Derivation of Soil Moisture Retention Characteristics from Saturated Hydraulic Conductivity

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Abstract: Knowledge of the physics of soil water movement is crucial to the solution of many problems in watershed hydrology, for example, the prediction of runoff and infiltration following precipitation, the subsequent distribution of infiltrated water by drainage and evaporation, and estimation of the contribution of various parts of a watershed to the ground water storage. Mathematical models of hydrologic and agricultural systems require knowledge of the relationships between soil moisture content (θ), soil water pressure (h) and unsaturated hydraulic conductivity (K). Sustained research effort towards the parameterisation of K(h) and h(θ) has resulted in the development of several laboratory, field and theoretical methods. This study involved field and laboratory determination of soil moisture characteristics along the Hindon river in its upstream reach. The soils in this area are mainly sand, loamy sand, sandy loam and silt loam. A total of 37 soil samples were collected from 13 sites in 24 km upstream reach of Hindon river. Extensive laboratory measurements were made for each soil sample. Saturated hydraulic conductivity was measured through ICW Permeameter in the laboratory. Retention curve data was obtained through pressure plate apparatus. These have been used to develop an empirical relationship to derive the approximate soil moisture retention curve at the places in upper part of Hindon river basin where only saturated hydraulic conductivity data are available. (***Key Words***: *Soil Moisture, Hydraulic Conductivity, Retention Curve, Soil Water Pressure, Unsaturated Zone*)

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The water movements in the unsaturated zone, together with the water holding capacity of this zone, are very important for assessing the water demand of the vegetation, as well as for the recharge of the ground water storage. A fair description of the flow in the unsaturated zone is also crucial for predictions of the movement of pollutants into ground water aquifers.

For analytical studies on soil moisture regime, critical review and accurate assessment of the different controlling factors is necessary. The controlling factors of soil moisture may be classified under two main groups viz. climatic factors and soil factors. Climatic factors include precipitation data containing rainfall intensity, storm duration, interstorm period, temperature of soil surface, relative humidity, radiation, evaporation, and evapotranspiration. The soil factors include soil matric potential and water content relationship, saturated and unsaturated hydraulic conductivity, and effective medium porosity. Besides these factors, the information about depth to water table is also required.

Saturated and unsaturated hydraulic conductivity are related to the degree of resistance from soil particles when water flows in soil pores. These resistances are affected by the forms, sizes, branchings, jointings, and tortuosities of pores as well as viscosity of water. In addition, unsaturated hydraulic conductivity is affected markedly by the volumetric water content of soil.

The relation between matric potential and volumetric water content in a soil is termed as the soil moisture characteristic curve because the curve is characteristic of each soil. The differences among soil moisture characteristic curves are attributed primarily to the differences in pore size distribution among soils. These curves are sensitive to the changes in bulk densities and disturbances of soil structures. In addition, the curves generally show hysteresis according to the degree of wetting or drying of soils.

In the present study, field and laboratory investigations have been carried out to determine the soil moisture characteristics (saturated hydraulic conductivity and soil moisture retention curve) at various locations along the uppermost part of Hindon river basin and an empirical relationship has been derived to obtain the soil moisture retention characteristic from saturated hydraulic conductivity.

Materials and Methods

The study area lies in the upper part of Hindon basin, bounded between latitude 29°55' and 30°6' N and longitude 77°35' and 77°46' E (figure 1). The area is located within Saharanpur district of Uttar Pradesh (India) and included in the Survey of India topographic sheets 53 F/12, 53 F/16, 53 G/9 and 53 G/13 in the scale of 1:50,000. The investigated area covers a reach of around 24 km along the Hindon river in its upstream reach. The study is confined to a stretch of Hindon river in between Aurangabad and Dudhil Bukhara villages.

The soil is alluvial type deposited by Hindon river system. Lithologically, it mainly consists of clay, silt and fine to coarse sand. The soils are very fertile for growing wheat, sugarcane and vegetables. However, along the sandy river course, fruit orchards are also common.

