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Texture Based Estimation of Soil Moisture Retention and Transmission Characteristics

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ABSTRACT

Knowledge of soil moisture retention characteristics (SMRC) and hydraulic conductivity (HC) in unsaturated soils is of prime importance for sustainable use of soil and water resources. Because of time and expenses involved in making direct measurements, several texture-based regression models for prediction of SMRC and HC have been proposed in literature. In this study, Brooks and Corey model has been applied to predict SMRC and HC of soils in the valley of Satluj River in Himachal Pradesh. Soil samples representing soils of five different areas were collected and physio-chemical properties were determined experimentally. The SMRC and HC characteristics can be utilised for bringing necessary improvements in soil in the context of sustainability of agro forestry system of the region.

Key words: Soil texture, matric potential, soil moisture retention, hydraulic conductivity, soil improvement

Introduction

There is growing urgency to sustain and increase the productive potentials of the mountainous soil in Himalayan region where any mismanagement can result in rapid decline in soil conditions and loss of top soil, water and of productivity. Without water from within the soil, plants can neither grow nor rivers can sustain flow. Insufficiency of water for plant growth is of far more significant than that of erosion of soil, for two reasons: (i) water stress has far quicker effect (within hours or days) on plant function and final yield, and (ii) erosion is a consequence of soil damage, not a primary cause, and yield-decline is related to differences between quality and depth of root zone conditions before and after erosion, not to the quantity and quality of soil eroded. In many regions rain water for plant growth is insufficient for fullest expression of plants' production potentials over time, and deserves to be treated as a valuable resource. A key challenge is how best to manage it so that avoidable surface runoff, representing lost potential soil moisture and ground water, does not occur. Thus, a significant cause of low crop production and crop failure in rainfed area is the combination of (i) low/erratic rainfall and (ii) poor utilisation of rainfall. Little can be done to increase rainfall or the number of rainfall events; therefore efforts should concentrate on improving the capture of rainfall, soil water availability and water use efficiency in rainfed areas. How much rain will fall during the growing season can not be predicted, but improving the available water in soils for plant growth will help in sustaining production potential of soil. In the mountainous region, soils are generally under three land uses i.e. forest, grasses and cultivation. These land uses have important role in conditioning the soil and ultimately affecting its moisture retention and transmission characteristics. For the sustainable use of the scarce soil and water resources, proper knowledge of moisture retention and transmission characteristics is essential as the soils are shallow and rainfall is intense and highly variable in the Himalayan mountainous catchments. Very little such information exists on soils representing mountainous region of Himanchal Pradesh (Kumar *et al*., 2002; Sharma and Bhandari, 1989).

Knowledge of soil moisture retention characteristics (SMRC) expressing the relationship between matric potential (h) and moisture content (θ) is of prime importance in modelling water and solute movement in the unsaturated soil zone. Because of the time and expenses involved in making direct measurements, several models for the prediction of SMRC and hydraulic conductivity (HC) using routinely available soil physical and chemical properties have been proposed in the literature (Brooks and Corey, 1964; Cassel *et al*. 1983; Clapp and Hornberger, 1978; Ghosh, 1980; Gupta and Larson, 1979; Hutson and Cass, 1987; Nandagiri and Prasad, 1997; Saxton *et al*, 1986). Nandagiri and Prasad, 1997 assessed performance of six texture-based regression models (Table 1) for soils near Bangalore, India. Model estimates were compared separately with SMRCs developed from laboratory and in-situ measurements.In the present study, Brooks and Corey, model has been used to estimate SMRC and HC of soils in the valley of Satluj river between Nathpa and Jhakri in Himanchal Pradesh. Physical properties of eight samples were determined and used to assess SMRC and HC of soils. The particle size properties which have the greatest effect on soil water retention are the percentages of sand, silt, clay, fine sand, coarse sand, very coarse sand and coarse fragments (> 2.0 mm). The morphological properties having the major effect on soil water properties are soil porosity (total volume occupied by pores per unit volume of soil), bulk density (ratio of the weight of dry solids to the bulk volume of the soil), organic matter and clay type.

Methodology

Soil Water Retention Characteristic

Water retention characteristic of the soil describes the soil's ability to store and release water and is defined as the relationship between the soil water content (θ) and the soil suction or matric potential (h). Other terms that are synonymous with matric potential but may differ in signs or units are soil water suction, capillary potential, capillary pressure head, matric pressure head, tension and pressure potential. Matric potential is the measure of the energy status of water in soil. Since unsaturated soil water pressures are less than atmosphere, the capillary pressure and matric potential are negative numbers.

