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43

SOIL-WATER RELATIONSHIP OF INDIAN SOILS

INDIAN COUNCIL OF AGRICULTURAL RESEARCH

A Review on Soil-Water Relationship of Indian Soils

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INTRODUCTION

Soil-water retention and its rate of movement are of considerable importance in agriculture and are being actively investigated. The interactions between the active soil fractions and soil-water give rise to water retention forces. Clays and clay minerals forming the finer and active fractions of the soil have much higher specific surface area than the sand and silt fraction forming the coarse fractions. Clay minerals are negatively charged owing to the isomorphic substitution of ions in the silica and alumina sheets and exposed hydroxyl groups at the broken edges. Water molecules being dipole in nature, get oriented by this negative charge, and are held on the soil surface by the short range adhesion and cohesive forces or so-called 'Vander Waal' forces. The water held in the soil by these forces is relatively immobile, and is sometimes referred to as film water. Its thickening continues until the water starts accumulating at the contact points of the particles in the soil pore, and develops an air-water interface.

The pressure difference across the air-water interface, or so-called soil-moisture tension, determines the amount of water held in a soil against the force of gravity. However, the magnitude of the pressure difference is inversely proportional to the size distribution of the pores which is determined by the textural and structural arrangement of the soil particles. Various groups in which the soils of India have broadly been divided, namely, Alluvial, Black, Red, Laterite and Lateritic, Mountain and Forest, Desert, Saline and Alkaline, and Peat, vary in their textural and structural classifications. The type of clay minerals vary from kaolinitic in Red and Laterite groups, illitic in Alluvial and Desert groups, to montmorillonitic in Black group. The amount of organic matter varies from less than 0.4 per cent in Desert and Alluvial soils to more than four per cent in Mountain and Forest, and Peat soils.

A considerable amount of work has been done in India to evaluate the soil-water relationships of these divergent soils, specially the soil moisture characteristics and infiltration rates. The objective of this review is to bring together the information available on soils of India.

METHODOLOGY

Estimation of Moisture Content

A number of methods have been developed and tested by different workers to make a rapid estimate of the moisture content of soil, but none of these methods have been of extensive use owing to some inherent limitations. The use of Gravimetric Method is still common and has been considered to be the most satisfactory, even though it is laborious and time-consuming.

A rapid method based on drying of the soil by the heat produced during burning of the spirit or alcohol mixed with the moist soil (Bouyoucos, 1937), was found to be quite satisfactory by Hukkeri and Dastane (1968), as long as the organic matter of the soil remained essentially unchanged and within reasonable limits. The Immersion Method based on the principle that the amount of water in a moist soil is directly related to the difference in the weight of soil in air and in water (Wilde and Spyridakis, 1962), which eliminated oven-drying of the soil, was found to be quite useful by Prihar and Sandhu (1967). Prihar and Sandhu (1968) developed a flask with a long stem to read the moisture content of the soil directly from the scale provided on the stem. The presence of high amounts of clay and organic matter in the soil were found to limit the usefulness of this flask. In the Carbide Method, based on the principle that acetylene gas is produced when calcium carbide reacts with water, the mixing of the moist soil with an equivalent amount of oven-dry sand before the chemical was added to it was found to improve the estimation of the moisture content, especially in heavy textured soil, at the IARI.

To eliminate both oven-drying and weighing of the soil, thermal methods and electrical resistance methods have been suggested in the literature. Momin (1947) estimated the moisture content of the soil from the time taken to heat a wire buried in the soil. The method was based on the principle that rise in temperature of the wire was inversely proportional to the conduction of heat by the soil, which depended on the moisture content. The thermal methods are independent of the salt content, but a very close contact has to be assured between soil and the probe to obtain reliable results. In the electrical methods, a change in resistance to flow of current between the two fixed electrodes, due to the change in moisture content, is measured. Abichandani and Bhatt (1962) and Kashyap and Ghildyal (1964) buried the electrodes in plaster of Paris and gypsum blocks respectively, to avoid the inter-

ference of salts present in the soil. Mohsin and Ghildyal (1968) used the terylene blocks to fix the electrodes and found that they were more sensitive than the gypsum blocks in the wet range, but the gypsum blocks were more sensitive than terylene blocks in 0 to 25 per cent available moisture range, whereas both were equally sensitive in 25 to 100 per cent available moisture range. Deb and Singh (1963) used fibre glass block with thermister to measure the moisture content and the temperature of the soil, simultaneously.

Evaluation of Soil Moisture Characteristics

The pressure plate and the pressure membrane apparatus developed by Richards (1947) have been used by most of the workers in India to study the soil moisture and tension relationships in the range from 1/10 to 15 atmospheres, and the sintered glass funnels below 1/10 atmospheres. The saturation percentage has been determined either by the use of Keen's moisture boxes with screen bottoms or by the use of sintered glass funnels maintained at zero tension. In comparing different methods of determination of the wilting percentage, Fatch Lal *et al.* (1967) reported that the 15-atmosphere percentage determined by the use of Pressure Membrane apparatus correlated best with the wilting percentage determined by the Sunflower Method. An attempt was made by Abrol and Khosla (1966) to determine the wilting percentage from the surface area of the soil. Singh and Mehta (1939) used Osmotic Solution Method for the determination of the water retention force of the soil.

The tensiometers developed by Richards (1949), consisting of water filled porous cup buried in the soil and connected to a manometer or vacuum gauge, have been used by most of the workers to evaluate the soil moisture and tension relationships under field conditions for irrigation scheduling. The tensiometers have been found to be quite useful in the range from 0 to 0.85 atmosphere, thus covering over 90 per cent of available moisture in sandy soils and about 50 per cent of available moisture in the fine textured soils. The fine textured soils have been found to clog the porous cup and shrink away from it, but this could be avoided by setting the tensiometer in the sand. The effect of temperature fluctuations has been reduced by the use of double-walled acrylic tensiometers with weather proof Borrdon vacuum gauges.