Laboratory Investigations

Augers were used to obtain undisturbed soil cores at different depths. Retention curve data and saturated hydraulic conductivity were measured in the laboratory for all the 37 soil samples collected from 13 sites in Aurangabad, Kamalpur, Budhakhera, Gagalheri and Dudhil Bukhara comprising around 24 km upstream reach of Hindon river. Soil moisture retention data were obtained through Pressure Plate Apparatus and saturated hydraulic conductivity were measured through ICW Permeameter. Table 1 presents the location and depth of soil samples collected from uppermost part of the Hindon river basin and the saturated hydraulic conductivity measured through ICW laboratory permeameter.

Results and Discussion

To model the retention and movement of water and chemicals in the unsaturated zone, it is necessary to know the relationships between soil water pressure, water content and hydraulic conductivity. It is often convenient to represent these functions by means of relatively simple parametric expressions. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model. The measurements of $\theta(h)$ from soil cores (obtained through pressure plate apparatus) can be fitted to the desired soil water retention model e.g. van Genuchten model (1980). Once the retention function is estimated, the hydraulic conductivity relation, $K(h)$, can be evaluated if the saturated hydraulic conductivity, K_s, is known.

Table 1. Location of Soil Sampling Sites and Saturated Hydraulic Conductivity

S. No.	Soil Sample Code	Village	Normal Distance from Centre of River (m)	Bank	Depth Range (cm)	Saturated Hydraulic Conductivity (cm/hour)
1	A11	Aurangabad	200	Left	90 – 110	0.041
2	A12	Aurangabad	200	Left	150 – 180	0.010
3	A21	Aurangabad	100	Left	0 – 40	0.080
4	A22	Aurangabad	100	Left	100 – 120	0.022
5	A23	Aurangabad	100	Left	160 – 180	0.588
6	A31	Aurangabad	100	Right	0 – 30	0.058
7	A32	Aurangabad	100	Right	90 – 110	0.080
8	A33	Aurangabad	100	Right	160 – 180	0.036
9	A41	Aurangabad	200	Right	0 – 30	1.884
10	A42	Aurangabad	200	Right	90 - 110	0.175
11	A43	Aurangabad	200	Right	170 - 190	0.412
12	K11	Kamalpur	100	Left	0 - 100	33.753
13	K12	Kamalpur	100	Left	100 – 150	16.157
14	K13	Kamalpur	100	Left	150 - 200	17.785
15	K21	Kamalpur	200	Left	0 – 70	0.677
16	K22	Kamalpur	200	Left	70 – 110	24.984
17	K23	Kamalpur	200	Left	110 – 180	14.430
18	K31	Kamalpur	400	Left	0 - 100	0.303
19	K32	Kamalpur	400	Left	100 – 180	0.350
20	K33	Kamalpur	400	Left	180 – 220	4.603
21	K41	Kamalpur	100	Right	40 – 60	84.992
22	K42	Kamalpur	100	Right	105 – 125	48.204
23	K51	Kamalpur	200	Right	40 – 60	20.196
24	K52	Kamalpur	200	Right	100 – 120	0.421
25	K53	Kamalpur	200	Right	160 – 180	0.245
26	K61	Kamalpur	400	Right	45 – 65	0.845
27	K62	Kamalpur	400	Right	100 – 120	0.230
28	B11	Budhakhera	100	Right	35 – 55	14.937
29	B12	Budhakhera	100	Right	70 – 90	5.493
30	B13	Budhakhera	100	Right	120 – 140	17.588
31	G11	Gagalheri	100	Right	35 – 55	17.270
32	G12	Gagalheri	100	Right	70 – 90	0.177
33	G13	Gagalheri	100	Right	130 - 150	8.519
34	D11	Dudhil Bukhara	100	Right	5 - 15	0.207
35	D12	Dudhil Bukhara	100	Right	30 – 50	66.640
36	D13	Dudhil Bukhara	100	Right	85 – 95	70.013
37	D14	Dudhil Bukhara	100	Right	110 - 120	89.857

However, in India, soil water retention data is only sparsely available. In order to have a quick derivation of soil water retention curve for typical regions without detailed laboratory investigations, an attempt has been made to derive the same from saturated hydraulic conductivity.

The following typical functional relation was assumed for characterizing the soil moisture retention characteristics:

$$\theta = a \; [\log |h|]^{b} \; [K_s]^{c} \qquad \ldots (1)$$

where,

θ = volumetric water content (cm^3/ cm^3);

h = soil water pressure (relative to the atmosphere) expressed in cm of water;

K_s = saturated hydraulic conductivity; and

a, b, c = constants.

