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Estimating S-index, Unsaturated Hydraulic Conductivity and Diffusivity through RETC in Indian Agricultural Research Institute Farm

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The hydraulic properties of *vadoze* zone like hydraulic conductivity, diffusivity and soil water retention characteristics are required to study soil water, nutrient and pollutant dynamics and their management. Surface layer of ten master profiles of Indian Agricultural Research Institute (IARI) farm, New Delhi were studied for different physicochemical and hydraulic properties. All ten master profiles were grouped under the order Inceptisol, subgroup Typic Haplustept and hyperthermic soil temperature regime. The soil water retention data were measured for all the sample layers and fitted to van Genuchten model using RETC software. The R^2 value of fitted curve varied between 0.98 to 0.99 with residual sum of squares from 0.001 to 0.003. The θr value varied between 0.0332 to 0.0760 $cm^3\ cm^{-3}$ and the saturated water content between 0.4665 to 0.3613 $cm^3\ cm^{-3}$. In the present study, α ranged between 0.0018 to 0.0164 cm^{-1}. The n value varied between 1.381 to 2.437. Combined for all profiles the prediction equation developed for K(θ) is $K(\theta) = 1.17\times10^{6}\times\theta^{11.93}$ and D(θ) is $D(\theta) = 2.07\times10^{7}\times\ \theta^{7.71}$ with R^2 value of 0.77 both for K(θ) and D(θ). The S-index varied between 0.068 to 0.128. The S-index was significantly positively correlated with θr (r = 0.73*), θs (r = 0.64*), n (r = 0.97**) and significantly negatively correlated with α (r = -0.80**). The S-index value for all the 10 master profiles were more than 0.050 indicating very good physical quality for all the 10 master profiles of IARI experimental farm.

Key words: S-index, hydraulic conductivity, diffusivity, RETC, IARI

Water is a limited and precious natural resource in agriculture. Efficient use of water resources for optimization of crop and water productivity under both irrigated and rainfed condition requires a thorough understanding of the *vadoze* zone soil hydraulic properties (Pradhan *et al*. 2010). Hydraulic conductivity as a function of water content, K(θ), or pressure head, K(h), is the most important parameter governing the water flow and mass transport in unsaturated soils (Arya *et al*. 1999). While a large number of laboratory and field methods have been developed to directly measure the unsaturated hydraulic conductivity (Klute and Dirksen 1986; Green *et al*. 1986), most methods are costly and time consuming, and the results are variable, error-prone, and applicable to only a narrow range of saturation (Arya *et al*. 1999). Thus, there is a need for cheaper and more expedient methods for estimating the hydraulic properties for managing water and chemicals in the *vadoze* zone.

Now-a-days an alternative to direct measurement of the unsaturated hydraulic conductivity is the use of theoretical methods, which predict the conductivity from more easily measured soil water retention data (Childs and Collis-George 1950; Burdine 1953; Mualem 1976b). Such theoretical methods are generally based on statistical pore-size distribution (PSD) models, which assume water flow through cylindrical pores and incorporate the equations of Darcy and Poiseuille. These models require measured soil water retention data either in tabular form, or by

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means of closed-form analytical expressions, which contain parameters that are fitted to the observed data. Though there are large numbers of soil water retention functions, only few can be incorporated into the PSD models to yield relatively simple analytical expressions for the unsaturated hydraulic conductivity function.

There are many advantages of use of analytical functions in soil water flow studies and one of the important advantages is that it allows for a more efficient representation and comparison of the hydraulic properties of different soils and soil horizons. Because of their simplicity and ease of use, predictive models for the hydraulic conductivity estimation have become very popular in numerical studies of unsaturated flow. However, it has been found that predictive models work reasonably well for many coarse-textured soils and other porous media having relatively narrow pore-size distributions, and fail for many fine-textured and structured field soils. But considering the practical difficulty of direct field measurement and field scale spatial variability problem, predictive models provide the only viable means of characterizing the hydraulic properties of large areas of land.

