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Determining Saturated Hydraulic Conductivity of Medium Land Soils under Different Cropping Systems in Semi-Arid Red and Lateritic Region

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ABSTRACT

To predict the saturated hydraulic conductivity of the semi-arid red and lateritic medium soils of West Bengal, India, different statistical procedures such as correlation matrix, multiple regression equations and principal component analysis were employed on the measured dataset for different soil variables. The correlation and regression functions suggested sand fraction as the key indicator in regulating the saturated hydraulic conductivity of the soils. While the PCA and minimum data set (MSD) techniques showed that the first component could explain maximum variance of the saturated hydraulic conductivity than the second and third component. The soil porosity, cation exchange capacity and clay fraction in combination were identified as the best predictors which could contribute maximum variability of the saturated hydraulic conductivity. This unorthodox technique may provide an alternative way of estimating the saturated hydraulic conductivity indirectly from the easily measured basic soil properties.

Key words: *Saturated hydraulic conductivity, Red and lateritic soil, Correlation, Regression, Principal components.*

INTRODUCTION

Saturated hydraulic conductivity (Ks) plays an important role in regulating the groundwater recharge, water retention, water and solute movement within the soil profile, and its accessibility for plant uptake and growth[19]. The knowledge of hydraulic conductivity of soil is indispensable for proper irrigation and drainage planning, crop and groundwater modeling, and regulation of risks of pollutant impacts on surface and groundwater[10]. The physical, chemical and biological environment of soil such as soil texture, porosity, pore size distribution, bulk density, organic carbon content, exchangeable cations, vegetation types, and land cover can strongly influence the soil hydraulic properties[4,8,18]. Many direct methods have been developed for measurement of saturated hydraulic conductivity in the field and laboratory conditions[6]. These analytical procedures are time-consuming, capital-intensive and laborious process and often fail to represent the larger areas[14].

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Many indirect methods have been developed and advocated for predicting the saturated hydraulic conductivity from easily measured soil properties[9,20]. This statistical analysis for predicting the saturated hydraulic conductivity is an excellent tool which is intended to translate easy to measure soil physical and chemical properties into soil hydraulic properties. These provisions often prove to be good predictive indicators for unknown soil hydraulic characteristics[1]. Since various approaches on saturated hydraulic conductivity were generated in different sets of soil and climatic conditions and have location specificity, these may not be applicable in all environments. The objective of the present study was to predict the saturated hydraulic conductivity of medium land soils under different cropping systems in semi-arid red and lateritic region of West Bengal, India from measured soil properties.

MATERIAL 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 32.6 to 43.5 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 medium land 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 other 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[11], core method for bulk density and particle density, and saturation method for porosity[2], potentiometric method for soil pH and saturated soil paste extraction for electrical conductivity[5], ammonium acetate extraction method for cation exchange capacity[15], wet digestion method for organic carbon[17]. Saturated hydraulic conductivity of the soil samples were measured according to constant head method[3]. 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: $Ks = \frac{Q\Delta L}{AT\Delta H}$ where, Q is quantity of water discharged, ΔL is soil length, A is cross-sectional area of soil, T is total time of discharge and ΔH is 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. Eigenvalues less than one explains less variance than individual soil attribute. Only the PCs with eigenvalues ≥1 and those that explained at least 5% of the data variation were considered for identifying the minimum data sets (MDSs). The indicators within each component receiving weighted loading values between the highest and 10% reduction of the highest weighted loading were selected for the MDSs. The uncorrelated variable and a single variable in any PC were also selected in MDSs. When more than one variable was retained within a PC, the correlations sum were examined to determine if any variable could be considered to be redundant. All MDSs in each principal component with respect to cropping system and soil depth were considered as independent variables to predict the dependent variable as saturated hydraulic conductivity. 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 coefficient of regression (R^2), adjusted R^2 and standard error of estimate (SE_{est}) values.