A total of 243 sets of data (θ, h, K_s) were available from the laboratory investigations of 37 soil samples. The constants a, b, c of the above function were obtained through non-linear regression analysis carried out in three cases.

Case 1 - The constants a, b, c were obtained for different ranges of saturated hydraulic conductivity. Table 2 presents the constants a, b, c of empirical function (equation 1) for different ranges of saturated hydraulic conductivity. It can be seen from Table 2 that the constants 'a' and 'b' decrease with increase in saturated hydraulic conductivity while no fixed pattern was observed for constant 'c'. Good correlation for the empirical relationship was found for low saturated hydraulic conductivity ranges (0 to 1 cm/hour).

Case 2 - The constants a, b, c were obtained location specific. Table 3 presents the constants a, b, c of empirical function (equation 1) and associated range of saturated hydraulic conductivity for different villages. It can be observed from Table 3 that wide variations in saturated hydraulic conductivity exist in all places except Aurangabad where it was found to be less than 2 cm/hour for all the soil samples. Good correlation for the empirical relationship was found for Aurangabad, Kamalpur and Budhakhera with 'proportion of variance explained' more than 80%.

Table 2. Constants of Empirical Function for Different Ranges of Saturated Hydraulic Conductivity

S. No.	Range of Saturated Hydraulic Conductivity (cm/hour)	Number of Data Sets (θ, h, K_s)	Constant a	Constant b	Constant c	Proportion of Variance Explained (%)
1	0 - 0.1	47	1.002	- 1.785	- 0.060	85.73
2	0.1 – 1	75	0.798	- 1.845	- 0.231	82.89
3	1 – 20	70	0.488	- 2.080	0.056	31.24
4	20 – 90	51	0.399	- 2.967	0.196	38.34

Table 3. Constants of Empirical Function for Different Villages

S. No.	Village	Range of Saturated Hydraulic Conductivity (cm/hour)	Number of Data Sets (θ, h, K_s)	Constant a	Constant b	Constant c	Proportion of Variance Explained (%)
1	Aurangabad	0.010-1.884	73	1.012	-1.842	-0.079	81.17
2	Kamalpur	0.230-84.992	90	0.960	-2.178	-0.297	93.57
3	Budhakhera	5.493-17.588	24	0.534	-3.797	0.332	86.68
4	Gagalheri	0.177-17.270	24	0.915	-1.672	-0.061	53.75
5	Dudhil Bukhara	0.207-89.857	32	1.658	-2.672	-0.102	67.16

Case 3 - All the available 243 data sets were considered for regression analysis to find the average relationship for upper part of Hindon river basin. The constants a, b, c of the above function were obtained as 0.88, -2.0 and -0.18 respectively through non-linear regression analysis. The resulting functional relation therefore becomes

$$\theta = 0.88 \; [\log |h|]^{-2.0} \; [K_s]^{-0.18} \qquad \ldots (2)$$

The "proportion of variance explained" was found to be 72.94% for the above empirical relation.

The analysis in above three cases shows that equation (1) can reasonably be applied to obtain soil moisture retention characteristics from saturated hydraulic conductivity in the upper part of Hindon river basin. Depending upon the location, range of saturated hydraulic conductivity and 'proportion of variance explained' (as obtained in cases 1, 2 and 3), suitable values can be chosen for constants a, b, c of the empirical relationship for use in hydrological studies.

Remarks

Water relations are among the most important physical phenomena that affect the use of soils for agricultural or engineering purposes. During the recent years, mathematically sophisticated theories of transport in porous material have been proposed. However, the difficulties of making reliable field measurements at an appropriate scale and using them in physically realistic predictive models are undiminished.

Field and laboratory based soil investigations were carried out for the uppermost part of Hindon river basin. Soil moisture characteristics such as soil moisture retention curve and saturated hydraulic conductivity were measured at various locations along the Hindon river. An empirical relationship has been proposed to derive the approximate soil moisture retention curve from saturated hydraulic conductivity data. However, it is to be emphasized that the functional relation has been developed for upper part of Hindon river basin and applicability of this approach for other regions needs to be further explored.

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