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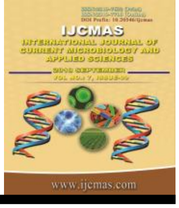

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Estimation of Saturated Hydraulic Conductivity of Red and Lateritic Highland Soils under Diverse Land Use Systems

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ABSTRACT

Fifteen soil profile samples representing the highlands of Purulia, Birbhum, Bardhaman, Bankura and Medinipur districts in red and lateritic zone of West Bengal were collected from 0-15, 15-30 and 30-45 cm depth under rice-vegetable, rice-mustard and rice-fallow cropping systems with a view to assess the predictability of saturated hydraulic conductivity of the soils as influenced by different physical, hydro-physical and chemical properties of the farmlands. Various statistical procedures such as correlation, regression, principal component analysis (PCA) and minimum data set (MSD) matrix were employed on the measured laboratory based dataset for comprehensive agreement of dependable hydraulic conductivity of soils as a model function of independent soil variables. The correlation and regression model suggested CEC as the key parameter in regulating the hydraulic conductivity in the soils. Based on the PCA and MSD techniques, it is revealed that clay, silt, sand, CEC, bulk density, porosity and organic carbon played varying role in estimating the variability of hydraulic conductivity of soils. The present study suggests that saturated hydraulic conductivity of the highland soils could be predicted largely from the measured values of silt and clay fraction, CEC and bulk density which seems be useful for efficient irrigation, drainage and crop planning programmes.

Introduction

The saturated hydraulic conductivity (Ks) is an important soil physical property which represents the ability of soil for water retention, water availability, crop suitability and land capability for groundwater recharge. The understanding of Ks of soil is essential for irrigation and drainage management, crop and groundwater modeling, and other hydrological and environmental processes. Hydraulic conductivity influences the water storage and water and solute transport in soil (Wijaya *et al.*, 2010).

The knowledge of Ks is indispensable for planning of life saving irrigation in rainfed region. The physical properties such as clay mineralogy, particle size, pore size distribution, organic carbon content and chemical characteristics and biotic activity of soil with Ks under varied land use systems play a vital role in the efficient utilization of soil and water resources programme (Fikry, 1990; Paramasivam, 1995). Infiltration, drainage and chemical leaching were strongly influenced by spatial and temporal distribution of soil Ks (Reynolds and Zebchuk, 1996). Soil hydraulic properties estimated from a laboratory experiment use commonly on relatively small soil cores, and they often fail to represent the entire field condition. Large numbers of soil samples are required to properly characterize an area of land. Many direct methods have been developed for measurement of saturated hydraulic conductivity in the field and laboratory conditions (Klute and Dirksen, 1986).

These methods are generally difficult, laborious and costly, and time consuming processes, so they are not practical to apply in all cases, especially for larger areas (Saikia and Singh, 2003). Many indirect methods have been used including prediction of Ks from more easily measured soil properties, such as texture classes, the geometric mean particle size, organic carbon content, bulk density and effective porosity (Wösten and van Genuchten, 1988). In recent years, pedotransfer functions (PTFs) were widely used to estimate the difficult to measure soil properties such as hydraulic conductivity from easy to measure soil properties (Bouma and van Lanen, 1987; Fodor and Rajkai, 2004). PTFs were intended to translate easily measured soil properties such as bulk density, particle size distribution, and organic matter content into soil hydraulic properties. Pedotransfer functions are multiple regression equations or models, which correlate the soil properties with easily available other soil properties (Salchow *et al.*, 1996). In practice, these functions often prove to be good predictors for missing soil hydraulic characteristics (Aimrun, 2009). The objective of this study was to predict the hydraulic conductivity of red and lateritic highland soils of West Bengal, India under different land use systems using some easily measurable soil parameters.