Brooks and Corey Model

The simplest method for estimating h(θ) is to use soil texture reference curves. Water retention

Table 1. Details of texture-based regression models

Model	Description	Database		Input data/parameters (U.S. D.A. texture class)
		Location	Nature	
Clapp and Hornberger, 1978	Texture representative values for Campbell parameters	United States	Laboratory	S, C, Si
Gupta and Larson, 1979	Regression equations for θ at various values of h	United States	Laboratory	S, C, Si, OM, BD
Ghosh, 1980	Regression equations for exponent of Campbell model	India	Laboratory	h_e, θ_s, Si, S, C
Saxton *et al*, 1986	Regression equations for assumed constant, linear and power (Campbell) parts of SMC	United States	Laboratory	S, C
Hutson and Cass, 1987	Regression equations for è at various values of h	South Africa	Laboratory	Si, C, BD
Cassel *et al*., 1983	Regression equations for è at drained upper and lower limits	United States	In situ	C, percent 200-sieve (or S, Si, C)

curves for USDA soil textures are available in the literature (Maidment, 1992). Also, soil water content and matric potential have a power function relationship. The model proposed by Brooks and Corey, 1964 to describe this relationship is as follows,

Soil water retention $$\frac{\theta - \theta_r}{\phi - \theta_r} = \left(\frac{h_b}{h}\right)^{\lambda} \quad \ldots(1)$$

Where,

λ = pore size index = $f_1(C, \Phi, S)$

h_b = bubbling capillary pressure = $f_2(C, \Phi, S)$

θ_r = residual water content of soil = $f_3(C, \Phi, S)$

Φ = porosity (volume fraction)

Estimation of Soil Porosity

It was estimated using following equation

Soil porosity, $\Phi = 1 - BD/PD$ . . . (2)

where,

BD = Soil bulk density (g/cc)

PD = Particle density (g/cc); normally assumed to be 2.65 g/cc

As bulk density increases, water retention and hydraulic conductivity near saturation decreases. Also water retention increases as the amount of soil organic matter increases.

(i) For material less than 2 mm,

$$BD = 1.51 + 0.0025\,(S) - 0.0013\,(S)\,(OM) - 0.0006\,(C)\,(OM) - 0.0048\,(C)\,(CEC) \quad \ldots(3)$$

where,

C = percent clay (5 % to 60 %)

S = percent sand (5 % to 70 %)

OM = % organic matter = 1.7 × % organic carbon

CEC = cation exchange capacity of clay; depends on % clay and ranges from 0.1 to 0.9

$$= \frac{\text{cation exchange capacity of clay}}{\text{percent clay}}$$

(ii) For material containing particles larger than 2 mm,

Corrected porosity, $\Phi_c = \Phi.CFC$ …(4)

$CFC = 1 - VCF/100$ …(5)

$$VCF = \frac{WCF}{2.65}\left[\frac{100}{(100 - WCF)BD} + 1\right] \quad \ldots(6)$$

where,

WCF = % weight of coarse fragments

BD = bulk density of soil fraction less than 2 mm; g/cc

Estimation of model parameters (λ, h_b and θ_r)

Brooks and Corey, 1964 gave the following regression equations for the estimation of parameters in their model:

$$\lambda = \exp\,[-0.7842831 + 0.0177544\,(S) - 1.062498\,(\Phi) - 0.00005304\,(S^2) - 0.00273493\,(C^2) + 1.11134946\,(\Phi^2) - 0.03088295\,(S)\,(\Phi) + 0.00026587\,(S^2)\,(\Phi^2) - 0.00610522\,(C^2)\,(\Phi^2) - 0.00000235\,(S^2)\,(C) + 0.00798746\,(C^2)\,(\Phi) - 0.00674491\,(\Phi^2)\,(C)] \quad \ldots(7)$$

$$h_b = \exp\,[5.3396738 + 0.1845038(C) - 2.48394546(\Phi) - 0.00213853(C^2) - 0.04356349(S)(\Phi) - 0.61745089(C)(\Phi) + 0.00143598(S^2)(\Phi^2) - 0.00855375(C^2)(\Phi^2) - 0.00001282\,(S^2)\,(C) + 0.00895359\,(C^2)\,(\Phi) - 0.00072472\,(S^2)\,(\Phi) + 0.0000054\,(C^2)\,(\Phi) + 0.50028060\,(\Phi^2)(C)] \quad \ldots(8)$$

$$\theta_r = 0.0182482 + 0.00087269(S) + 0.00513488\,(C) + 0.02939286\,(\Phi) - 0.00015395\,(C^2) - 0.0010827(S)(\Phi) - 0.00018233(C^2)(\Phi^2) + 0.00030703(C^2)(\Phi) - 0.0023584(\Phi^2)\,(C) \quad \ldots(9)$$

Hydraulic Conductivity

The hydraulic conductivity is a measure of the ability of the soil to transmit water and depends upon both the properties of the soil and the fluid. Total porosity, pore size distribution and pore continuity are the major soil characteristics affecting hydraulic conductivity.

Brooks and Corey Model

The hydraulic conductivity is a non-linear function of volumetric soil water content and varies with soil texture. Hydraulic conductivity prediction model proposed by Brooks and Corey, 1964 is represented by the following equation:

$$\frac{k(\theta)}{k_s} = \left(\frac{\theta - \theta_r}{\phi - \theta_r}\right)^n \qquad \ldots(10)$$

where,

k_s = saturated hydraulic conductivity, cm/h

$n = 3 + 2/\lambda$ …(11)

All other terms have the same denotation as for water retention equation (equation 2).

