*

*' ** indicate significant at 5% and 1% levels of probability, respectively

Table 4: Regressive Models of Saturated Hydraulic Conductivity (Y) with Soil Variables

Model	Regression Equation	R^2	Adj. R^2	SE_{est}
1	Y = -7.434 + 0.861 sand	0.934	0.931	0.627
2	Y = -7.976 + 0.727 sand + 0.998 OC	0.957	0.954	0.513
3	Y = 5.956 + 0.618 sand + 0.867 OC – 0.613 CEC	0.969	0.965	0.449
4	Y = -10.267 + 0.689 sand + 0.315 OC – 0.613 CEC + 8.361 BD	0.975	0.970	0.413

Table 5: Principal Component Loading Matrix for Soil Properties for Predicting Variance of Saturated Hydraulic Conductivity

Variables	Principal Components	
	PC 1	PC 2
Eigen Indicators		
Sand	0.889	0.420
Silt	-0.777	-0.397
Clay	-0.820	-0.344
Bulk density	-0.903	-0.070
Particle density	-0.510	**0.674**
Water holding capacity	0.867	-0.383
Porosity	0.843	-0.460
pH	-0.635	0.629
Electrical conductivity	0.880	0.243
Organic carbon	**0.905**	-0.151
Cation exchange capacity	-0.862	-0.078
Hydraulic conductivity	**0.932**	**0.313**
Eigenvalues	8.211	1.852
Variance explained (%)	68.42	15.43
Cumulative (%)	**68.42**	**83.85**