RESULTS AND DISCUSSION

Soil properties

The mechanical composition of the soils under different cropping systems varied from 47.36 to 56.08% for sand, 17.42 to 19.30% for silt and 26.17 to 34.11% for clay (Table 1). The sand fraction was decreasing and silt and clay fractions were increasing with depth of profile with some deviations. All soils were sandy loam in texture and were relatively finer in the sub-surface horizons than in the surface horizon, thereby indicating the occurrence of clay migration and accumulation under pedogenic as well as anthropogenic processes[12]. The bulk density (BD) and particle density (PD) of soils ranged between 1.24 and 1.44 Mg m^{-3} and 2.58 and 2.67 Mg m^{-3}, respectively. Irrespective of cropping systems, both values were found increasing with increase in depth. These could be attributable to higher sand fraction[13] and greater compactness and reduced organic matter content[16] in surface layer than in sub-surface layers. Comparatively higher BD in surface soil than the soils underneath under paddy land use system were ascribed to the collapse of non-capillary pores as result of puddling operation[12]. The soil porosity ranging from 25.36 to 29.73% decreased with depth in all the pedons. This was related to the increased sand fraction in surface soil resulting in increased non-capillary pore, thereby facilitated the higher saturated hydraulic conductivity. Other reasons might be the increase in bulk density and particle density of the soils down the profile[12]. The water holding capacity (WHC) of soils ranged from 27.51 to 33.44%. The quantity increased with increase in depth which was probably due to higher amounts of finer silt and clay particles in the sub-soils than in the surface soil. The saturated hydraulic conductivity of the soils in all the pedons varied from 20.28 to 28.63 cm hr^{-1} and the magnitude of variation seemed to be more closely related with the sand contents of the soils. Soil pH ranging between 5.5 and 6.5 was strongly acidic to mildly acidic in reaction and increased with increasing soil depth (Table 2)). The electrical conductivity (EC) of the soils varied from 0.20 to 0.36 dS m^{-1}. The organic carbon contents and CEC of the soils varied from 4.0 to 5.6 g/kg and 9.7 to 13.7 cmol kg^{-1}, respectively. Higher values of organic carbon in surface soil as compared with sub-surface soils were possibly due to incorporation of organic matter and crop residues accentuated by restricted downward leaching.

Correlation matrix of saturated hydraulic conductivity with soil variables

A highly significant positive correlation was found between saturated hydraulic conductivity and sand particles (r=0.89**), porosity (r=0.792**), EC (r=0.777**) and OC (r=0.61**) and a strong negative correlation with clay (r=-0.814**), BD (r=-0.442*), PD (r=-0.806**), WHC (r=-0.898**), pH (r=-0.6474**) and CEC (r=-0.48*) of the soils (Table 3). It is assumed that increasing sand content increases the non-capillary pores in the soils which facilitate the higher Ks values of soils[7]. Conversely, higher clay content in the soils is the impediment of saturated hydraulic conductivity and thus decreased the water transmission in the soil profile. These significantly correlated soil parameters were considered to be the most eligible independent variables for principal component analysis.

Multiple regressive models for saturated hydraulic conductivity of soils

A perusal of the stepwise regressive models developed for predicting the saturated hydraulic conductivity using all the independent soil variables showed that sand fraction alone could explain 79.2% of the total variation in the saturated hydraulic conductivity (Table 4). The second variable entered in the model was particle density which improved the R^2 to 0.855 and the third variable pH further improved R^2 to 0.866. In other words, the inclusion of three independent soil variables could measure 86.6% of the variability in saturated hydraulic conductivity. In brief, sand fraction of the soils was the key predictor among the three variables examined in the predictive model and largely regulated the saturated hydraulic conductivity of soils.