Evaluation of Hydraulic Conductivity

Shukla and Nayar (1943) made a detailed study of the constants

used in Harris equation (1931) for the estimations of the permeability of Na-Ca system based on the clay content and suggested that the Harris equation may be written as

$$Y = \frac{K_1}{\log c} e^{-K_2 (\text{cation})}$$

where y is the permeability ; c , the clay content ;

$$K_1=0.25, K_2=0.18$$

In the laboratory, the saturated hydraulic conductivity of the fragmented soil, packed in cylinders has been evaluated by most of the workers using Darcy's law and overflow method. Seth and Yadav (1958) used soil cores collected in 22.5 cm long cylinders for the permeability determinations. Gupta (1966) described a system consisting of a permeameter cell, a constant head water supply unit, and a piezometer stand to evaluate the saturated hydraulic conductivity and permeability of different layers of the soil profile simultaneously by packing the fragmented soil passed through a 2 mm-sieve in the same sequence.

The constant head system is preferred for the soils with conductivities greater than approximately 0.6 cm per hour, whereas the falling head system is preferred for the soil with lower conductivities.

The conductivity coefficient being a function of the properties of both the porous material and the fluid, is subject to considerable variation. Any change in the pore geometry and the effective pore space due to the entrapment of air during wetting, release of gases from the fluid during flow, swelling and flocculation of the colloids, slaking of aggregates and growth of micro-organism, deserve to be avoided by wetting the soil under vacuum and by the use of air free liquid containing some electrolyte and disinfectant.

The errors arising from the heterogeneity in the bulk density during packing and due to temperature fluctuations are also avoided by the use of mechanical packers, and by correcting the results to a standard temperature.

The unsaturated hydraulic conductivity values for the sandy loam soil have been calculated by Singh (1971) from the diffusivity coefficients by the use of unsaturated flow theory developed by Phillip (1955).

Evaluation of Infiltration and Capillary Rise Rates

Single- and double-ring infiltrometers have been used with constant and variable head water supply units by most of the workers to evaluate the infiltration rates of soils of India. Bonde and Subrama-

nyam (1968) compared the variable head single ring infiltrometer with a constant head self-dispensing infiltrometer, and found that both the types were equally effective in determining the infiltration rates. Singh (1971) calculated the infiltration rate of sandy loam soil by the use of flow theory developed by Phillip (1957, 1958).

The initial rate of water intake is greatly influenced by the moisture content and surface conditions of the soil; knowledge of these conditions is important for interpretation of the results obtained. The use of larger infiltration areas with sufficient border strips is essential to minimise the lateral subsurface movement of water and to satisfy the assumption of unidirectional flow. The use of sprinkler-type system of water supply may be preferred to that of flood-type.

The rate of capillary rise and evaporation have been determined by most of the workers by packing the soil in glass or metal tubes at known bulk density, and by maintaining a constant depth of water table.

SOIL-MOISTURE CHARACTERISTICS

The amount of water held in a soil by the forces of adhesion, cohesion and surface tension depends upon the total surface area of the soil constituents and the size distribution of pores in the soil. The total surface area is determined by the amount and type of clay in the soil, and the pore size distribution is determined by the texture and structure of the soil.

Soils in India vary in their clay content from less than 15 per cent to greater than 60 per cent, with a considerable variation in their organic matter, cation exchange capacity, sodium saturation and aggregation. A knowledge of the soil moisture characteristics of each type of these soils is essential for the proper management of irrigated, unirrigated, waterlogged and saline-alkali soils.

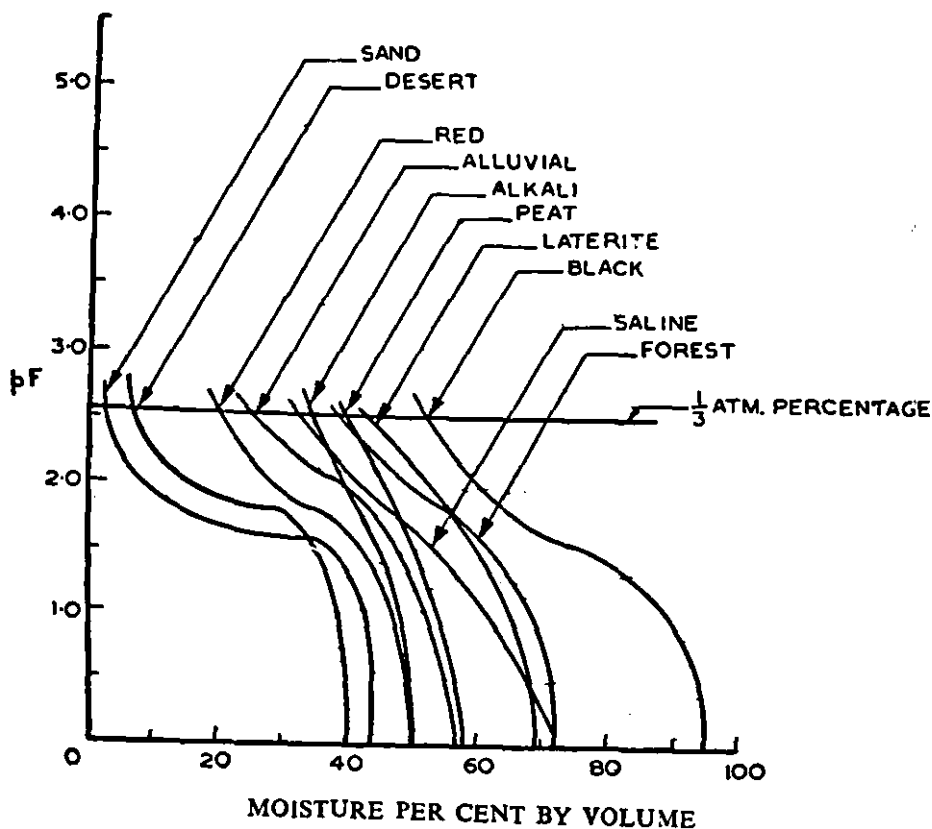


Fig. 1. Soil-moisture characteristic curves (Rao and Ramacharlu, 1959)

