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Prediction of saturated hydraulic conductivity from soil physical properties under different forest vegetation using multivariate analysis techniques

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Abstract

Saturated hydraulic conductivity of five types of forest soils at two depths was assessed from the physical properties using multivariate analysis techniques. All the soil variables had very strong correlations with each other. Multiple regression models linking original data set demonstrated that clay and bulk density predicted 81.7% of total variation in saturated hydraulic conductivity. The principal component analysis (PCA) involving several soil parameters explained 92% of the variance. The regressive model for saturated hydraulic conductivity using minimum data set (MDS) from PCA such as sand and bulk density accounted for 81.2% of the variability. It was almost competitive with multiple regression equations in assessing the saturated hydraulic conductivity, but less predictive than PCA because of the involvement of several contributory soil parameters. All these statistical approaches may thus provide an alternative way of measuring the saturated hydraulic conductivity of forest soils indirectly from the measured values of soil physical properties.

Keywords: saturated hydraulic conductivity, forest soil, step-wise multiple regression, principal component analysis

1. Introduction

Saturated hydraulic conductivity (Ks) is one of the most important soil physical properties measuring the ability of the soil to transmit water through its voids. The knowledge of Ks is essential for planning irrigation and drainage design, crop module and groundwater modeling, and level of toxic pollutants intrusion in groundwater (Patil *et al.*, 2016) [16]. It is linked to groundwater recharge, soil water storage and release in the potential root zone for plant growth and agricultural production (Wijaya *et al.*, 2010) [26]. Some soil characteristics viz., structure, texture, grain size, the distribution of pore sizes, pore geometry and tortuosity, bulk density, organic matter, exchangeable cations, type and amounts of clay minerals substantially affect the soil hydraulic properties (Fikry, 1990; Paramasivam, 1995; Ndiaye *et al*., 2007; Wang *et al*., 2012; Chaudhari *et al*., 2015; Bardhan *et al*., 2016) [15, 13, 5, 2]. Among different land use and land cover systems, forest cover greatly influences the infiltration rate and hydraulic conductivity of soils mainly by way of developing surface and sub-surface macro-porosity, reducing surface runoff, controlling soil erosion and improving water retention capacity of soil as a result of leaf litter fall from the forest trees and its storage underneath the tree canopy. Different tree species along with land topography and climate also manipulate the hydraulic characteristics mainly by way of altering physical, chemical and biological environment of the soil (Newaj *et al*., 2007) [14]. Many direct methods have been developed over time for measurement of saturated hydraulic conductivity in the laboratory and field conditions (Klute and Dirksen, 1986) [11]. However, these practices are laborious, time-consuming and costly and often fail to represent in all soil types and environmental conditions due to extreme soil heterogeneity and experimental errors (Saikia and Singh, 2003; Zhang *et al*., 2007) [21, 28]. The high level of spatial and temporal variability of Ks in field condition calls for an inexpensive and rapid method to measure the soil Ks. Many indirect methods have been proposed to estimate Ks from easily measured soil properties in order to minimize the hardships and cost of estimation (Wösten and van Genuchten, 1988; Patil *et al*., 2009) [27, 17]. The application of multivariate analysis for prediction of soil Ks is a powerful tool which intends to translate laboratory measured soil variables into soil hydraulic properties. In this approach, the classical principal component analysis (PCA) is used for data reduction tool to select a few more interpretable soil components from the list of large data sets of soil properties. The provision proves to be good predictive indicators for unknown soil hydraulic characteristics (Aimrun, 2009) [1]. The purpose of the present study was to investigate the Ks of forest soils of semi-arid red and lateritic zone of West Bengal (India) having varying topography and vegetation, where the vast tract of land remained unattended for economic utilization. The objectives were to develop some predictive models on the Ks of the soil modified by soil properties and forest vegetation and its interrelations with other measured soil properties.