The RETC computer program may be used to fit several analytical models to observed water retention and/or unsaturated hydraulic conductivity data. The soil water retention data are described with the equations of Brooks and Corey (1964) and van Genuchten (1980) whereas the pore-size distribution models of Burdine (1953) and Mualem (1976a) are used to predict the unsaturated hydraulic conductivity function.

Soil physical properties like texture, structure, bulk density control soil hydraulic behaviour and ultimately the water and solute movement in the soil. Recently, Dexter (2004) has proposed the use of single value "S-index" to quantify soil physical quality and is equal to the slope of the water retention curve at its inflection point. Tormena *et al*. (2008), Chakraborty *et al*. (2010) and Sinha et al. (2014) have used Dexter's S-index to quantify soil physical quality under different tillage, fertilizer and manure applications. So it necessitates the study of physical property along with the soil hydraulic properties for efficient water management in a farm. Keeping these in view, the present study was conducted to find out the predictive functions for soil hydraulic properties like K(θ) and D(θ) and soil physical quality S-index in the master profiles of experimental farm of Indian Agricultural Research Institute (IARI), New Delhi.

Materials and Methods

Study Area

The present study was conducted at the experimental farm of Indian Agricultural Research Institute, New Delhi (28°38' N Latitude, 77°09' Longitude and 228 m above mean sea level). The climate is semi arid with warm summer and mild winter. The annual maximum temperature goes as high as 45 °C in summer, whereas the minimum temperature dip to as low as 1°C in winter. The mean summer and mean winter temperatures were 33.0 and 17.3 °C, respectively. The mean annual rainfall is around 750 mm, of which a substantial amount (80%) is received during July to September.

Total cultivated area of the farm is about 278 ha. Different administrative blocks, such as Main Block (MB), Middle Block (MID), Genetic Block (GEN), Shadipur orchard and block, New Area (NA), Sewage irrigated area (SA), Top Block (TB), Todapur (TDPR), Water Technology (WTC) Block, NBPGR Block, Paddock field, Precision Farming and Development Centre (PFDC) area, greenhouse area and forest area are delineated in the farm for efficient farm operation. Diversified crop farming has been carried out in the farm. The major cultivated crops during *kharif* season are rice, maize, sorghum, pearl millet, soybean, black gram, pigeon pea, cowpea, vegetables, flowers, *etc*. whereas during *rabi* season, the major crops such as wheat, rice, maize, cotton, chick pea, pea, lentil, pigeon pea, vegetables, flowers, cowpea, *etc*. are grown. Cultivation of high value crops within greenhouse is followed in southern part of the farm under Indo-Israel project. Sewage water is specifically used for irrigating the crops in western edge of the farm. Permanent fruit orchards of ber, mango, citrus, aonla, guava, jamun, grape, *etc*. are seen in the Shadipur block, Todapur block and NBPGR block of IARI farm. Block plantation of Jatropha curcas and Eucalyptus has also been done in Genetic block and natural forest is located in south east corner of IARI farm.

Soil Sampling and Analysis

Thirty three profiles upto the depth of 2 m were excavated in IARI farm in collaboration with National Bureau of Soil Survey and Land Use planning (NBSS&LUP), Regional Centre, New Delhi. Soil morphology of each soil profile was studied in the field. Out of the 33 profiles, 10 profiles were categorized as master profiles representative to ten soils from IARI farm (A, B, C, D, E, F, G, H, I and J soils). Each diagnostic layer of the master profile was studied for physicochemical properties. Each profile was also classified as per USDA soil taxonomy. In the present study, analyses of all the soil parameters were done for the surface layers of the 10 master profiles.

Soil samples were collected in polythene bags, air-dried, ground with pestle and mortar, sieved through 2-mm sieve for analysis of different soil parameters. The soil samples were analyzed for pH (Jackson 1973), electrical conductivity (EC) (Richards 1954), organic carbon (Walkley and Black 1934) and mechanical composition (Bouyoucos 1962) and are presented in table 2. Soil bulk density was found out by core method (Blake and Hartge 1986) and saturation water content by gravimetric method (Wilcox 1951) and are also presented in table 2.