TABLE I
 MOISTURE HELD AT VARIOUS TENSIONS, PER CENT BY DRY
 WEIGHT (ALI *et al.*, 1966)

Soil		Atmospheres				Available Moisture	Dominant Clay Mineral
		0	1/10	1/3	15		
<i>Alluvial</i>							
Delhi	A	34.0	27.2	10.7	4.4	6.3	I
	B	37.4	29.9	17.7	7.7	10.0	I
Lucknow	A	47.0	42.1	29.2	8.1	21.1	I
	B	41.2	34.6	25.8	6.0	19.8	I
Chinsurah	A	54.1	48.2	36.7	19.0	17.7	I
	B	46.5	42.9	33.6	17.3	16.3	I
Burdwan	A	47.6	47.0	35.3	16.1	19.2	I
	B	55.6	41.8	32.3	17.0	15.3	I
Ludhiana	A	24.8	20.5	12.1	3.6	8.5	K
	B	25.7	21.9	11.3	3.7	7.6	K
Pusa	A	32.1	31.6	15.5	1.9	13.6	I
	B	36.6	34.9	23.8	2.8	21.0	I
<i>Black</i>							
Rajendranagar	A	58.1	36.4	23.7	12.7	11.0	M
	B	54.5	34.4	23.2	12.0	11.2	M
Achalpur	A	60.9	48.1	38.0	15.8	22.2	M
	B	61.5	55.5	41.1	20.0	20.1	M
Tharsa	A	58.1	45.8	30.0	16.1	13.9	M
	B	54.5	40.5	28.3	16.2	12.1	M
Padegaon	A	83.8	68.3	43.5	25.7	16.8	M
	B	76.3	68.8	43.3	27.2	16.1	M
Nagpur	A	58.1	54.4	38.9	21.1	17.8	M
	B	54.5	51.3	34.8	20.5	14.3	M
<i>Red</i>							
Cheruvukomimupalem	A	33.8	30.2	17.5	8.5	9.0	K
	B	41.4	34.9	23.0	12.3	10.7	K
Yemmiganur	A	34.5	31.4	19.8	8.2	11.6	K
	B	44.3	38.7	24.9	13.6	11.3	K
Hebbal	A	26.1	24.9	11.6	5.6	6.0	K
	B	29.3	62.2	12.8	7.8	5.0	K
Tolukhal	A	35.0	27.4	13.4	8.8	4.6	K
	B	35.6	25.8	16.8	11.6	5.2	K
Raichur	A	31.4	26.2	13.7	7.4	6.3	K
	B	32.0	24.3	14.0	7.5	6.5	K

TABLE I (Contd)

Soil		Atmospheres				Available Moisture	Dominant Clay Mineral
		0	1/10	1/3	15		
<i>Laterite and Lateritic</i>							
Midnapore	A	27.6	21.8	13.7	5.2	8.5	K
	B	37.2	27.9	18.2	9.1	9.1	K
Kuttapana	A	30.0	36.8	15.1	9.7	5.4	K
	B	43.0	33.8	25.6	19.9	5.7	K
Narkodu	A	51.6	43.2	22.2	16.9	5.3	K
	B	55.0	43.4	29.4	21.1	8.3	K
Bhata	A	43.0	35.2	26.5	13.1	13.4	K
	B	48.5	36.9	27.5	15.5	12.0	K
Suri	A	24.0	22.5	14.2	4.3	9.9	K
	B	23.0	20.5	13.3	4.4	8.9	K
<i>Mountain and forest</i>							
Bhowali	A	56.2	44.9	32.0	9.1	22.9	I
	B	50.3	36.4	27.2	10.4	16.8	I
Ootacamand	A	49.7	42.0	30.5	18.7	11.8	K
	B	45.2	34.9	26.7	17.3	9.4	I
Dehra Dun	A	41.3	37.0	29.1	8.4	20.7	I
	B	43.7	35.0	26.8	9.8	16.9	I
<i>Desert</i>							
Pali	A	40.1	29.8	19.0	8.0	11.0	I
	B	48.2	36.5	29.5	10.7	9.8	I
Beriganga	A	29.4	24.5	8.5	3.7	4.8	I
	B	24.9	20.8	6.0	2.7	3.3	I
<i>Saline</i>							
Sonapur	A	52.5	45.4	38.1	11.9	26.2	I
	B	57.9	42.1	36.3	13.2	23.1	I
Mankhanda	A	50.7	42.3	33.6	10.5	23.1	I
	B	44.2	38.8	32.0	10.5	21.5	I
Canning	A	55.6	54.2	41.9	15.5	26.4	I
	B	48.8	47.5	35.1	15.4	19.7	I

A and B represent surface (0-15 cm) and sub-surface (15-30 cm) samples, respectively

K=Kaolinite, I=Illite, M=Montmorillonite

TABLE 2

MOISTURE HELD AT VARIOUS TENSIONS IN SOIL PROFILE
PER CENT BY DRY WEIGHT (ABROL AND BHUMLA, 1968)