Principal component analysis for predicting saturated hydraulic conductivity of soils

The principal component analysis (PCA) of rice-vegetable, rice-mustard and rice-fallow cropping systems at a depth of 0-15, 15-30 and 30-45 cm (Tables 5, 6 and 7) showed that different selected soil factors at each depth in each component receiving eigenvalues >1 have differential contributory role in predicting the variance of saturated hydraulic conductivity of the soils. Irrespective of soil depths and cropping systems, the overall PCA could account for 57.30 to 71.72% of the total variation in saturated hydraulic conductivity in the first component and 28.28 to 42.70% of the variation in the second component. Also using the PCA technique, the variability of saturated hydraulic conductivity in the soils at 0-15, 15-30 and 30-45 cm depth could explain by 57.30 to 71.72%, 64.29 to 68.51% and 59.72 to 71.72% in the first component and 28.28 to 42.70%, 31.49 to 35.71% and 28.28 to 40.28% in the second component, respectively. However, the integrated soil indicators in the first component in PCA technique in explaining the maximum variability of the saturated hydraulic conductivity in all the layers of the pedons was likely to be the most practical and useful for irrigation management point of view.

Regression analysis using MDS for predicting saturated hydraulic conductivity of soils

MDS variables were selected based upon PCA technique and the resulted component matrix where from positively loaded porosity and CEC variable and negatively loaded clay variable were selected from PC-1, PC-2 and PC-3, respectively as independent MDS variables (Table 8). The total three factors/components extracted explained 84.27% of total variance in saturated hydraulic conductivity of soils with reference to eigenvalues more than one. The first factor (porosity) explained 64.45%, second factor (CEC) 10.53% and third factor (clay) 9.29% of total variation in saturated hydraulic conductivity. A full model regression equation was thus developed keeping saturated hydraulic conductivity (Ks) as dependent variable and MDSs as predictor or independent variables as follows:

Ks = 12.703 - 0.549 clay** + 0.771 porosity** + 0.376 CEC* where, *P<0.05 and **P<0.01; R^2 = 0.749, Adjusted R^2 = 0.716, SE(est) = 1.543. The predictive model for Ks using MDSs was slightly less predictive than the PCA. This is obvious, because several factors were assigned with PCA study which has their own contribution in forecasting the saturated hydraulic conductivity.

Table 1: Physical and hydro-physical properties of soils for different cropping systems

Cropping system	Soil depth (cm)	Textural class	Sand (%)	Silt (%)	Clay (%)	BD (Mg m^{-3})	PD (Mg m^{-3})	Porosity (%)	WHC (%)	HC (cm hr^{-1})
Rice-Vegetable	0-15	scl	56.08	17.75	26.17	1.24	2.62	26.95	29.34	26.57
	15-30	scl	52.12	19.30	28.57	1.33	2.64	26.43	30.34	23.47
	30-45	scl	48.52	18.59	32.88	1.36	2.67	26.31	32.47	20.54
	SEm(±)	-	0.579	0.648	0.32	0.02	0.004	0.06	0.81	0.11
	CD (*P*=0.05)	-	2.335	NS	1.29	0.08	0.02	0.34	0.20	0.42
Rice-Mustard	0-15	scl	55.08	18.08	26.84	1.25	2.58	29.27	29.68	27.96
	15-30	scl	51.46	19.08	29.00	1.37	2.62	27.53	31.45	24.27
	30-45	scl	53.86	18.63	27.51	1.43	2.64	25.36	33.44	26.75
	SEm(±)	-	0.42	0.47	0.49	0.04	0.01	0.35	0.17	0.06
	CD (*P*=0.05)	-	1.70	NS	NS	NS	0.03	2.41	0.68	0.23
Rice -Fallow	0-15	scl	55.08	17.42	27.50	1.28	2.58	29.73	27.51	28.63
	15-30	scl	50.75	18.79	30.46	1.38	2.63	26.51	30.34	25.31
	30-45	scl	47.36	18.53	34.11	1.44	2.65	25.64	32.41	20.28
	SEm(±)	-	0.46	1.31	1.31	0.04	0.003	0.46	0.39	0.07
	CD (*P*=0.05)	-	1.84	NS	NS	NS	0.013	3.86	1.58	0.27