Water retention (θ) of the samples at various suctions (ø) was estimated by using pressure plate apparatus (Richards 1965). The soil water retention curve can be described using a number of empirical equations. A related smooth function to describe the soil water characteristics is the equation of van Genuchten (1980), herein referred to as the VG equation:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \quad \ldots(1)$$

where, h is the suction head form of the matirc potential (L) having positive values, θ is the volumetric water content (L^3/L^{-3}), θ_r is the residual water content and specifies the maximum amount of water in a soil that will not contribute to liquid flow because of blockage from the flow paths or strong adsorption on the solid phase, θ_s is the saturated/ satiated water content which denotes the maximum volumetric water content of a soil, and α (L^{-1}), m and n are empirical constants affecting the shape of the retention curve.

A simplified case, which appears to be valid for many soils, can be obtained by adopting the relationship m = 1 - (1/n). Prediction of the unsaturated hydraulic conductivity requires relationship between the hydraulic conductivity and moisture-retention relationship.

The model of Mualem (1976a) for predicting the relative hydraulic conductivity (K_r) can be written as

$$K_r(S_e) = (S_e)^l \frac{\eta(S_e)}{\eta(1)} \quad \ldots(2)$$

$$\text{and } \eta(S_e) = \left[\int_0^{S_e} \frac{1}{h(x)} dx\right]^2 \quad \ldots(3)$$

where, S_e is effective saturation: $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$, l is empirical constant and is equal to 0.5 for many soils.

The simplest case arises when K=0, which leads to the restriction m = 1 - 1/n allows the hydraulic conductivity $K(S_e)$, to be expressed as

$$K(S_e) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad \ldots(4)$$

The soil water diffusivity function, D, corresponding to (4) is

$$D(S_s) = \frac{(1-m)K_s S_e^{1-1/m}}{\alpha m(\theta_s - \theta_r)} \left[\left(1 - S_e^{1/m}\right)^{-m} + \left(1 - S_e^{1/m}\right)^m - 2\right] \quad \ldots(5)$$

RETC (Van Genuchten *et al*. 1991), a software available in the public domain, uses a nonlinear least-squares optimization approach to estimate the unknown model parameters from observed retention and/or conductivity or diffusivity data. In this experiment the unknown model parameters (θ_r, θ_s, α, n) and unsaturated hydraulic conductivity and diffusivity were obtained by the van Genuchten and Mualem model of RETC software.

Then the model parameters were used to compute S value, a soil physical quality index (Dexter 2004), as follows:

$$S = -n(\theta_s - \theta_r)\left[\frac{2n-1}{n-1}\right]^{\frac{1}{n}-2} \quad \ldots(6)$$

Results and Discussion

Physiography, Soils and Land Use Pattern of Master Profiles

The 10 master profiles observed in IARI farm were profile 5, 7, 14, 16, 18, 20, 21, 24, 25 and 31. The physiography, soils and land use of master profiles are presented in table 1. The master profiles 5, 7, 25 and 31 came under Old alluvial plain, 14, 16 and 18 under Lower piedmont plain and 20, 21 and 24 under Upper piedmont plain. All the ten master profiles were grouped under the order Inceptisol, subgroup Typic Haplustept and hyperthermic soil temperature regime. The taxonomy and cropping sequence followed in these profiles during *kharif* and *rabi* season has been given in table 1.

Table 1. Physiography, soils and land use or cropping system of master profiles of IARI farm