Sl. No.	Depth (cm)	ATMOSPHERES							Available Moisture	Available moisture (cm)
		0	1/3	1.5	2.5	5	10	15		
PROFILE I										
1.	0-9.16	39.47	17.56	10.27	8.97	7.40	6.28	5.42	12.14	1.72
2.	9.16-34.56	34.98	17.92	11.04	9.68	7.86	6.36	5.98	11.94	4.24
3.	34.56-63.50	40.59	18.22	13.25	12.06	9.94	7.97	7.70	10.52	4.11
4.	63.50-126.00	40.56	21.28	15.64	13.91	11.60	9.86	8.90	12.38	10.99
5.	126.00-162.56	45.11	25.86	15.73	13.22	10.24	8.06	8.40	16.46	8.17
6.	162.56-175.26	41.16	23.55	10.68	8.97	7.17	5.64	5.25	18.30	3.25
PROFILE II										
7.	0-12.70	40.63	21.48	11.72	9.62	8.19	6.78	6.09	15.39	2.74
8.	12.70-30.48	42.04	23.34	18.19	15.54	12.72	10.33	8.92	14.41	3.58
9.	30.48-55.88	40.71	20.84	13.69	11.54	9.56	8.26	7.49	13.35	4.74
10.	55.88-78.74	38.93	20.82	12.86	10.83	8.67	7.40	6.71	14.11	4.77
11.	78.74-93.98	40.07	20.15	13.69	11.29	9.17	7.67	7.05	13.10	2.79
12.	93.98-154.94	43.09	25.59	21.87	17.32	14.25	12.29	10.67	14.92	12.72
13.	154.94-172.72	46.11	29.38	24.24	20.85	17.80	15.90	15.17	14.21	3.53

TABLE 3
MOISTURE HELD AT VARIOUS TENSIONS IN NORMAL AND SALINE-
ALKALI SOILS, PER CENT BY DRY WEIGHT
(SEKHON AND ARORA, 1967)

Soil*	Depth cm	Atmospheres				Available moisture	Hydrau- lic Con- ductivity cm/hr
		1/10	1/3	3	15		
Harkishanpura-I	0-30	14.9	8.00	5.54	3.95	4.05	0.72
	30-69	19.83	8.29	6.02	6.37	1.92	1.41
	69-82	18.54	7.19	5.21	3.94	3.25	1.28
	82-114	32.08	20.56	14.79	9.70	10.86	0.50
	114-127	20.33	9.48	5.90	4.29	5.19	1.00
	127-133	30.07	12.35	7.14	4.98	7.37	0.95
Harkishanpura-II	0-2.5	23.96	12.84	6.60	4.25	8.59	0.09
	2.5-11	24.11	14.09	8.70	5.67	8.42	0.05
	11-33	24.29	17.73	12.91	8.34	9.39	0.03
	38-76	24.21	20.03	16.36	10.25	9.78	0.06
	76-120	30.68	19.89	15.07	9.07	10.82	0.02
	120-137	27.82	19.23	14.08	8.09	11.14	0.13
	137-165	28.63	25.02	15.94	10.29	14.73	0.17
	165-183	25.80	18.74	10.88	6.42	12.32	0.15
Hansi	0-13	30.09	20.86	12.17	6.69	14.17	0.19
Rohtak	0-28	29.52	23.78	11.10	6.72	17.06	0.27
Shamgarh	0-18	29.30	17.05	11.16	5.99	11.06	0.38
Jagraon-I	0-18	28.66	17.31	10.63	6.73	10.58	0.53
Jagraon-II	0-30	25.89	15.20	8.48	5.61	9.59	0.57
Kama-I	0-23	30.29	20.15	11.10	6.88	13.27	0.44
Kama-II	0-15	27.75	16.34	8.36	5.13	11.21	0.46
Behram-I	0-18	31.66	25.74	12.44	7.78	17.96	0.22
Behram-II	0-13	31.90	22.76	9.45	5.76	17.00	0.32
Amritsar-I	0-20	29.08	19.38	11.26	7.09	12.29	0.25
Amritsar-II	0-5	35.15	29.42	14.91	8.65	20.77	0.02
Nabha-I	0-14	25.30	11.36	7.20	4.67	6.69	0.46
Nabha-II	0-14	21.51	14.34	7.95	5.20	9.14	0.50

* I are normal soils, and II are saline alkali soils

TABLE 4

EFFECT OF CHEMICAL FERTILIZERS AND MANURES ON THE
MOISTURE HELD AT VARIOUS TENSIONS, PER CENT
BY DRY WEIGHT (BISWAS *et al.*, 1969)

Treatments	Atmospheres				Available moisture
	0	1/10	1/3	15	
Control	37.8	30.9	23.2	10.7	12.5
N	38.0	31.3	24.3	11.4	12.9
No	40.6	35.3	25.3	11.9	13.4
NP	39.7	33.2	25.1	11.6	13.5
NoP	40.8	32.8	25.1	11.7	13.4
NPK	38.1	33.6	25.1	10.9	14.2
NoNPK	39.8	33.9	24.2	11.1	13.1
LNPK	39.6	32.5	24.2	11.4	12.8

N = 44.8 kg N/ha as $(\text{NH}_4)_2\text{SO}_4$

No = - do - as F.Y.M.