Ahuja *et al.*, 1985 developed a technique for estimation of saturated hydraulic conductivity, which related saturated hydraulic conductivity to an effective porosity ($Ö_e$, total porosity obtained from soil bulk density minus the soil water content at -33 kPa matric potential) by the following generalised Kozeny-Carman equation:

$$k_s = B\phi_e^{\,n} \qquad \ldots(12)$$

where n can be set equal to 4 and B equals 1058 when k_s has the units of cm/h.

Coarse fragments (> 2.0 mm) in the soil in addition to their effect in reducing porosity also affect the saturated hydraulic conductivity of the soil. The saturated hydraulic conductivity of the soil matrix should be multiplied by the following correction for coarse fragments (Brakensiek *et al.*, 1986):

$$\text{Coarse fragment correction} = 1 - \frac{\%\,\text{weight of coarse fragments}}{100} \qquad \ldots(13)$$

Results and Discussion

Eight soil samples from Satluj river catchment between Nathpa and Jhakri were collected for grain size analysis. Locations were chosen in a manner to represent soils in the valley along the river reach. Location of sampling sites is given in Figure 1. Grain size and texture analysis of the samples was carried out and the results are given in Table 2. Percentage finer of the soil samples are given in Table 3 and percentage finer curves (S-curves) are shown in Figures 2a to 2e.

According to the similarities in sampling sites, soil samples were classified into five categories: (i) Staluj river bed near Nathpa (T1), (ii) Satluj river side slopes (T2, T3 and T4), (iii) Sholding Khad (T5), (iv) Chaunda Khad (T6) and (v) Dharali Khad and Unoo Khad (T7, T8).

The physical and chemical properties, i.e. % organic matter, % sand, % clay, % coarse fraction, cation exchange capacity, bulk density and % water stable aggregates (> 0.25 mm), required for the parameter estimation of Brooks and Corey regression model were calculated using the Eq. 2 to Eq. 6 and are listed in Table 3.

As expected, soils of Satluj river bed contains the highest percentage of coarse particles (> 2 mm) i.e. 48 %. However, soils at other locations also contain high percentage of coarse particles (Table 2). Soil sample T5 is found to have high organic matter content (5.84 %) being located in the forest area (Table3).

Using the physical and chemical properties of soils (Table 3) as input to the regression models, parameters of the SMRC and HC were estimated using the Eq. 7 to Eq. 9 and Eq. 11 to Eq. 13, respectively and are presented in Table 4. The h-θ and k-θ curves were prepared using Eq. 1 and Eq. 10 and are shown in Figures 3 and 4.

For the soils studied considerable differences exist in the h-θ and k-θ curves as is evident from the model parameter values shown in Table 4. It is clearly visible from the h-θ and k-θ curves that the highest and lowest values of soil moisture content at a given matric potential correspond to Dharali and Unoo Khads (group 5) and Satluj river bed (group 1), however, the reverse occurs for hydraulic conductivity curves. This is mainly attributed to the percent coarse fraction (WCF) and organic matter.