2. Materials and Methods

2.1 Description of Study Area

The experimental site, Jhilimili village under jurisdiction of Ranibandh block in Bankura district of West Bengal, is located on the banks of Kangsabati River. It lies between 22º81'67" N latitude and 86º61'67" E longitude with average altitudes ranging between 290 to 500 m above mean sea level. The area is surrounded by Raipur block in the east, Khatra-1 block in the north, Belpahari in the south in West Midnapore and Bandwan in the west in Purulia district (Fig 1). The geographical area is 7049 ha with 50% area under diversified forest coverage. Physiographic ally the area is characterized by gently undulating topography with mild sloping in all directions. The climate is humid sub-tropical with long hot summer and short cold winter. The temperature ranges between 27.5 and 43.5 ^{o}C during summer and 10.0 to 16.3 ^{o}C during winter. The mean annual precipitation varies from 1250 mm to 1300 mm with more than 75% of it being received during June through September in south-west monsoon season. The relative humidity varies from 40-85%. It represents the semi-arid red and lateritic soils and taxonomically classified as fine loamy, mixed, hyperthermic Haplustalfs. The soil of the site is mainly sandy loam in texture and developed from granite-gneiss and quartzite parent materials. The natural vegetation includes grasses and forest tree species.

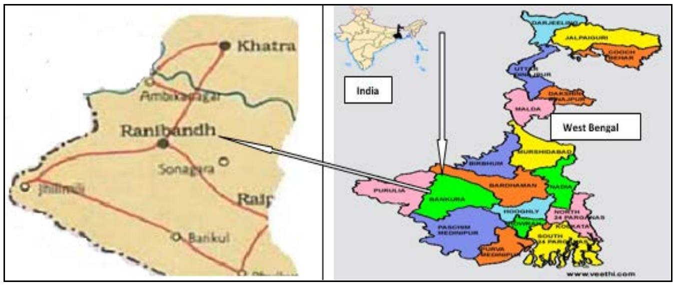

Fig 1: Location map of the study area with insets of West Bengal and India

2.2 Soil Sampling and Analyses

Composite soil profile samples were collected at random with the help of soil augur at a depth of 0-15 cm and 15-30 cm beneath the forest tree canopy of sal (*Shorea robusta*), segun (*Tectona grandis*), eucalyptus (*Eucalyptus tereticornis*), palas (*Butea monosperma*), and kendu (*Diospyros melanoxylon*). The samples after collection were cleaned, air-dried in shade and crushed to pass through a 2 mm size sieve and were used for physical, hydro-physical and chemical analysis. Standard analytical methods employed were hydrometer method for particle size distribution, core method for bulk density and particle density, and soil saturation method for porosity (Black, 1965), potentiometric method for soil pH and saturated soil paste extraction for electrical conductivity (Jackson, 1973), wet digestion method for soil organic carbon (Walkley and Black, 1934) and Keen Rackzowski method for water holding capacity (Piper, 1966). Saturated hydraulic conductivity of the soil samples were measured according to constant head method (Bouma *et al*., 1981). 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 column was measured over a period of time. The saturated hydraulic conductivity (Ks) using constant head method was calculated by Darcy's equation: $Ks = \frac{Q\Delta L}{AT\Delta H}$ where, Q is quantity of water discharged in time (cm^3), ΔL is soil length (cm), A is cross-sectional area of soil (cm^2), T is total time of discharge (hour) and ΔH is hydraulic head difference (cm).