P = 44.8 kg P_2O_5 /ha as superphosphate

K = 44.8 kg K_2O /ha as murate of potash

L = Liming 2688 kg, lime/ha every fifth year

TABLE 5

EFFECT OF ORGANIC CARBON ON THE MOISTURE HELD AT
VARIOUS TENSIONS, PER CENT BY DRY WEIGHT
(BISWAS AND ALI, 1969)

Soil Group	Location	Organic Carbon%	Atmospheres			Available moisture
			1/10	1/3	15	
Medium-black	Kopra	A 0.330	52.7	41.4	24.4	17.0
		B 1.397	62.5	49.0	26.7	22.3
Deep-black	Padegaon	A 0.666	64.6	49.1	28.2	20.9
		B 1.672	70.7	53.9	28.4	25.5
Alluvium	Chinsurah	A 0.822	45.3	38.0	19.8	18.2
		B 0.911	47.0	39.6	20.1	19.5
	Sabour	A 0.405	31.5	20.1	4.4	15.7
		B 0.971	37.1	24.2	6.7	17.5
	Delhi	A 0.438	27.4	15.9	6.6	9.3
		B 0.605	28.6	17.1	6.9	10.2
	Pusa	A 0.201	29.2	15.3	2.0	13.3
		B 0.338	32.0	17.8	2.4	15.4
Lateritic	Bhubaneswar	A 0.341	16.5	11.6	3.6	8.0
		B 0.368	18.0	12.8	4.1	8.7
Brownish	Coimbatore	A 0.190	32.1	13.6	6.1	7.5
		B 0.449	26.2	17.1	7.8	9.3

The symbols A and B indicate soils of the same locality with relatively lower and higher organic carbon status.

The soil moisture characteristics of different soils evaluated by Rao and Ramacharlu (1959), Ali *et al.* (1966), Sekhon and Arora (1967) and Abrol and Bhumbra (1968) are given in Figure 1 and Tables 1 to 3. It may be noted that the moisture content decreased with the increase in soil moisture tension, irrespective of the soil type, however the rate of decrease depended on the latter. An increase in tension from zero to $1/3$ atmosphere released more than 75 per cent of water in light-textured soils, but less than 50 per cent in heavy textured soils (Fig. 1, Table 1). The amount of available moisture ($1/3$ –15 atm) was found to vary from 6 per cent in light-textured soils to more than 15 per cent in heavy, textured soils. The soils having montmorillonitic type of clay held higher amounts of available water than the soils having illitic and kaolinitic type of clay. The black soils, having clay minerals of high hydration capacity such as montmorillonite, held more water at a given tension than the red and alluvial soils, having clay minerals of low hydration capacity such as illite and kaolinite. A positive and significant correlation coefficient of 0.665 for silt plus clay, 0.633 for silt and 0.453 for clay alone, with the amount of available water was reported by Sekhon and Arora (1967). Abrol and Bhumbra (1968) reported a correlation coefficient of 0.450 for silt only.

The 15 and $1/3$ atmosphere percentages were found to have a positive and significant correlation coefficient of 0.718 and 0.668 for silt plus clay, and 0.562 and 0.803 for silt alone, and a non-significant correlation coefficient of 0.371 and 0.036 for clay, respectively (Abrol and Bhumbra, 1968). Biswas and Ali (1967) reported a positive and significant correlation coefficient of 0.946 between clay content (illite-type) and 15-atmosphere percentage. Sekhon and Arora (1967) reported that the cation exchange capacity of the Punjab soils was significantly correlated with the amount of available moisture. The high amount of exchangeable sodium was found to be associated with increased moisture retention.

The application of chemical fertilizers consisting of N, P and K, either alone or in combination were found to increase the water retention of soils at low tensions, especially the combinations NPK and NP (Fig. 2).

Kanwar and Prihar (1962) and Biswas *et al.* (1964, 1969) also reported that the continuous application of phosphatic fertilizers improved the water-holding capacity of the soils.

The continuous application of farmyard manure was found to improve the water retention capacity of the sandy to silty loam soil of Pusa, Bihar (Das *et al.* 1966), and that of brown-sandy clay-soil of coimbatore, and silty clay-loam soil of Ranchi (Table 4), especially at the low tensions as compared with the application of N alone. Similar

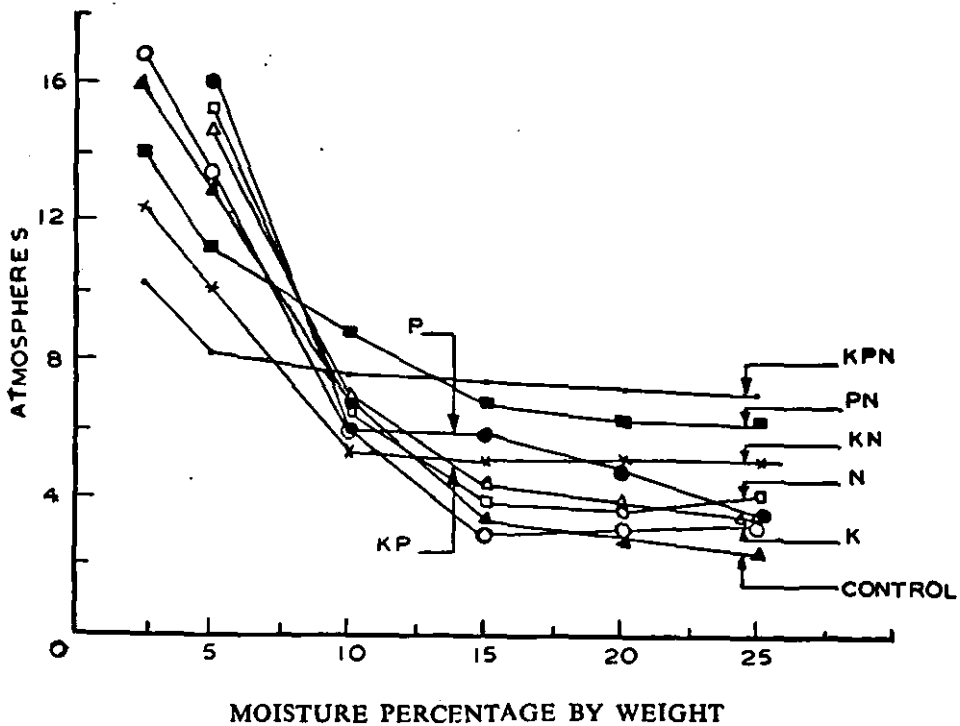


Fig. 2. Influence of chemical fertilizers on soil-moisture characteristics (Singh and Mehta, 1939)

results have been reported by Biswas and Ali (1969). The 1/3 atmosphere percentage was found to be affected to a much greater degree than the permanent wilting percentage, with a resultant increase in available moisture (Table 5) irrespective of the soil type.