scl: sandy clay loam, NB: 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 carbon (g kg^{-1})	Cation exchange capacity (cmol kg^{-1})
Rice-Vegetable	0-15	5.60	0.33	5.50	9.70
	15-30	6.20	0.31	5.20	10.80
	30-45	6.30	0.20	4.50	12.50
	SEm(±)	0.05	0.023	0.067	0.05
	CD (*P*=0.05)	0.21	0.091	0.269	0.21
Rice-Mustard	0-15	5.50	0.36	5.60	11.40
	15-30	6.40	0.32	5.30	12.50
	30-45	6.50	0.28	4.20	13.70
	SEm(±)	0.06	0.007	0.088	0.27
	CD (*P*=0.05)	0.23	0.027	0.355	0.07
Rice-Fallow	0-15	5.70	0.35	5.50	10.40
	15-30	6.30	0.33	5.40	12.60
	30-45	6.50	0.25	4.00	13.50
	SEm(±)	0.13	0.03	0.27	0.21
	CD (*P*=0.05)	0.03	0.01	0.07	0.05

Table 3: Pearson correlation coefficients (r) between saturated hydraulic conductivity and soil variables

Soil variables	Saturated hydraulic conductivity
Sand	0.890**
Clay	-0.814**
Bulk density (BD)	-0.442*
Particle density (PD)	-0.806**
Water holding capacity (WHC)	-0.898**
Porosity	0.792**
pH	-0.647**
Electrical conductivity (EC)	0.777**
Organic carbon (OC)	0.610**
Cation exchange capacity (CEC)	-0.480*

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

Table 4: Regression models of saturated hydraulic conductivity (Y) with soil variables

Model	Regression equation	R^2	Adjusted R^2	SE_{est}
1	Y= -19.66 + 0.85 sand	0.792	0.784	1.347
2	Y= 81.50 + 0.61 sand – 33.75 PD	0.855	0.843	1.149
3	Y= 93.47 + 0.73 sand – 45.65 PD + 2.18 pH	0.866	0.872	1.038

Table 5: Principal component loading matrix for soil properties under rice-vegetable cropping system

Soil variables	Soil depth (cm)					
	0-15		15-30		30-45	
	Principal Component					
	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2
Sand	**-0.913**	**-0.407**	**-1.000**	-0.012	**0.298**	**-0.955**
Silt	1.000	0.018	0.918	-0.397	**0.193**	0.981
Clay	**-0.956**	0.292	0.926	**0.377**	-0.818	**-0.575**
Bulk density	0.928	**-0.372**	1.000	**0.021**	-0.444	0.896
Particle density	**-0.928**	0.372	0.855	**0.518**	-0.998	0.063
Water holding capacity	0.967	0.255	0.938	**0.347**	**0.923**	0.386
Porosity	0.410	0.912	**-0.365**	**0.931**	**0.959**	0.285
pH	0.928	**-0.372**	0.537	**0.844**	-0.998	0.063
Electrical conductivity	**-0.142**	0.990	**-1.000**	-0.021	-0.675	0.738
Organic carbon	**-0.142**	0.990	**-0.998**	**0.061**	**0.964**	0.267
Cation exchange capacity	0.786	0.618	0.518	-0.855	-0.178	0.984
Hydraulic conductivity	**-0.100**	**-0.995**	**-0.474**	**0.880**	**0.998**	**-0.063**
Eigenvalues	7.106	4.894	8.221	3.779	7.167	4.833
Variance explained (%)	59.21	40.79	68.51	31.49	59.72	40.28

Table 6: Principal component loading matrix for soil properties under rice-mustard cropping system