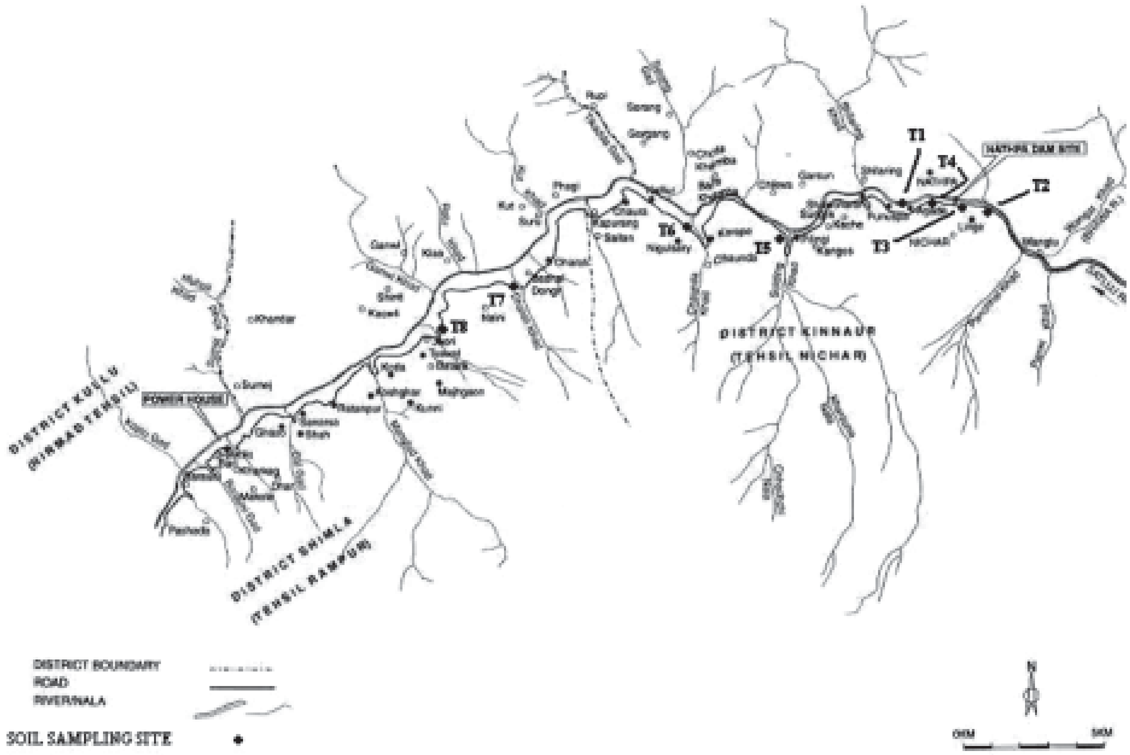

Fig. 1. Soil sampling sites in Satluj catchment between Nathpa and Jhakri

Table 2. Grain size analysis of soil samples

Sample	Location	% finer than size (mm)								
		2	1	0.85	0.6	0.425	0.3	0.15	0.075	0.063
T1	Satluj river bed, Nathpa dam	52.0	46.2	45.8	43.0	36.4	31.6	18.5	10.6	9.8
T2	Left bank of Satluj river, Linge village	75.7	72.9	71.5	68.3	61.9	51.0	39.5	23.9	15.9
T3	Left bank of Satluj river, Linge village	73.7	67.6	65.8	59.4	46.4	40.3	28.5	15.9	10.6
T4	Left bank of Satluj river, Linge village	73.4	65.7	63.1	57.2	45.5	39.2	26.7	11.7	7.1
T5	Sholding Khad, National highway	74.5	68.2	62.8	56.4	48.5	40.6	28.5	11.2	9.0
T6	Chaunda Khad, Nigulsari village	75.4	69.8	66.5	58.3	51.2	43.5	31.0	12.8	11.2
T7	Dharali Khad, Wadhal Dongri village	80.8	73.8	73.6	70.1	63.3	58.4	42.1	33.1	32.2
T8	Unoo Khad, Jeori town	83.4	77.5	77.2	74.8	68.7	63.3	44.4	33.8	32.2

Table 3. Physical and chemical properties of soil samples

Property		OM	S	C	WCF	CEC	BD	Water stable
Group	Sample	(%)	(%)	(%)	(%)	(meq/100g)	(g/cc)	aggregates (%)
1	T1	0.29	42.18	9.82	48.00	7.00	1.56	74.69
2	T2	0.38	59.75	15.90	24.35	10.16	1.58	52.80
	T3	0.51	63.07	10.60	26.33	10.39	1.57	63.00
	T4	0.29	66.34	7.10	26.56	10.00	1.60	64.30
	Average	0.39	63.05	11.20	25.75	10.19	1.58	60.03
3	T5	5.84	65.50	9.00	25.50	20.00	1.05	61.40
4	T6	0.32	64.20	11.20	24.60	10.05	1.59	60.00
5	T7	0.89	48.67	32.18	19.15	11.08	1.51	60.52
	T8	2.37	51.16	32.23	16.61	13.74	1.37	44.51
	Average	1.63	49.92	32.20	17.88	12.41	1.44	52.52

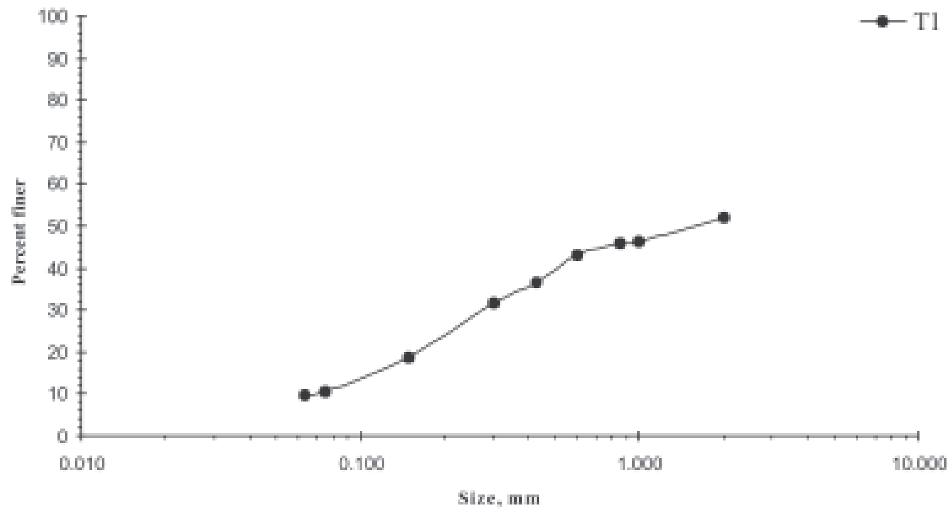

Fig. 2a. Percent curve for soil of Satluj river bed just downstream of Nathpa dam