Gulvadi *et al.* (1947) reported that the removal of organic matter decreased the sorption capacity of red and black soils. A negative correlation was reported by Abrol and Bhumbra (1968), and a small positive and non-significant by Sekhon and Arora (1967) between organic matter and available moisture in alluvial soils.

The addition of Na- or K-charcoal to H-soil was found to decrease the sorption capacity of the soil, whereas the addition of H- or Ca-charcoal to Na-soil was found to increase the sorption capacity of the soil (Puri and Mahajan, 1962).

The heating of the soil up to 60°C was found to decrease the amount of water held at zero tension, whereas further heating up to 650° was found to increase, this phenomenon has been attributed to the change in non-capillary pore space by Rao and Ramacharlu (1955, 1959). Biswas *et al.* (1967) reported that the moisture-retention characteristics

of the soil did not change much during the growth of berseem crop. Chibbar (1964) reported that the maximum water-holding capacity was the highest in aggregates between 0.2 to 1.0 mm size.

The phenomenon of hysteresis was found to be more marked in heavy-textured soils than in light-textured soil as reported by Gulvadi *et al.* (1947) and Deb and Singh (1963).

SOIL-WATER MOVEMENT

The rate of movement of water through soil is of considerable interest to agricultural scientists and engineers. The movement of water takes place through a soil in response to the various forces and gradients acting upon it. These may be pressure, gravitational, concentration, thermal, electrical and absorptive gradients. In the liquid phase, water moves both by mass flow and diffusion, whereas in the vapour phase mainly by diffusion.

The mass flow is also called percolation and the movement of water is governed by the Darcy's law written as:

$$Q = \frac{KA \Delta H}{L}$$

where Q is the rate of flow of water through a soil column of length L and cross sectional area A . K is the hydraulic conductivity and ΔH is the difference between the inlet and the outlet heads of water. Hydraulic conductivity is a function of both the properties of liquid and that of porous media, and may be explicitly written as :

$$K = \frac{dgk}{n}$$

where k is the permeability coefficient or the characteristic coefficient of the porous media, g is the gravitational acceleration, and d and n are the density and viscosity of the liquid, respectively, which are dependent on the temperature of the liquid.

The permeability coefficient of a porous media is a function of both the total pore space and the size distribution of pores as shown by the mathematical analysis of Gupta (1968).

In case of capillary flow, the movement of water through soil is governed by the partial differential flow equation written as :

$$\frac{d\theta}{dt} = \frac{d}{dx} \left(K_x \frac{d\phi}{dx} \right) + \frac{d}{dy} \left(K_y \frac{d\phi}{dy} \right) + \frac{d}{dz} \left(K_z \frac{d\phi}{dz} \right)$$

where θ is the moisture content; t is the time; K_x, K_y, K_z are the hydraulic conductivity values in x, y and z directions respectively, and ϕ is the total potential.

Hydraulic Conductivity Coefficients

The saturated hydraulic conductivity data are of use in analysis of any saturated-soil-water-flow system, and provides indirect infor-

mation about the structure and structural stability of soils. The hydraulic conductivity may be defined qualitatively, as the ability of the soil to transmit water, and quantitatively, as the amount of water flowing through a soil column of a unit cross sectional area, in a unit time, under a unit hydraulic gradient and isothermal conditions.

The hydraulic conductivity coefficients have been evaluated by a number of workers for different soils of India. Soni and Chakravarti (1959) reported that the hydraulic conductivity of soil profiles, of Siwan areas in north Bihar varied from 0.09 cm/hr to 2.76 cm/hr, for the surface soil with texture varying from heavy to light. The coefficient decreased with the increase in depth, and a compact layer in the soil profile between 75 to 120 cm was found to be limiting the permeability of the soil.

The structure of the soil has been shown to be closely related with the hydraulic conductivity values determined at the minimum bulk density by Dakshinamurti and Pradhan (1966). Seth and Yadav (1958) reported that the hydraulic conductivity of 22.5 cm long soil cores, collected from the demonstration area of the Forest Research Institute, Dehra Dun, was higher under the khair and sal plantations than under teak and chir plantations (Table 6).

TABLE 6
FOREST PLANTATIONS AND HYDRAULIC CONDUCTIVITY
(SETH AND YADAV, 1958)

Plantation	Hydraulic Conductivity cm/hr	
	*Surface (0-22.5 cm)	*Sub-surface (67.5-90 cm)
Chir	3.0	25.8
Teak	22.7	57.6
Sal	26.4	119.7
Khair	43.7	92.9

* Maximum values

Nayar and Shukla (1943 a, b, c) reported that the replacement of calcium by Na^+ , NH_4^+ or K^+ ion on the soil complex reduced the rates of percolation in the order $\text{Na} - \text{soil} < \text{NH}_4^+ - \text{soil} < \text{potassium soil} < \text{calcium soil}$, i.e. in order of increasing ionic radius and valency as evident from Table 7.