Master profile	IARI block in which profile is located	Latitude and longitude	Physiography	Pusa soils and taxonomy (*kharif* and *rabi* (2009-10 and 2010-11)	Cropping sequence
Profile 5	MB-15	28°38.59′N 77°09.13′E	Old alluvial plain	Pusa J soils : Fine loamy over coarse loamy, mixed (calc.), hyperthermic, Fluventic Haplustepts	Green manuring (*Dhaincha*) - chickpea
Profile 7	Gen-H	28°38.51′N 77°09.66′E	Old alluvial plain	Pusa H soils : Coarse loamy, mixed (calc.), hyperthermic, Typic Haplustepts	Maize, bajra and cotton/ Network project – Wheat, mustard, chickpea, vegetable
Profile 14	TB-2F	28°38.02′N 77°09.33′E	Lower piedmont plain	Pusa E soils : Coarse loamy, mixed (calc.), hyperthermic, Typic Haplustepts	Moong and green manuring – Chickpea
Profile 16	Paddock-2	28°38.74′N 77°09.43′E	Lower piedmont plain	Pusa D soils : Coarse loamy, mixed, hyperthermic, Typic Haplustepts	Arhar – seed production
Profile 18	TB-6E	28°37.87′N 77°09.47′E	Lower piedmont plain	Pusa F soils : Fine loamy, mixed (calc.), hyperthermic, Typic Haplustepts	Arhar, bajra – wheat, chickpea
Profile 20	TDPR-1C	28°37.74′N 77°09.73′E	Upper piedmont plain	Pusa C soils : Coarse loamy, mixed, hyperthermic, Typic Haplustepts	Arhar and Indo-israel project – Chickpea
Profile 21	Green House	28°37.58′N 77°09.65′E	Upper piedmont plain	Pusa B soils: Coarse loamy, mixed (calc.), hyperthermic, Typic Haplustepts	High value vegetable crops like tomato, cauliflower, broccoli, capsicum *etc*.
Profile 24	Orchard	28°37.45′N 77°09.68′E	Upper piedmont plain	Pusa A soils : Coarse loamy, mixed (calc.), hyperthermic, Typic Haplustepts	Citrus and mango orchard
Profile 25	MB-4A	28°38.41′N 77°09.64′E	Old alluvial plain	Pusa I soils : Fine loamy, mixed (calc.), hyperthermic, Typic Haplustepts	Maize. soybean – maize, wheat, mustard, chickpea
Profile 31	MID-A1,2	28°38.13′N 77°09.17′E	Old alluvial plain	Pusa G soils : Coarse loamy, mixed, hyperthermic, Typic Haplustepts	Bhendi, cowpea, brinjal, dhaincha, moong, soybean – maize, wheat, chickpea, broccoli, *etc*.

Soil Physicochemical Properties

Important physicochemical properties of surface layer of master profiles are presented in table 2. The depth of surface layer varied between 12 cm at profile 7 to 18 cm at profile 20. The soil bulk density ranged between 1.42 g cm^{-3} at profile 5 to 1.58 g cm^{-3} at profile 16. The sand content showed wide variation of 3.51% for profile 5 to 39.73% for profile 20. The silt content ranged between 25.64 (profile 20) to 48.20% (profile 31) and clay content between 20.27 (profile 21) to 56.49% (profile 5) for the master profiles. The surface soil texture observed for IARI farm was clay (profile 5), loam (profile 7, 14, 21 and 31) and clay loam (16, 18, 20, 24 and 25). The pH of the surface layer varied from neutral to slightly alkaline (pH 6.83 to 7.80) and the soil was non-saline (EC 0.33-1.52 dS m^{-1}). The organic carbon of IARI farm was low varying between 1.83 to 7.90 g kg^{-1} of soil. The saturation water content (θ_s) of the master profiles varied between 0.36 to 0.46 cm^3 cm^{-3} for profile 31 and Profile 5, respectively. Santra *et al*. (2008) also reported similar ranges of physicochemical properties for IARI farm.

Soil Water Retention Parameter and Soil Hydraulic Properties

The soil water retention data was fitted to van Genuchten model using RETC software for all master profiles and is presented in fig. 1. The R^2 value of fitted curve varied between 0.98 to 0.99 with residual sum of squares from 0.001 to 0.003. All the curves use the van Genuchten-Mualem models with m=1-1/