Materials and Methods

The study area is located between 22.43 and 23.84^0 N latitude and 87.06 and 87.86^0 E longitude with an average altitude ranging from 49.8 to 78.7 m above mean sea level. Physiographically the region is primarily characterized by undulating topography with numerous mounds and valley. The climate is humid sub-tropical with annual precipitation varying between 1100 mm and 1300 mm. The temperature ranges between 25.5 and 41.5 ^{0}C during summer and 12.7 to 18.3 ^{0}C during winter. Paddy is the staple crop of the area. The other major crops are oilseeds, wheat, pulses, and vegetables. Fifteen soil profile samples were collected from highland positions at a depth of 0-15, 15-30 and 30-45 cm with three land use systems (rice-vegetable, rice-mustard and rice-fallow) from Purulia, Birbhum, Bardhaman, Bankura and Medinipur districts under red and lateritic zone of West Bengal. 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 land use system from five different districts was then thoroughly mixed up to make a composite sample representing the soil of that particular layer under specific land use system. The same process was carried out for other soil layer under each cropping system also. The physical, hydro-physical and chemical characteristics of the soils were determined using standard methods (Black, 1965; Piper, 1973; Jackson, 1973). The Ks of the soil samples were determined by 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:

$$Ks = \frac{Q\Delta L}{AT\Delta H}$$

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 such as correlations, stepwise regression equations, principal component analysis (PCA), and minimum data set (MDS) were employed for analyzing the measured database with a view to have a meaningful prediction and interpretation of soil hydraulic conductivity vis-à-vis other soil properties.

Results and Discussion

Physical, hydro-physical and chemical characteristics of soils

The mechanical separates of the soils under different land use systems varied from 54.76 to 61.63% for sand, 22.95 to 25.45% for silt and 15.28 to 19.88% for clay (Table 1). The values consistently increased with increase in soil depth with some deviations. The texture of the soils was sandy loam and was relatively finer in the sub-surface horizons than in the surface horizon indicating the occurrence of clay illuviation under pedogenic processes (Rudramurthy *et al.*, 2007). The bulk density (BD) and particle density (PD) of the soils ranged between 1.23 and 1.40 Mg/m^3 and 2.62 and 2.66 Mg/m^3, respectively. The values were lower in the surface soil as compared with sub-surface soils. Increase in PD with profile depth could be attributed to higher sand fraction in surface soil than in sub-surface soils (Sahu and Mishra, 1997). Similarly, increase in BD down the profile could be attributed to the enhanced compactness and decrease in organic matter content (Walia and Rao, 1997). Relatively higher BD values in surface soil under paddy land use system were due to collapse of non-capillary pores during puddling operation (Rudramurthy *et al.*, 2007). The soil porosity varied from 30.35 to 36.44% and the values decreased with depth in all the pedons. This might be due to the dominance of finer clay and silt fractions in the sub-soils as compared with the surface soil. The water holding capacity (WHC) of soils ranged from 23.97 to 29.14%. The quantity of WHC increased with increase in soil depth. Higher amounts of finer fractions of soils *i.e.* silt and clay particles in the sub-soils might have resulted in the increased WHC. The saturated hydraulic conductivity (Ks) varied from 31.39 to 38.86 cm/h and the variation seemed to be more dependent on sand contents of the soils. Soil pH ranged between 5.53 and 6.20 indicating strongly acidic to slightly acidic in reaction (Table 2). The electrical conductivity (EC) of the soils varied from 0.16 to 0.24 dS/m. The organic carbon contents and CEC of soils varied within 2.43 to 5.80 g/kg and 6.0 to 10.37 cmol/kg, respectively. These high values of organic carbon in surface soil as compared with sub-surface soils were due to the accumulation of crop residues and restricted downward leaching.

Relationships of hydraulic conductivity with soil characteristics

There was highly significant positive correlation between Ks and sand fractions (r=0.919**), WHC (r=0.759**) and porosity (r=0.829**) and strong negative correlation with clay (r=-0.886**), PD (r=-0.844**) and CEC (r=-0.863**) of the soils (Table 3). It is assumed that increasing sand content increases the non-capillary pores in the soils which facilitates the higher Ks values of soils (Mathan and Mahendran, 1993). On the other hand, higher clay content in the soils is the impediment of Ks and thus decreased the soil water movement in the soil profile.