2.3 Statistical Analyses

Various classical statistical methods were employed for analyzing the measured data base. The strength of interrelations between the observed soil variables was examined by Pearson correlation matrix (Table 2) to identify the most important dependent variables for inclusion in the principal component analysis (PCA). The PCA is a multivariate technique of covariance structure modeling which transformed the observed variables linearly into orthogonal uncorrelated variables known as principal components (PCs), which maintained the total variance in the original data. The PCA was performed on the correlation matrix, which in effect standardized data measured on different scales to unit variance. As a result, the PCs became independent of the scales and units of the observed variables. The output from PCA comprised the eigenvalues, eigenvectors and weighted loading scores. The eigenvalues gave the variance accounted for by each component and the PCs are ranked accordingly (Table 5). The first PC explained most of the variation; subsequent components were orthogonal to one another and uncorrelated, with reducing variance accounted for. Principal components with eigenvalues < 1 were regarded in our case because they accounted for some information akin to the original variable. Only the PCs which could explain at least 5% of the data variation were considered for identifying the MDS (minimum data set). The indicators receiving weighted loading values between the highest and 10% reduction of the highest weighted loading were selected for the MDSs for each PC. The uncorrelated variables in any PC were also selected in MDSs. The multiple linear regression analysis as developed by using the selected MDSs as independent soil variables for prediction of the saturated hydraulic conductivity (Ks) of the soils was verified for their significance by coefficient of regression (R^2), adjusted R^2 and standard error of estimate (SE_{est}). In the step-wise regressive predictive models, the saturated hydraulic conductivity was used as the dependent variable and other soil factors as the independent variables. All the independent soil 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 soil variables in the prediction of the saturated hydraulic conductivity. All statistical analyses were worked out by using SPSS 16.0 version and Excel software.

3. Results and Discussion

3.1 Soil Properties

The mechanical composition of the soils irrespective of forest vegetation species varied from 15.33 to 26.46% for clay, 25.29 to 28.65% for silt and 45.07 to 58.45% for sand (Table 1). The clay and silt contents were higher in subsoil than in surface soil, while sand fractions followed the opposite trend, indicating the occurrence of clay and silt migration under pedogenic as well as pedoturbation processes (Rudramurthy *et al*., 2007) [19]. In general, the surface soil was sandy loam and subsoil was clay loam in texture. The bulk density (BD) and particle density (PD) of the soils ranged from 1.34 to 1.40 Mg/m^3 and 2.62 to 2.67 Mg/m^3, respectively. The higher BD values in subsoil as compared to surface layer could be attributed to higher clay and silt contents (Sahu and Mishra, 1997) [20] and reduced organic matter content, greater compactness and root penetration (Walia and Rao, 1997; Kisku *et al*., 2017) [23, 10]. The soil porosity ranged between 26.44 and 36.54% and decreased with depth in all the pedons. This was related to the higher sand content in surface soil resulting in increased non-capillary pore and consequently dictated the higher values of Ks. The values of water holding capacity (WHC) of soils ranged from 44.48 to 49.22% and increased with depth. High amounts of finer silt and clay particles in subsoil as compared with the surface soil portrayed higher WHC. The saturated hydraulic conductivity of the soils varied from 19.23 to 20.09 cm/hr. Increased sand content in surface soil increased the macro porosity, thereby the higher soil Ks (Thorar *et al*., 1993) [22]. Soil pH under different tree plantation was strongly to mildly acidic in nature (5.45 and 6.2) and decreased with soil depth.

The variations in acidity among the soils were due to production of organic acids on decomposition of leaf litter and their difference in biochemical composition (Datta *et al.*, 2015) [6]. The electrical conductivity (EC) of the soils varied from 0.17 to 0.30 dS/m and the values were higher in surface soil than in subsoil. The magnitude of variation was little in subsoil layer under different tree vegetation. The organic carbon contents were medium to high (6.11 to 7.82 g/kg) and decreased with depth. Maximum organic carbon content in surface soil as compared with subsoil was due to accumulation of organic matter on decomposition of forest leaf litter fall in varying level (Deb *et al.*, 2016) [7].

3.2 Correlations between Saturated Hydraulic Conductivity and Some Soil Properties

All the soil variables showed very strong correlation with each other (Table 2). Saturated hydraulic conductivity gave the highly significant positive correlations with porosity (r=0.893) organic carbon (r=0.793) and sand contents (r=0.891) and highly significant negative correlations with bulk density (r=-0.884), particle density (r=-0.914), water holding capacity (r=-0.945), silt (r=-0.844) and clay contents (r=-0.894) of soils at 0.1% level of probability. This indicates that an increase in sand and a decrease in clay and silt contents did contribute to the enhancement of the saturated hydraulic conductivity. This was presumably due to the increase in non-capillary pores in the soils as sand having single grain structure likely to control the textural permeability and thereby the magnitude of saturated hydraulic conductivity. This shows the dependence of saturated hydraulic conductivity on the textural variability of the soil matrix which corroborated with the findings of Kisku *et al.* (2017) [10]. 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.