Table 2. Surface layer characteristics of master profiles of IARI farm

Master profile	Thickness of surface layer (cm)	BD (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Texture	pH	EC (dS m^{-1})	OC (g kg^{-1})	Θs (cm^3 cm^{-3})
Profile 5	15	1.42	3.51	40.00	56.49	Clay	6.83	0.86	7.50	0.46
Profile 7	12	1.45	33.17	41.21	25.62	Loam	7.74	0.61	7.90	0.40
Profile 14	15	1.48	34.52	38.97	26.51	Loam	7.55	0.39	5.31	0.38
Profile 16	14	1.58	33.97	37.11	28.92	Clay loam	7.68	1.52	5.31	0.37
Profile 18	17	1.46	29.11	38.97	31.92	Clay loam	7.72	0.37	4.58	0.41
Profile 20	18	1.47	39.73	25.64	34.63	Clay loam	7.58	0.37	4.55	0.39
Profile 21	16	1.56	33.21	46.52	20.27	Loam	7.80	0.33	2.93	0.37
Profile 24	10	1.47	35.26	35.24	29.50	Clay loam	7.70	0.79	5.49	0.39
Profile 25	18	1.55	36.02	34.87	29.11	Clay loam	7.75	0.55	1.83	0.37
Profile 31	14	1.52	30.26	48.20	21.54	Loam	7.50	0.79	6.23	0.36

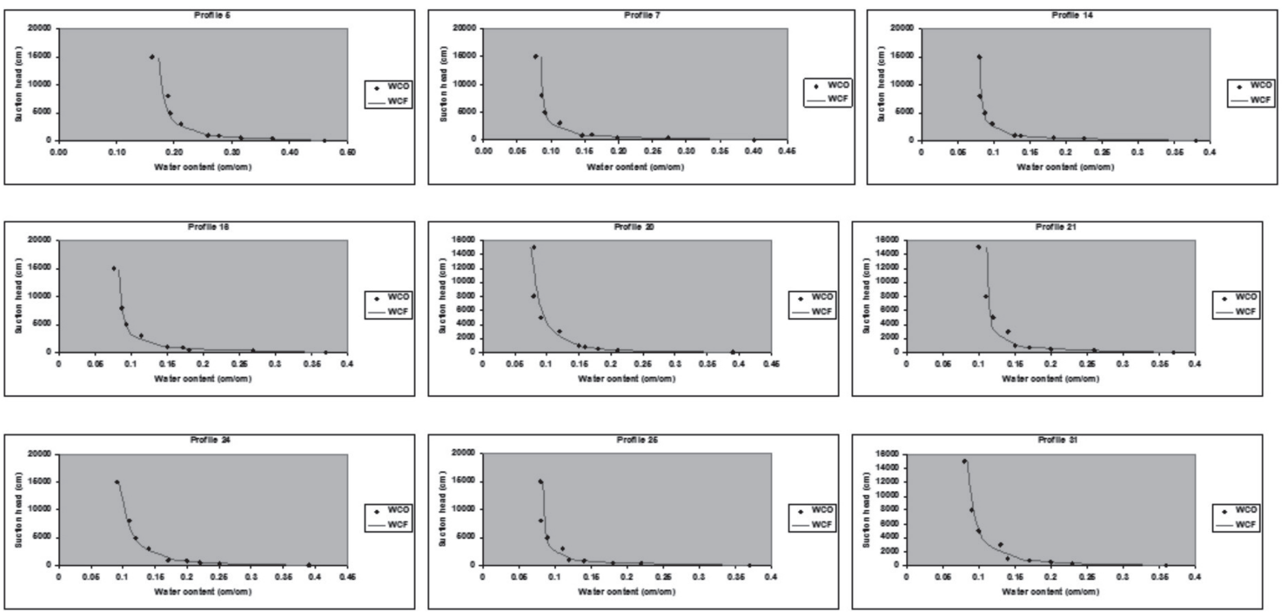

Fig. 1. Retention curve of master profiles (WCO: Water content observed and WCF: Water content fitted)

n. The estimated retention parameters (θr, θs, α and n) are presented in table 3. The fitted curves were smooth as n was allowed to hold finite value. The θr value varied between 0.0332 (profile 31) to 0.0760 cm^3 cm^{-3} (profile 5) and the saturated water content between 0.4665 (profile 5) to 0.3613 cm^3 cm^{-3} (profile 31) (Table 3). The α equals the inverse of air entry value for smaller m/n values, while for larger m/n this parameter equals the inverse of pressure head at the inflection point curves. In the present study α ranged between 0.0018 (profile 18) to 0.0164 cm^{-1} (profile 20). The product m×n determines the slope of the curve at large value of suction head and hence mostly affected by soil texture, while soil structure effect is seen near saturation. The n value varied between 1.381 (profile 20) to 2.437 (profile 18). Among all the profiles, profile 20 and profile 24 retention data showed best fit with residual sum of squares (SSQ) value of 0.001 and R^2 value of 0.997.