Regressive models of soil saturated hydraulic conductivity

An attempt was made to improve the predictability of Ks of cultivated soils by inclusion of other soil parameters. The Ks was used as the dependent variable to develop predictive models using stepwise regression equations with other soil parameters as independent variables. At first, no restriction was imposed, allowing independent variables to enter into the models competitively. The sequence of entry into the models depends solely upon the extent of contribution of each variable to the model. The levels of significance at which variables entered into the models and stayed in the models were both set at $P \leq 0.05$. The estimated coefficient of determination (R^2) indicated the relative suitability of different variables. The different sets of models with individual soil parameters are presented in Table 4. A critical examination of this regression equation showed that CEC alone could contribute about 72.9% of total variation in Ks. The second variable entered was sand, which improved the R^2 to 0.826. With the entry of third variable soil pH into the model, the R^2 raised to 0.857. The fourth variable entered into the model was BD which further increased the R^2 to 0.882. In other words, inclusion of four independent soil variables altogether could explain about 88.2% variability of Ks. In brief, CEC of soils was the key predictor among the variables examined and largely regulated the Ks of soils.

Principal component analysis for estimating the hydraulic conductivity of soils

The principal component analysis (PCA) was carried out to assess the effects of various soil parameters in determining the variability of Ks in different soil depths under different land use systems. All the variables having components loading with same sign (+/-) as Ks are highly associated. The opposite group (-/+) are responsible to reduce Ks. In PCA study if any variable is not included it means the variable has failed to create any variance.

The PCA of rice-vegetable cropping system at 0-15 cm depth revealed that the first component could explain about 59.81% of the variance when Ks was loaded by clay and PD of the soils (Table 5). In the second component, the soil Ks was regulated by sand, BD, PD, porosity, EC and OC for explanation of another 36.47% of the variance. For 15-30 cm depth, the first component could explain 65.83% of variance where Ks was positively regulated by sand, silt, BD, WHC, porosity, OC and CEC. Similarly, the second component revealed that Ks was controlled by silt, BD, PD, pH and EC explaining further 34.17% of the variance. In 30-45 cm depth, the first component could explain 64.42% of the variance where Ks were positively regulated by sand, BD, WHC, porosity, pH and OC. In the second component, Ks were commanded by sand, clay, PD, porosity, pH and EC for explaining another 35.58% of variance.

Under rice-mustard cropping at 0-15 cm depth, PCA showed that the first component could explain 62.5% of the variance when Ks was positively affected by sand, PD, WHC, porosity and pH of the soils (Table 6). Similarly, the second component further revealed that Ks was controlled by sand, BD, PD, porosity and EC for elucidation of another 37.5% of variance. For 15-30 cm depth, the first component could explain 60.46% of variance where Ks was positively regulated by silt, BD, PD, porosity, EC, OC and CEC. Likewise, the second component was mainly controlled by clay which could explain 39.54% variance of Ks. In 30-45 cm layer, the first component would explain 65.27% of variance where Ks was positively affected by silt, clay, PD, WHC, porosity, pH and OC.

Table.1 Physical and hydro-physical characteristics of soils for different land use systems

Land use system	Soil depth (cm)	Textural class	Sand (%)	Silt (%)	Clay (%)	BD (Mg/m^3)	PD (Mg/m^3)	Porosity (%)	WHC (%)	HC (cm/hr)
Rice-Vegetable	0-15	Sandy loam	61.63	22.95	15.42	1.31	2.62	34.44	25.32	38.86
	15-30	Sandy loam	58.44	24.45	17.11	1.38	2.63	32.45	25.41	35.92
	30-45	Sandy loam	58.44	25.18	16.38	1.40	2.65	30.58	25.73	35.47
	SEm(±)	-	0.464	0.584	0.334	0.041	0.007	0.071	0.054	0.097
	CD (0.05)	-	1.869	-	-	-	-	0.285	0.216	0.390
Rice-Mustard	0-15	Sandy loam	60.40	24.31	15.28	1.27	2.62	36.44	24.30	38.26
	15-30	Sandy loam	57.44	24.45	18.11	1.36	2.64	33.45	26.60	35.90
	30-45	Sandy loam	55.11	25.45	19.45	1.40	2.65	30.68	29.14	32.47
	SEm(±)	-	0.468	0.750	0.494	0.025	0.008	0.196	0.547	0.194
	CD (0.05)	-	1.886	-	1.992	0.100	-	0.791	3.204	0.782
Rice -Fallow	0-15	Sandy loam	60.74	23.98	15.28	1.23	2.63	34.44	23.97	36.26
	15-30	Sandy loam	57.44	24.78	17.78	1.32	2.64	32.45	26.65	33.31
	30-45	Sandy loam	54.76	25.36	19.88	1.35	2.66	30.35	28.43	31.39
	SEm(±)	-	0.528	0.675	0.792	0.011	0.007	0.057	0.730	0.066
	CD (0.05)	-	2.129	-	3.193	0.043	-	0.231	2.941	0.264