3.3 Regressive models for predicting saturated hydraulic conductivity

In the linear regressive models developed, only two independent variables out of a large data set of raw soil variables were involved to predict the saturated hydraulic conductivity of the soils. The first variable accommodated in the model was negatively correlated clay fraction which could explain 78.1% of the total variation in the saturated hydraulic conductivity (Table 3). The second variable entered into the model was negatively correlated bulk density which improved the R^2 value to 0.817, of which 3.6% was contributed by bulk density. In other words, the inclusion of two independent soil variables *i.e.* clay and bulk density could predict 81.7% of the variability in saturated hydraulic conductivity of the soils. However, clay fraction was found to be the key indicator in the predictive models and largely regulates the saturated hydraulic conductivity of the soils.

3.4 Minimum data set using principal component analysis for predicting saturated hydraulic conductivity

All the replicated data for soil variables of the five forest soil horizons were subjected to principal component analysis (PCA) to identify the representative soil factors as MDS from the eight indicators examined (Table 4). Under a particular PC, each variable had corresponding eigenvector weight value or factor loading. In each PC, only the highly weighted variables with factor loading value within 10% of the highest values that explaining 5% of total variance were retained as the most appropriate indicators for the MDS. The highly weighted eigenvectors with eigenvalues > 1 initially selected as MDSs from PC 1 were positively loaded water holding capacity, silt and clay variables and negatively loaded porosity, organic carbon and sand variables as these PCs explained 85% of the total variation. The eigenvectors with eigenvalues < 1 from PC 2 was also primarily considered as MDS to account for another 7% of the variance where bulk density alone was the highest weighted positive variable. Thus the indicators in both PC 1 and PC 2 in PCA could explain 92% variability of the soil saturated hydraulic conductivity. As more than one variable was retained under PC 1, multivariate correlation matrix was used to determine the correlation coefficients between the soil parameters. The cluster or proximity of the variables on the correlation circle shown in Fig 2 indicates a similar correlation of these variables to the two PCs, and thus a high correlation between these variables. Therefore, these variables most likely behave similarly. Only single variable with higher strength of correlation showing maximum distance from the centre of circle from each PC was selected as MDS variable. Accordingly, the sand from PC 1 and bulk density from PC 2 which has the highest loading factor was retained in the final MDS. All other variables were eliminated from the MDS to avoid redundancy. After selection of variables for the MDS, all the replicated and mean values for each forest soils versus depth sequences were transformed into dimension less values using linear scoring method (Table 5). The numerical scores were displayed in stacked column diagram for both liner scored and weighted liner scored MDS variables (Figs. 3 and 4). In the soil versus depth sequences, higher hydraulic conductivity of soil was portrayed where the column height was relatively higher and sand fraction was more pronounced than bulk density in augmenting the hydraulic conductivity. This study is useful to compare the hydraulic conductivity performance of each soil depth under different forest vegetation system.

A full model regression equation was thus developed keeping saturated hydraulic conductivity (Ks) as dependent variable and selected MDSs as predictor or independent variables as follows: Ks = 22.56 + 0.055 sand** - 3.308 bulk density*, where $*P<0.05$, $**P<0.01$; $R^2 = 0.812$, Adjusted $R^2 = 0.794$, $SE_{est.} = 0.143$. However, PCA based MDS model for Ks using only two soil variables was less predictive than the PCA involving PC 1 and PC 2. This may be explained that several other soil factors assigned with PCA technique might have contributed positive role in determining the saturated hydraulic conductivity of the soils.