Table 3. Soil water retention parameters of master profiles of IARI farm

	θr (cm^3 cm^{-3})	θs (cm^3 cm^{-3})	α (cm^{-1})	n
Profile 5	0.0760	0.4665	0.0029	1.5996
Profile 7	0.0383	0.3860	0.0048	1.5725
Profile 14	0.0354	0.3772	0.0103	1.4289
Profile 16	0.0399	0.3663	0.0039	1.6021
Profile 18	0.0558	0.4097	0.0018	1.9134
Profile 20	0.0397	0.3940	0.0164	1.3839
Profile 21	0.0389	0.3634	0.0070	1.4551
Profile 24	0.0399	0.3882	0.0083	1.4501
Profile 25	0.0362	0.3657	0.0116	1.4077
Profile 31	0.0332	0.3613	0.0097	1.4325

Table 4. Predictive equations of K(θ) and D(θ) for master profiles of IARI farm

Profile No	Predictive equation for K(θ)	R^2	Predictive equation for D(θ)	R^2
Profile 5	$K(\theta)= 7984155\times\theta^{17.32}$	0.84	$D(\theta)= 91314385\times\theta^{11.28}$	0.88
Profile 7	$K(\theta)=576562\times\theta^{10.29}$	0.87	$D(\theta)= 36694461\times\theta^{7.10}$	0.89
Profile 14	$K(\theta)=1241639\times\theta^{10.52}$	0.87	$D(\theta)= 49570389\times\theta^{7.19}$	0.89
Profile 16	$K(\theta)=715891\times\theta^{11.11}$	0.87	$D(\theta)=24521611\times\theta^{7.48}$	0.89
Profile 18	$K(\theta)=35063\times\theta^{8.89}$	0.86	$D(\theta)=13556617\times\theta^{7.10}$	0.90
Profile 20	$K(\theta)=1326270\times\theta^{13.18}$	0.92	$D(\theta)=16620437\times\theta^{7.53}$	0.93
Profile 21	$K(\theta)=14824200\times\theta^{12.55}$	0.85	$D(\theta)=540405642\times\theta^{8.86}$	0.88
Profile 24	$K(\theta)=5425978\times\theta^{14.40}$	0.90	$D(\theta)=7440470\times\theta^{8.28}$	0.91
Profile 25	$K(\theta)=605767\times\theta^{10.88}$	0.87	$D(\theta)=20015470\times\theta^{7.44}$	0.89
Profile 31	$K(\theta)=33000148\times\theta^{13.35}$	0.88	$D(\theta)=114841567\times\theta^{8.16}$	0.90

Table 5. Correlation matrix between soil water retention parameters and physical properties

	BD	sand	silt	clay	OC	θr	θs	*α*	*n*	*S*
BD	1.00									
sand	0.48	1.00								
silt	0.19	-0.30	1.00							
clay	-0.60	-0.80**	-0.32	1.00						
OC	-0.63*	-0.49	0.21	0.36	1.00					
θr	-0.58	-0.90**	-0.01	0.90**	0.36	1.00				
θs	-0.78**	-0.83**	-0.17	0.93**	0.49	0.95**	1.00			
α	0.15	0.56	-0.49	-0.25	-0.40	-0.57	-0.40	1.00		
n	-0.28	-0.35	0.14	0.26	0.22	0.56	0.43	-0.81**	1.00	
S	-0.47	-0.53	0.08	0.47	0.35	0.73*	0.64*	-0.80**	0.97**	1.00

Mualem (1976a) model was used to predict soil hydraulic parameters, K(θ) and D(θ), for all the master profiles of IARI and the predictive equation describing K(θ) and D(θ) at a particular value of θ has been presented in table 4. The coefficient of determination in the prediction of K(θ) varied between 0.84 (profile 5) to 0.92 (profile 20) whereas for D(θ) varied between 0.80 (profile 5 and 21) to 0.93 (profile 20). Combined for all profiles, the prediction equation for K(θ) is $K(\theta) = 1.17\times10^{6}\times\theta^{11.93}$ and for D(θ) is $D(\theta) = 2.07\times10^{7}\times \theta^{7.71}$ with R^2 value of 0.77 for both K(θ) and D(θ).