Soil variables	Soil depth (cm)					
	0-15		15-30		30-45	
	Principal Component					
	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2
Sand	0.999	-0.036	**-0.903**	**-0.429**	**0.989**	0.150
Silt	0.914	**0.406**	0.999	**-0.033**	-0.987	**-0.159**
Clay	**-0.964**	-0.267	0.720	**-0.694**	**0.858**	0.513
Bulk density	**-0.589**	**0.808**	**-0.760**	0.650	**0.985**	**-0.174**
Particle density	**-0.966**	-0.260	0.041	0.999	-0.342	0.940
Water holding capacity	0.899	**0.437**	0.958	**-0.288**	-0.985	0.174
Porosity	0.846	**0.533**	**-0.931**	0.366	**0.558**	**-0.830**
pH	0.876	-0.483	0.782	0.623	**0.487**	0.874
Electrical conductivity	0.708	-0.707	0.931	**-0.366**	**0.985**	**-0.174**
Organic carbon	0.588	**0.809**	0.650	0.760	-0.643	**-0.766**
Cation exchange capacity	0.708	-0.707	**-0.995**	**-0.102**	**0.980**	**-0.198**
Hydraulic conductivity	**-0.961**	**0.275**	**-0.579**	**-0.816**	**0.985**	**-0.174**
Eigenvalues	8.606	3.394	7.921	4.079	8.606	3.394
Variance explained (%)	71.72	28.28	66.01	33.99	71.72	28.28

Table 7: Principal component loading matrix for soil properties under rice-fallow cropping system

Soil variables	Soil depth (cm)					
	0-15		15-30		30-45	
	Principal Component					
	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2
Sand	**0.899**	0.439	0.312	**-0.950**	**0.720**	0.694
Silt	**0.627**	**-0.779**	0.988	**-0.153**	**0.704**	**-0.710**
Clay	-0.880	0.474	**-0.788**	0.615	-0.964	0.267
Bulk density	**0.505**	0.863	**-0.968**	0.249	**0.997**	0.081
Particle density	-0.376	0.927	0.429	**-0.903**	-0.569	0.823
Water holding capacity	-0.971	0.237	0.998	**-0.062**	-0.773	**-0.634**
Porosity	-0.997	0.080	0.865	0.502	**0.453**	0.892
pH	**0.614**	0.789	**-0.991**	0.132	-0.997	**-0.081**
Electrical conductivity	**0.947**	**-0.322**	0.997	**-0.080**	-0.569	0.823
Organic carbon	**0.614**	0.789	0.514	0.858	-0.428	**-0.904**
Cation exchange capacity	-0.880	**-0.476**	0.568	0.823	**0.997**	0.081
Hydraulic conductivity	**0.376**	**-0.927**	**-0.768**	**-0.640**	**0.936**	**-0.352**
Eigenvalues	6.875	5.125	7.715	4.285	7.431	4.569
Variance explained (%)	**57.30**	**42.70**	**64.29**	**35.71**	**61.92**	**38.08**

Table 8: Principal component loading matrix for soil properties for predicting variance of saturated hydraulic conductivity

Variables	Principal components		
	PC 1	**PC 2**	**PC 3**
Sand	0.889	0.254	-0.080
Silt	-0.274	-0.089	0.939
Clay	-0.826	-0.254	**-0.294**
Bulk density	-0.760	0.383	-0.034
Particle density	-0.825	-0.316	0.039
Water holding capacity	0.740	-0.522	0.107
Porosity	**0.928**	0.049	-0.024
pH	-0.881	0.223	0.182
Electrical conductivity	0.788	0.293	0.236
Organic carbon	0.856	-0.155	0.153
Cation exchange capacity	-0.827	**0.470**	0.101
Hydraulic conductivity	**0.838**	**0.475**	**-0.046**
Eigenvalues	7.734	1.263	1.115
Variance explained (%)	64.45	10.53	9.29
Cumulative (%)	64.45	74.98	84.27

CONCLUSION

The principal component analysis (PCA) revealed that different soil factors in combination could play an important role in predicting a large variation in the saturated hydraulic conductivity of the soils. In different cropping systems and soil depths, the first component of this unorthodox technique could explain the maximum variance of the saturated hydraulic conductivity than the remaining second and third component. In medium cultivated land, porosity, cation exchange capacity and clay fraction were identified as the most important indicators for predicting the larger variability of the saturated hydraulic conductivity of the soils studied

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