TABLE 7
EXCHANGEABLE ION AND HYDRAULIC CONDUCTIVITY
(NAYER AND SHUKLA, 1943C)

Ion	Radius A°	Rate of Percolation in/hr	
		Observed	Calculated
Li ⁺	0.78	0.0005	0.00048
Na ⁺	0.98	0.0027	0.00272
NH ⁺⁺	1.14	0.0115	0.01084
K ⁺	1.33	0.0600	0.05598
Rb ⁺	1.49	0.2250	0.2239
Mg ⁺⁺	0.65	0.150	0.153
Ca ⁺⁺	0.99	0.275	0.272
Sr ⁺⁺	1.13	0.350	0.345
Ba ⁺⁺	1.35	0.500	0.504

A very good agreement was obtained between the experimental rates and those calculated by the use of Harris equation (1931), when these values varied from 10 to 100 per cent. The Harris equation is written as :

$$Y = a e^{-bs}$$

where y is the percolation rate and s is the per cent saturation with respect to alkali ion ($s = \text{amount of alkali cation} \times 100 / \text{base exchange capacity}$). The equation did not fit well when the soil was pure calcium saturated or s was zero. The constants a and b in the above equation were found to be dependent on the type of the ion on the soil complex. The constant ' a ' increased with the atomic weight whereas the constant ' b ' decreased in the same order. The replacement of exchangeable sodium through leaching by exchangeable hydrogen increased the rate of percolation. Sekhon and Arora (1967) reported that the presence of sodium salts in some soils decreased the hydraulic conductivity values to 1/10th that of normal soil.

The presence of different cations in the irrigation water was found to influence the hydraulic conductivity of both the light- and heavy-textured soils of Ludhiana (Table 8).

The maximum hydraulic conductivity was obtained when the calcium ions were present in the irrigation water in both the light- and

heavy-textured soils. The hydraulic conductivity decreased as the ratio of K/Ca, K/Mg, Na/Ca, and Na/Mg increased.

TABLE 8
CATIONS IN IRRIGATION WATER AND HYDRAULIC CONDUCTIVITY
(KANWAR AND DEO, 1969)

Treatments	Hydraulic Conductivity cm/hr	
	Light-textured soil (A)	Heavy-textured soil (B)
Control	4.21	0.60
Ca-dominant	6.00	0.79
Na-dominant	0.18	0.01
Mg-dominant	4.90	0.67
K-dominant	0.95	0.12

RATIOS

Systems	0.2		0.5		2.0		5.0	
	A	B	A	B	A	B	A	B
K : Mg	4.33	0.53	1.87	0.38	1.56	0.17	1.52	0.08
K : Ca	4.99	0.32	3.75	0.45	1.68	0.19	1.66	0.15
K : Na	0.39	0.02	1.43	0.25	1.52	0.07	1.45	0.05
Na : Ca	5.77	0.45	5.23	0.34	2.18	0.04	1.83	0.03
Na : Mg	5.15	0.60	1.86	0.16	1.51	0.02	1.77	0.01
Mg : Ca	3.28	0.57	5.30	0.42	4.68	0.46	4.61	0.26

An increase in the bulk density of the soil decreased the hydraulic conductivity. More than 100-fold decrease in the hydraulic conductivity was reported by Ghildyal and Satyanarayana (1965) with about 25 per cent increase in the bulk density of the light-textured soil (Table 9).

Rao and Wadhawan (1953) found that the heating of the soil up to 60°C decreased the permeability and the hydraulic conductivity of the soil, whereas further heating of the soil up to 650°C increased the permeability; this was attributed to the change in non-capillary pore space of the soil. The general trend of the final hydraulic conductivity values of the soil heated to different temperatures was to revert to that of normal soil after a prolonged flow.

TABLE 9

EFFECT OF COMPACTION ON HYDRAULIC CONDUCTIVITY
(GHILDYAL AND SATYANARAYANA, 1965)

<i>Hijli Sandy Loam</i>		<i>Anand Sand</i>		<i>Nagpur Clay</i>		<i>Kharagpur Sandy Clay Loam</i>	
<i>Bulk density (g/cm³)</i>	<i>K* (cm/sec)</i>	<i>Bulk density (g/cm³)</i>	<i>K* (cm/sec)</i>	<i>Bulk density (g/cm³)</i>	<i>K* (cm/sec)</i>	<i>Bulk density (g/cm³)</i>	<i>K* (cm/sec)</i>
1.56	52.78	1.40	114.6	1.53	98.65	1.11	42.70
1.71	7.84	1.45	82.07	1.67	26.61	1.18	13.15
1.80	1.54	1.50	68.90	1.72	9.82	1.28	6.31
1.87	1.23	1.55	47.90	1.83	6.96	1.43	4.11
1.97	0.31	1.60	28.30	1.96	1.47	1.50	0.213

* Hydraulic Conductivity in 10⁻¹

The hydraulic conductivity of the soil has been found to decrease with the decrease in the moisture content (Fig. 3). The hydraulic