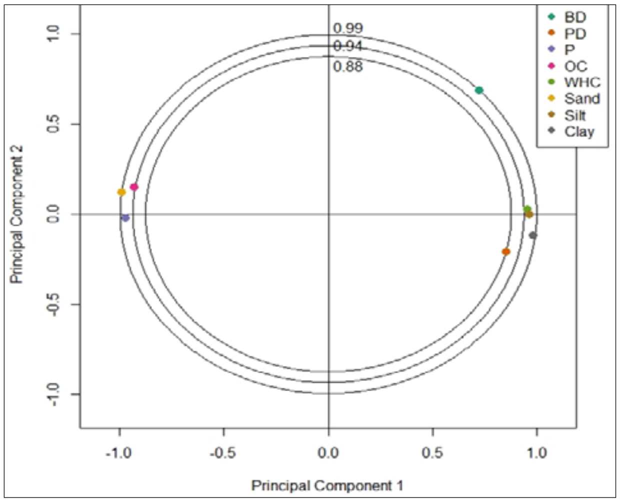

Fig 2: Circular diagram of different regression factor scores of all forest soils and depth sequences for first two principal components

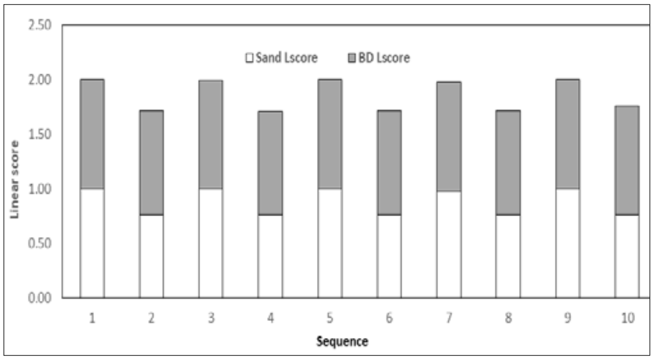

Fig 3: Column diagram to show the relative total linear score along with the MDS contribution for each forest soil at each depth

Fig 4: Column diagram to show the relative total weighted linear score along with the MDS contribution for each forest soil at each depth

Table 1: Physical and physicochemical properties of the experimental soils under different forest vegetation

Vegetation	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture	Bulk density (Mg/m³)	Particle density (Mg/m³)	Porosity (%)	WHC (%)	HC (cm/hr)	pH (1:2.5)	EC (dS/m)	OC (g/kg)
Sal	0-15	16.17	25.41	58.41	Sandy loam	1.34	2.63	48.56	45.32	20.12	5.86	0.29	7.61
	15-30	26.17	28.35	45.48	Clay loam	1.37	2.65	47.32	48.22	19.52	5.72	0.18	6.30
	SEm(±)	0.05	0.03	0.03	-	0.01	0.01	0.01	0.03	0.03	0.07	0.006	0.01
	CD (0.05)	0.21	0.12	0.10	-	0.03	0.02	0.22	0.14	0.14	0.28	0.02	0.03
Segun	0-15	15.33	26.52	58.15	Sandy loam	1.36	2.62	48.14	46.14	20.09	6.15	0.30	7.82
	15-30	26.46	28.47	45.07	Clay loam	1.40	2.67	47.16	49.22	19.23	5.77	0.18	6.50
	SEm(±)	0.30	0.18	0.19	-	0.01	0.01	0.03	0.02	0.05	0.07	0.004	0.02
	CD (0.05)	1.20	0.73	0.75	-	0.03	0.02	0.10	0.08	0.21	0.26	0.01	0.06
Eucalyptus	0-15	16.08	25.53	58.39	Sandy loam	1.35	2.63	48.70	44.48	20.13	6.13	0.26	7.32
	15-30	25.99	28.65	45.37	Clay loam	1.38	2.66	47.23	47.82	19.75	5.67	0.17	6.11
	SEm(±)	0.24	0.14	0.15	-	0.01	0.01	0.07	0.17	0.03	0.11	0.01	0.01
	CD (0.05)	0.95	0.55	0.61	-	0.03	0.03	0.26	0.67	0.13	0.41	0.03	0.03
Palas	0-15	16.10	26.49	57.41	Sandy loam	1.34	2.62	48.47	44.83	20.12	6.20	0.29	7.40
	15-30	26.32	28.41	45.27	Clay loam	1.37	2.65	47.32	47.82	19.75	5.57	0.18	6.21
	SEm(±)	0.06	0.03	0.06	-	0.01	0.01	0.04	0.05	0.03	0.09	0.006	0.01
	CD (0.05)	0.23	0.13	0.24	-	0.04	0.02	0.17	0.21	0.10	0.37	0.02	0.03
Kendu	0-15	16.26	25.29	58.45	Sandy loam	1.34	2.63	48.42	45.45	20.09	6.03	0.28	7.61
	15-30	26.09	28.65	45.26	Clay loam	1.36	2.66	47.26	48.30	19.64	5.70	0.18	6.60
	SEm(±)	0.15	0.12	0.05	-	0.01	0.01	0.03	0.03	0.04	0.07	0.01	0.01
	CD (0.05)	0.60	0.47	0.18	-	0.03	0.03	0.12	0.11	0.17	0.29	0.03	0.03