Table.2 Chemical characteristics of soils for different land use systems

Land use system	Soil depth (cm)	pH (1:2.5)	EC (dS/m)	OC (g/kg)	CEC (cmol/kg)
Rice-Vegetable	0-15	5.60	0.24	4.70	6.60
	15-30	5.80	0.22	3.37	8.40
	30-45	6.20	0.16	2.43	9.70
	SEm(±)	0.067	0.012	0.113	0.176
	CD (0.05)	0.269	0.048	0.456	0.711
Rice-Mustard	0-15	5.60	0.22	5.70	6.20
	15-30	5.70	0.21	3.63	7.30
	30-45	6.00	0.18	2.63	9.60
	SEm(±)	0.088	0.008	0.061	0.067
	CD (0.05)	-	0.032	0.245	0.269
Rice-Fallow	0-15	5.53	0.22	5.80	7.20
	15-30	5.80	0.21	3.70	8.23
	30-45	6.13	0.17	2.77	10.37
	SEm(±)	0.051	0.008	0.069	0.078
	CD (0.05)	0.205	0.034	0.280	0.315

Table.3 Coefficients of correlation (r) between hydraulic conductivity and soil variables

Soil variables	Hydraulic conductivity
Sand	0.919**
Clay	-0.886**
Particle density	-0.844**
WHC	0.759**
Porosity	0.829**
CEC	-0.863**

*’ ** indicate significant at 5 and 1% probability level, respectively

Table.4 Stepwise regression equation of hydraulic conductivity (Y) with different physical and physicochemical parameters of soils

Model	Regression equation	R^2	Adjusted R^2	SE_{est}
1	$Y = 47.028 - 1.455\ \text{CEC}$	0.729	0.718	1.291
2	$Y = 15.699 - 0.866 + 0.455\ \text{Sand}$	0.826	0.811	1.055
3	$Y = 1.547 + 1.398\ \text{CEC} + 0.440\ \text{Sand} + 3.333\ \text{pH}$	0.857	0.839	0.976
4	$Y = -9.937 - 1.637\ \text{CEC} + 0.462\ \text{Sand} + 3.706\ \text{pH} + 7.477\ \text{BD}$	0.882	0.861	0.906

BD = bulk density, CEC = cation exchange capacity

Table.5 Principal Component matrix for predicting variance of hydraulic conductivity of soils under rice-vegetables cropping system

Soil variables	Soil depth (cm)					
	0-15		15-30		30-45	
	Component		Component		Component	
	1	2	1	2	1	2
Sand	0.068	**0.998**	**0.221**	0.975	**0.643**	**0.766**
Silt	0.993	-0.118	**0.789**	**-0.615**	-0.122	-0.993
Clay	**-0.748**	-0.663	-0.885	0.465	-0.874	**0.487**
Bulk density	0.923	**0.385**	**0.969**	**-0.247**	**0.999**	-0.042
Particle density	**-0.795**	**0.607**	-0.978	**-0.208**	-0.985	**0.174**
Water holding capacity	1.000	-0.027	**0.087**	0.996	**0.342**	-0.940
Porosity	0.128	**0.992**	**0.978**	0.208	**0.643**	**0.766**
pH	0.795	-0.607	-0.996	**-0.095**	**0.998**	**0.068**
Electrical conductivity	0.923	**0.385**	-0.978	**-0.208**	-0.967	**0.254**
Organic carbon	0.128	**0.992**	**0.483**	0.876	**0.835**	-0.551
Cation exchange capacity	0.998	**0.062**	**0.978**	0.208	**1.000**	-0.001
Hydraulic conductivity	**-0.795**	**0.607**	**0.669**	**-0.743**	**0.643**	**0.766**
Variance explained (%)	59.81	40.19	65.83	34.17	64.42	35.58