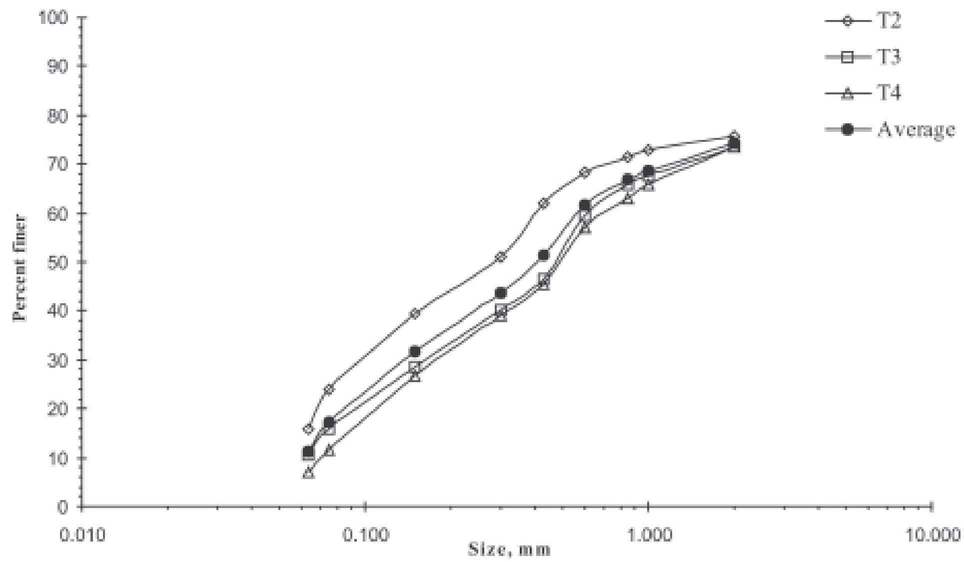

Fig. 2b. Percent curves for soils of side banks of Satluj river at Nathpa dam

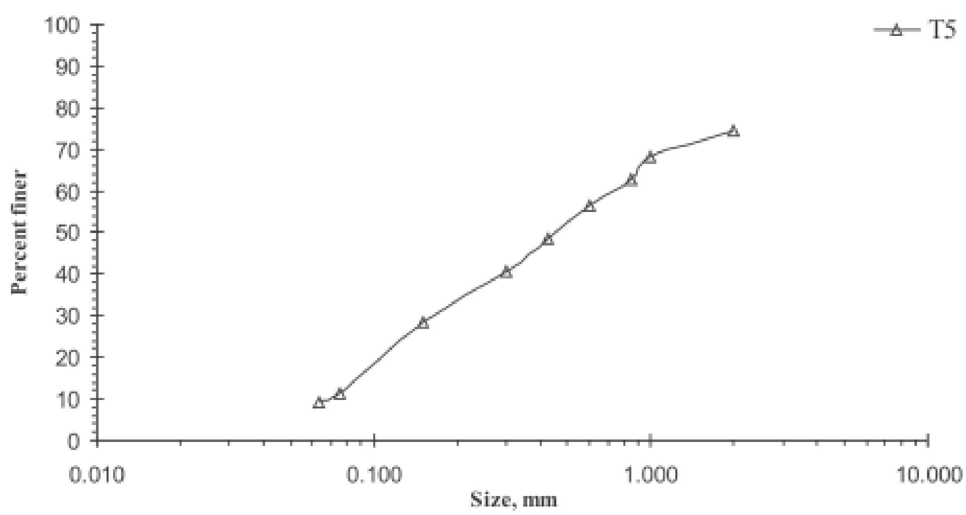

Fig. 2c. Percent finer curve of soil of Sholding Khad near highway crossing

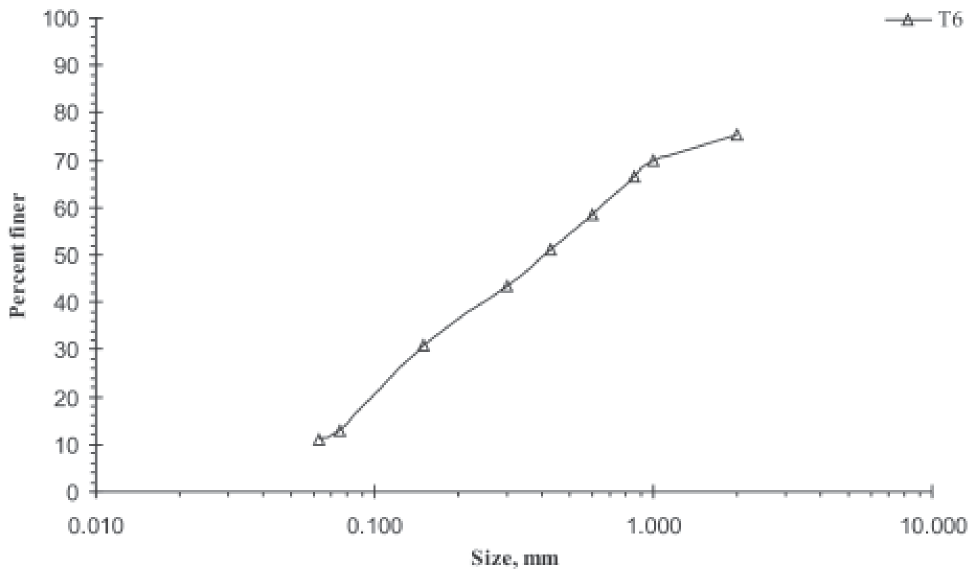

Fig. 2d. Percent finer curve of soil of Chaunda Khad near Nigulsari village

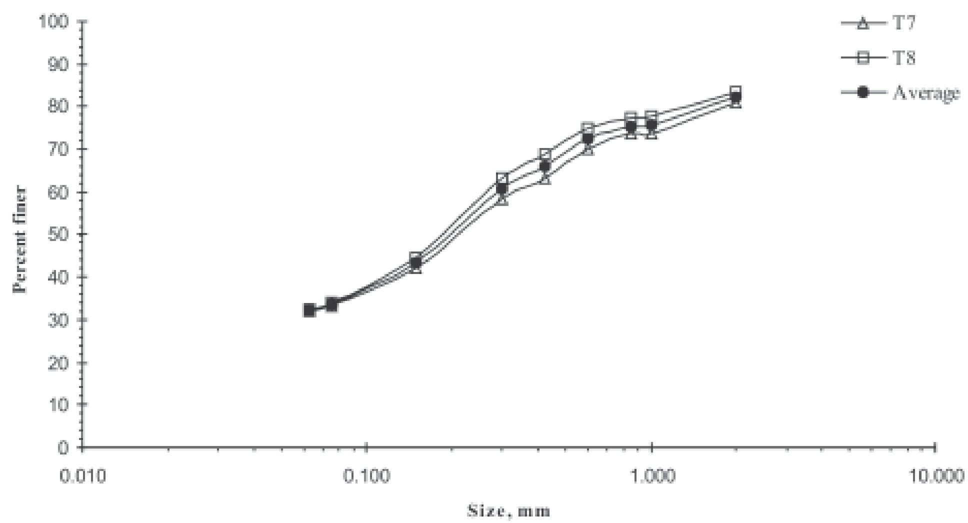

Fig. 2e. Percent finer curves of Dharali Khad and Unoo Khad catchments at Wadhal Dongri village and Jeori town

Table 4. Parameters of Brooks and Corey model

Group	Sample	Φ (vol./vol.)	Φc (vol./vol.)	λ	h_b (cm)	θ_r (vol./vol.)	n
1	T1	0.410	0.244	0.394	30.179	0.053	8.079
2	T2	0.405	0.336	0.357	13.884	0.080	8.603
	T3	0.407	0.331	0.404	13.817	0.065	7.956
	T4	0.396	0.322	0.440	14.517	0.054	7.547
	Average	0.402	0.330	0.400	14.072	0.066	8.035
3	T5	0.604	0.472	0.362	7.023	0.049	8.519
4	T6	0.399	0.331	0.402	13.485	0.068	7.979
5	T7	0.432	0.375	0.226	15.868	0.108	11.852
	T8	0.484	0.427	0.239	9.352	0.112	11.364
	Average	0.458	0.401	0.233	12.610	0.110	11.608