Correlation Matrix between Soil Water Retention Parameter and Soil Physical Property

The correlation matrix between soil water retention parameters and physical properties of soil is presented in table 5. The BD was significantly ($P<0.05$) negatively correlated with the OC (r = -0.63*) and θs (r = -0.78**). Similar reports have been reported by many workers (Tiraks *et al*. 1974; Bandyopadhyay *et al*. 2010). Sand content was significantly, negatively correlated with clay content (r = -0.80**), θr (r = -0.90**) and θs (r = -0.83**). Clay content was significantly positively correlated with θr (r = 0.90**) and θs (r = 0.93**). The θr was significantly positively correlated with θs (0.95**) and α was significantly negatively correlated with n (r = -0.81**). The S-index was significantly and positively correlated with θr (r = 0.73*), θs (r=0.64*), n (r=0.97**) and significantly and negatively correlated with α (r = -0.80**).

S-index

The S-indices of all the 10 master profiles are presented in fig. 2. The S-index varied between 0.068 at profile 25 to 0.128 at profile 18. The highest S-index value in profile 18 may be attributed to lower OC (1.83 g kg^{-1}), lower clay content (29.11%), higher sand content (36.02%) and higher BD (1.55 g cm^{-3}) in Profile 18 than the corresponding values for profile 25. Garg *et al*. (2009) observed inverse relationship of S-index with clay content and BD and direct relationship with organic carbon content of soil. Similarly, Sinha *et al*. (2014) have also reported that S-index decreased significantly with increase in BD and increased with increase in organic carbon percentage of soil. The S-index value for all the 10 master profiles were more than 0.050 indicating very good physical quality for all the 10 master profiles of IARI experimental farm.

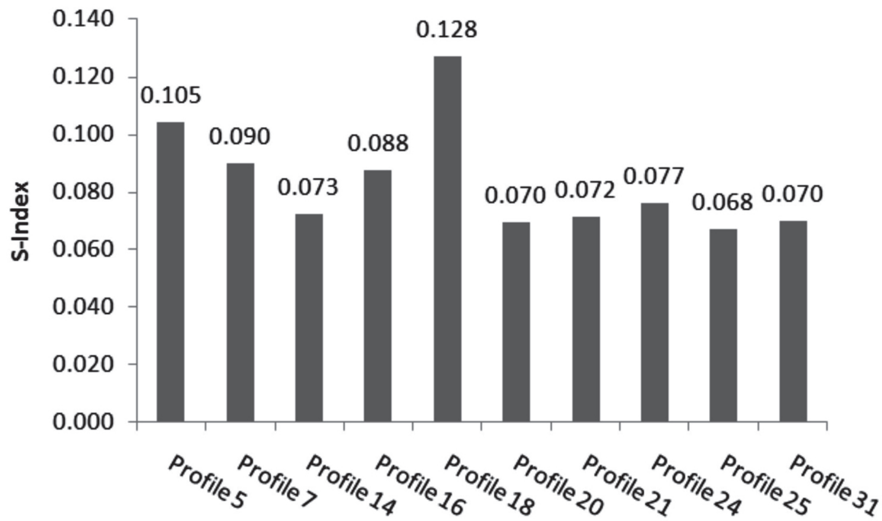

Fig. 2. S-index of master profiles of IARI farm

Conclusions

The study inferred that all ten master profiles representing the experimental farm were having very good physical quality as evidenced by S-index. Predictive functions for soil hydraulic properties like K(θ) and D(θ) developed from the soil moisture characteristics curves for these profiles showed high level of coefficient of determination ranging from 0.84 to 0.92 for K(θ) and 0.88 to 0.91 for D(θ). These equations will be very useful for study of soil water dynamics and water management at the IARI experimental farm.

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