Table.6 Principal component matrix for predicting variance of hydraulic conductivity of soils under rice-mustard cropping system

Soil variables	**Soil depth (cm)**					
	0-15		**15-30**		**30-45**	
	Component		Component		Component	
	1	2	1	2	1	2
Sand	**0.996**	**0.094**	-0.645	0.765	-0.982	-0.189
Silt	-0.997	-0.075	**0.517**	0.856	**0.958**	**0.285**
Clay	0.694	-0.720	-0.011	**-1.000**	**0.965**	-0.263
Bulk density	-0.511	**0.859**	**0.972**	0.235	-0.265	**0.964**
Particle density	**0.859**	**0.511**	**0.988**	0.155	**0.390**	-0.921
Water holding capacity	**0.964**	-0.265	-0.628	0.778	**0.603**	**0.798**
Porosity	**1.000**	**0.013**	**0.988**	0.155	**0.978**	**0.209**
pH	0.511	-0.859	-0.639	0.769	**0.670**	-0.742
Electrical conductivity	-1.000	-0.013	**0.988**	0.155	-0.209	**0.978**
Organic carbon	-1.000	-0.013	**0.941**	0.339	**0.998**	**0.067**
Cation exchange capacity	-0.511	**0.859**	**0.360**	0.933	-0.992	**0.128**
Hydraulic conductivity	**0.489**	**0.872**	**.939**	**-.344**	**0.603**	**0.798**
Variance explained (%)	**62.50**	**37.50**	**60.46**	**39.54**	**65.27**	**34.73**

Table.7 Principal component matrix for predicting variance of hydraulic conductivity of soils under rice-fallow cropping system

Soil variables	**Soil depth (cm)**					
	0-15		**15-30**		**30-45**	
	Component		Component		Component	
	1	2	1	2	1	2
Sand	**0.588**	**0.809**	**0.304**	-0.953	**0.679**	**0.734**
Silt	-0.091	-0.996	**0.865**	**0.502**	-0.915	-0.404
Clay	-0.698	**0.716**	-0.646	**0.763**	**0.894**	-0.449
Bulk density	-0.789	**0.614**	-0.487	**0.873**	-0.471	**0.882**
Particle density	-0.194	**0.981**	**1.000**	-0.015	-0.528	-0.849
Water holding capacity	-0.974	**0.225**	**0.314**	-0.950	-0.999	-0.034
Porosity	**0.322**	**0.947**	**0.666**	**0.746**	**0.734**	-0.679
pH	**0.752**	**0.659**	-0.979	**0.203**	**0.734**	-0.679
Electrical conductivity	-0.659	**0.752**	**0.666**	**0.746**	**0.528**	**0.849**
Organic carbon	**0.990**	**0.143**	**0.979**	-0.203	-0.471	**0.882**
Cation exchange capacity	**0.981**	**0.194**	-0.950	-0.314	**0.999**	-0.033
Hydraulic conductivity	**0.981**	**0.194**	**0.980**	**0.197**	**0.559**	**0.829**
Variance explained (%)	**53.83**	**46.17**	**60.50**	**39.50**	**54.06**	**45.94**