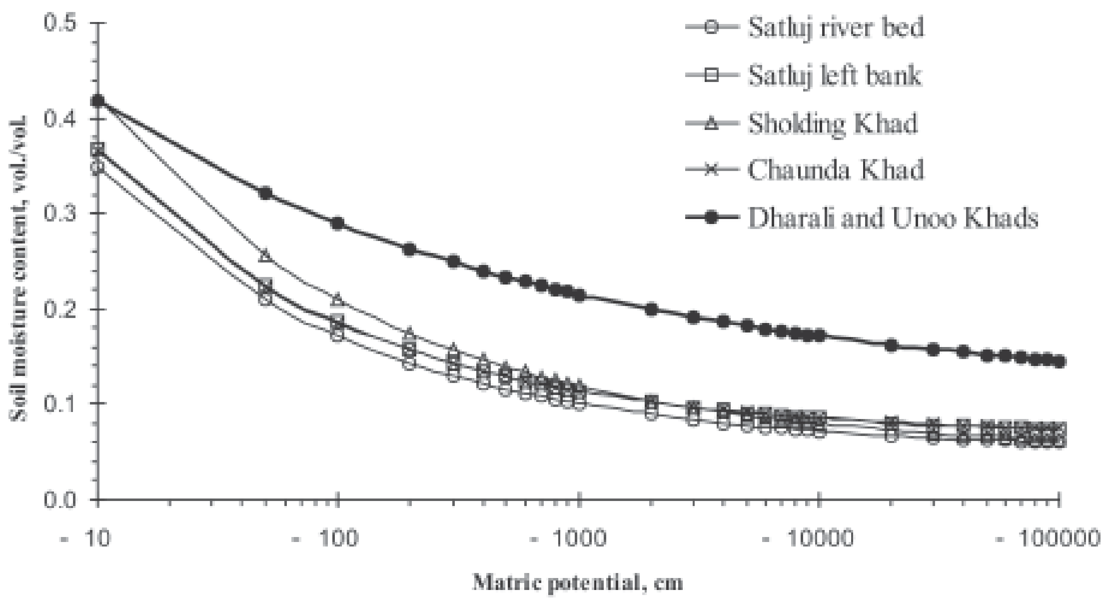

Fig. 3. Soil moisture retention curves

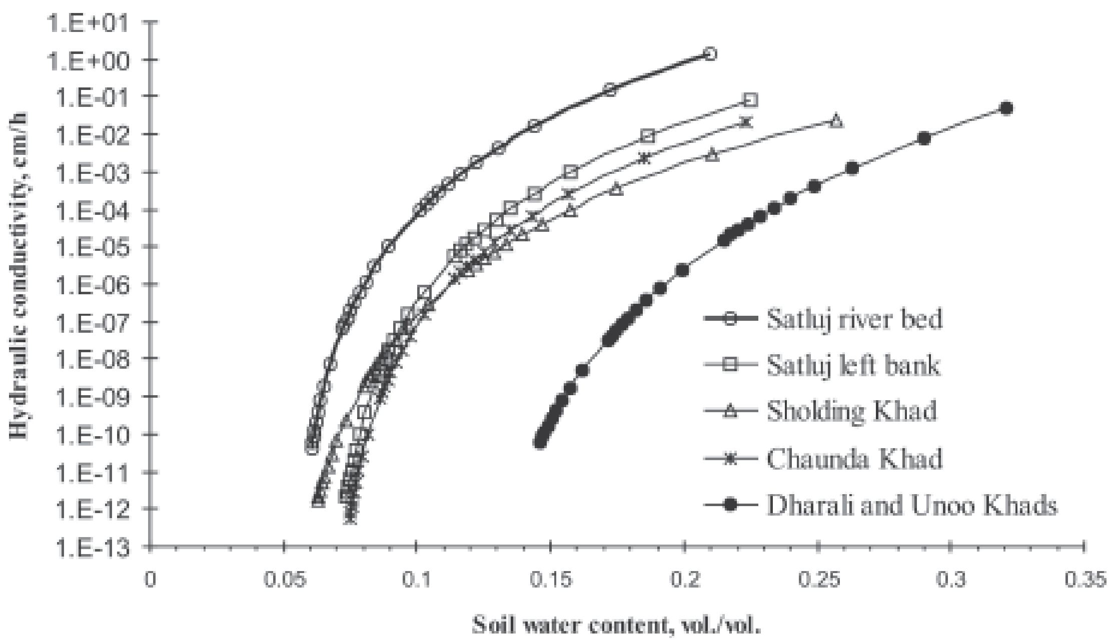

Fig. 4. Hydraulic conductivity curves

Soil moisture available for plants at different matric potentials were also estimated and are presented in Figure 5 as a percentage of maximum available moisture holding capacity. The variation of maximum available moisture holding capacity with soil properties along with correlation coefficients between maximum available soil moisture holding capacity and each soil property is presented in Table 5. The values of correlation coefficient are higher for organic matter, porosity and bulk density as compared to the values for other soil properties. This agrees with the results of Sharma and Bhandari, 1989 which states that organic matter significantly correlates with the moisture content of soil. Hence, organic matter, porosity and bulk density are the major soil properties significantly affecting available moisture holding capacity of a soil.