HC: hydraulic conductivity, WHC: water holding capacity, OC: organic carbon

Table 2: Linear correlation coefficient matrix between saturated hydraulic conductivity and soil physical properties

Variable	Clay	Silt	Sand	BD	PD	Porosity	WHC	HC
Silt	0.948*							
Sand	-0.998*	-0.967*						
BD	0.796*	0.805*	-0.805*					
PD	0.937*	0.846*	-0.926*	0.834*				
Porosity	-0.966*	-0.972*	0.976*	-0.845*	-0.898*			
WHC	0.936*	0.921*	-0.941*	0.869*	0.911*	-0.977*		
HC	-0.894*	-0.844*	0.891*	-0.884*	-0.914*	0.893*	-.945*	
OC	-0.962*	-0.906*	0.958*	-0.746*	-0.872*	0.894*	-.822*	0.793*

*correlation is significant at 0.1% level of probability; BD: bulk density, PD: particle density, OC: organic carbon, HC: hydraulic conductivity

Table 3: Stepwise regression equations of saturated hydraulic conductivity (Y) with different soil physical variables

Model	Prediction equation	Model R^2	Adjusted R^2	$SE_{est.}$	β value	Rank
1	Y = 20.659 + 0.0527 clay	0.781	0.773	0.148	clay: -0.732	I
2	Y = 25.46 – 0.043 clay – 3.448 BD	0.817	0.804	0.137	BD: -0.244	II

Table 4: Principal components, eigenvalues and component matrix variables from principal component analysis

Principal components	PC 1	PC 2
Eigenvalues	6.80	0.56
Proportion of variance (%)	84.99	7.05
Cumulative proportion of variance (%)	84.99	92.04
Eigen vectors or factor loading		
Bulk density	0.72	0.69
Particle density	0.85	-0.21
Porosity	-0.97	-0.02
Organic carbon	-0.93	0.15
Water holding capacity	0.95	0.03
Sand	-0.99	0.12
Silt	0.96	-0.002
Clay	0.98	-0.12

Bold face factor loadings are highly weighted and underlined bold faces are retained in MDS

Table 5: Forest cover versus soil depth sequence

Sequence	1	2	3	4
Soil cover	**Sal forest**		**Segun forest**	
Depth (cm)	0-15	15-30	0-15	15-30
Sequence	5	6	7	8
Soil cover	**Eucalyptus forest**		**Palash forest**	
Depth (cm)	0-15	15-30	0-15	15-30
Sequence	9	10		
Soil cover	**Kendu forest**			
Depth (cm)	0-15	15-30		

4. Conclusion

The above study on the saturated hydraulic conductivity vis-à-vis soil physical properties gave an idea about the behaviour of hydraulic conductivity of the soils as modified by different forest vegetation. All the soil variables displayed very strong correlation with each other. Multiple regression model using clay and bulk density variables predicted 81.7% of the variability in soil Ks. The principal component analysis (PCA) involving two components altogether explained 92% of the variance. However, PCA based regressive model using sand and bulk density as MDS variables assessed 81.2% of the total variance of Ks. The MDS through PCA technique and other associated statistical tools may thus provide an alternative way of measuring the Ks indirectly from the measured basic soil properties. This precious information is being useful for sustainable management of land and water, soil nutrients, erosion control and crop production.

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