Table.8 Component matrix due to principal component analysis

Variables	**Principal component**			
	PC-1	PC-2	PC-3	PC-4
Sand	**0.956**	0.072	-0.053	0.069
Silt	0.566	**-0.559**	0.326	0.454
Clay	0.775	-0.292	-0.135	**-0.483**
Bulk density	0.67	0.228	**0.615**	-0.03
Particle density	0.778	0.139	-0.437	0.04
Water holding capacity	0.75	0.423	0.21	-0.183
Porosity	-0.96	-0.13	-0.014	0.013
pH	-0.873	0.241	0.118	0.222
Electrical conductivity	0.865	0.176	-0.206	0.27
Organic carbon	-0.805	-0.074	0.225	-0.399
Cation exchange capacity	-0.938	-0.197	-0.149	0.055
Eigenvalues	8.13	1.04	0.87	0.78
Variance explained (%)	67.78	8.67	7.28	6.53

Whereas the second component could explain 34.73% variability of Ks which was regulated by silt, BD, WHC, porosity, EC, OC and CEC.

In rice-fallow system for the depth 0-15 cm, PCA indicated that the first component could explain 53.83% of variance when Ks was positively outcome by sand, porosity, pH, OC and CEC of the soils (Table 7). Similarly, the second component was mainly contributed by sand, clay, BD, PD, porosity, WHC, pH, EC and OC for explanation of additional 46.17% of the variance. For 15-30 cm depth, the first component could explain 60.50% of variance where Ks was positively influenced by sand, silt, PD, WHC, porosity, EC and OC. Whereas, the second component revealed that Ks was controlled by silt, clay, BD, porosity, pH and EC for elucidating another 39.5% of variance**.** In the depth of 30-45 cm, PCA study showed that the first component was found to explain 54.06% of variance where Ks was positively affected by sand, clay, porosity, pH, EC and CEC. Likewise, the second component could explain of another 45.94% of variance of Ks which was regulated by sand, BD, EC and OC. The overall results showed that various soil factors have differential role in predicting the variability of hydraulic conductivity of the soils. Irrespective of soil depth and land use patterns, PCA could account for 53.83 to 65.83% of total variation in Ks in the first component and 34.17 to 46.17% of variation in second component. Also using the PCA technique, the variability of Ks in the soils at 0-15, 15-30 and 30-45 cm depth could explain by 53.83 to 62.50, 60.46 to 65.83 and 54.06 to 65.27% in first component and 37.50 to 46.17, 34.17 to 39.54 and 34.73 to 45.94% in second component, respectively. However, the component-I in PCA technique in predicting the maximum variability of Ks in all the layers of the soil profiles was found to be the most practical and useful for crop-irrigation management.

Minimum data set for predicting soil hydraulic conductivity

All retained physical, hydro-physical and chemical variables were then further explored under principal component analysis (PCA), through which, the number of independent variables could be reduced and could explain at least 5% of total variance. The variables within a component were considered which had a loading between the highest and 10% reduction on that highest loading value. The uncorrelated variable was also selected in minimum data set (MDS) along with the highest loaded variable. A single variable in any component was also selected in MDS. All MDS data were considered as independent variables to predict the dependent variable as hydraulic conductivity following the full model multiple techniques. All important predictors were tested for their significance by coefficient of regression (R^2), adjusted R^2 and standard error of estimate (SE_{est}) values.

Variables were auto-scaled prior to PCA. The number of components was determined by the Eigenvalue-one criterion. Here the hydraulic conductivity is nothing but the goal variable which was influenced by only seemingly uncorrelated predictors which have significant contribution towards Ks values. Replicated index value was further compared for mean values for each MDS variable due to soil versus depth sequences. All meaningful loadings were included in the interpretation of principal components (PC), which were considered significant if >5% of the total variance was explained. The minimum data set and associated tools for careful monitoring and observation will be essential for evaluating soil hydraulic conductivity in farmer's fields.

MDS variables were selected based upon PCA technique and the resulted component matrix where from sand, silt, BD and clay variables were selected from PC-1, PC-2, PC-3 and PC-4, respectively as MDS variables (Table 8). Full model regression equation was developed keeping dependent variable as hydraulic conductivity (Ks) and predictor variables as MDS as follows:

Ks = 52.30 - 0.029 silt* – 0.57 clay** + 6.02 BD* – 1.00 CEC** where, *$P<0.05$ and **$P<0.01$; $R^2 = 0.85$, Adjusted $R^2 = 0.82$, SE(est) = 1.00.

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