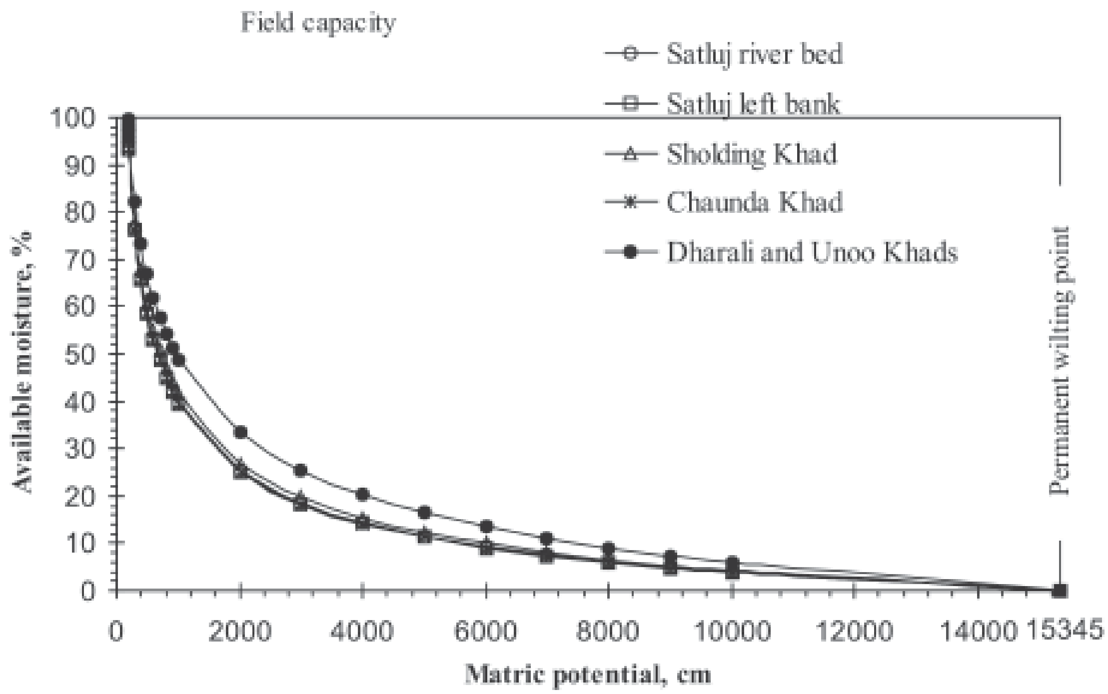

Fig. 5. Available soil moisture characteristic curves

Table 5. Variation of available moisture holding capacity with soil physical and chemical properties

Group	WCF %	S %	C %	OM %	Porosity %	Bulk density g/cc	Available moisture holding capacity vol./vol.
1	48.00	42.18	9.82	0.29	0.24	1.56	0.080
2	25.75	63.05	11.20	0.39	0.33	1.58	0.091
3	25.50	65.50	9.00	5.84	0.47	1.05	0.116
4	24.60	64.20	11.20	0.32	0.33	1.59	0.089
5	17.88	49.92	32.20	1.63	0.40	1.44	0.102
	0.62	0.49	0.20	0.92	0.99	0.91	Correlation coefficient

Measures for Soil Improvements

Results of various experimental studies in India and abroad suggest various measures to modify soil texture (and hence dependent properties such as available water capacity) by intimately mixing in particles of appropriate size such as pulverised fly ash; a waste product of coal burning electricity generating stations. Volcanic ash, fine coral sand and pulverised silica have also been used. However, waste products may possibly contain phytotoxic substances which may cause pollution of aquifers and water resources.

A more immediately practical method of increasing available water property of a soil is to incorporate in it large quantities of dead roots, peat or other organic material whose function is merely to act as a sponge. Primary cultivation (ploughing or discing) itself temporarily increases the available water capacity of a soil by increasing the proportion of voids to solid material, voids which can later be filled with water. This effect disappears as the season advances and the soil once more becomes compacted on dehydration.

Larger soil particles of greater than 2.0 mm are of importance in making the soil free from draining and thus highly and deeply leached. However, existing high percentage of coarse particles needs to be reduced to less than 15 % in agricultural lands.

In the study area, soils located down the steep slope acquire and accumulate materials and water from sites upslope. The water that flows to sites lower in the steep landscape by either surface runoff or subsurface lateral flow has profound influence on their hydrologic regimes. Water in excess of field capacity needs to be conserved in situ so as to make better utilisation of soil water reservoir over a longer period of time rather than allowing excess water to drain down the slopes.

Conclusions

For practical horticulture and agro-forestry, attempts at extreme precision in determination of available water capacity though costly and time consuming, field/laboratory experiments may not be required. Regression models such as Brooks and Corey model used in the present study can serve useful purpose in initial planning for soil improvement.

Under low and variable rainfall conditions in the mountainous region of Himachal Pradesh efficient soil moisture management is a good way for improving water use efficiency. Unfortunately, very little information exists on soils representing mountainous region of the Satluj river. Present study, though limited in scope, highlights variation in soil characteristics. For the soils studied, considerable differences exist in the SMRCs as well as HCs at different locations. These differences arise mainly due to variation in organic matter content and content of coarse fraction. Available water holding capacity of the soils in the study area are found to be less corresponding to textural class of coarse sand and coarse sandy loam. This soil characteristic can be improved for better water use efficiency. Percent weight of coarse fraction in the soils is significantly high emphasizing the artificial nature of the available water concept as pebbles and stones contain no available water.

Acknowledgement

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Notations

BD = bulk density

C = percent clay

cc = cubic centimetre

CEC = cation exchange capacity

h = matric potential

h_b = bubbling capillary pressure

HC = hydraulic conductivity

h_e = air entry suction pressure

k = hydraulic conductivity

k_s = saturated hydraulic conductivity

OM = percent organic matter

PD = particle density

S = percent sand

Si = percent silt

SMRC = soil moisture retention characteristics

VCF = coarse fraction (percent volume basis)

WCF = coarse fraction (percent weight basis)

θ = soil moisture content

θ_r = residual water content of soil

θ_s = moisture content at saturation

λ = pore size index

Φ = porosity

Φ_c = corrected porosity

Φ_e = effective porosity

kPa = kilo Pascal

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