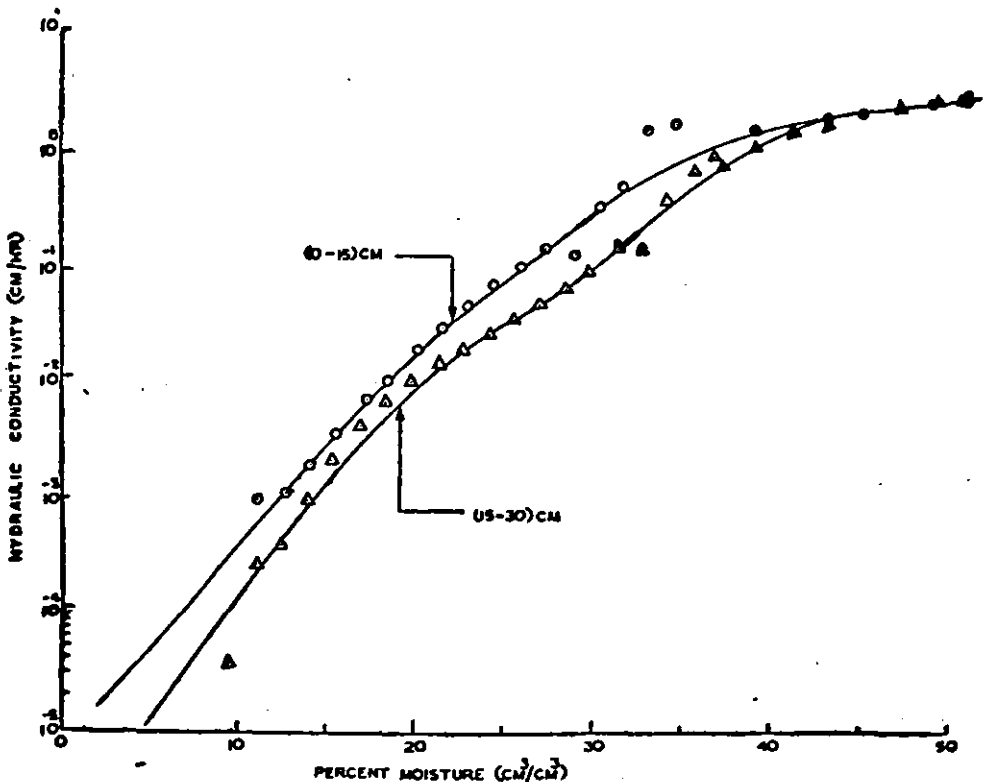


Fig. 3. Hydraulic conductivity coefficients

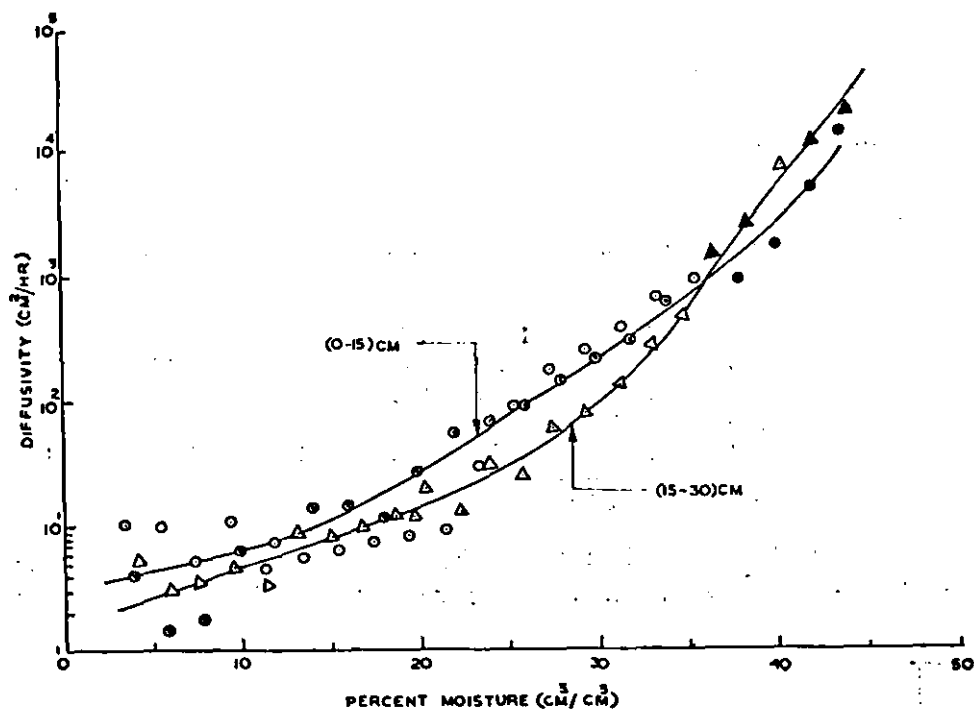


Fig. 4. Diffusivity Coefficients

conductivity varied from 2×10^{-5} cm/hr for the air-dry soil to 2.5 cm/hr for the saturated soil. The diffusivity coefficients were also found to vary from 2 cm²/hr for the air-dry soil to 4.6×10^4 cm²/hr for the soil at zero soil moisture tension (Fig. 4).

Infiltration

The amount of water stored in the soil profile, water-sheds, and lakes; and lost as run-off depends upon the infiltration capacity of the soil, in addition to its soil-moisture characteristics. The infiltration capacity of the soil depends upon the soil slope, surface roughness, vegetal cover and the management of the soil. Patnaik and Virahi (1962), Khybri (1965), Mistry and Chatterjee (1965), and Bonde and Subramanyam (1968) reported that the infiltration rates were greatly influenced by the surface cover, and were also found to decrease with the increase in infiltration time (Tables 10 to 13).

In the watershed of River 'Asan' (Table 10), the initial infiltration rates were found to vary from 2.05 to 9.60 cm/hr, and the rates

TABLE 10
INFILTRATION RATES IN DOON VALLEY
(PATNAIK AND VIRAHI, 1962)

Site	Infiltration Rate cm/hr	
	1st hr	2nd hr
<i>A-Cultivated Area</i>		
1. Dholkot—Under cover crop, surface soil having no pebbles or stones	4.0	2.75
2. Sahaspur—Ploughed fallow with a few stones and pebbles on the surface soil	3.55	1.95
3. Lakhewala—Harvested rice field with some stones and pebbles on surface soil	2.70	1.90
4. Tapkeshwar—Ploughed field with stone and pebbles on surface soil	4.50	2.25
5. Babagarh—Fodder sorghum harvested, no pebbles on surface soil	7.30	4.55
6. Bhurpur—Ploughed field, no stones and pebbles on surface compact layer below	3.75	0.85
<i>B-Cultivated Himalayan Upland</i>		
7. Sinola—Ploughed land with some stones on surface	7.90	4.20
8. Kinderwal—do—	7.50	4.40
9. Bakhtawarpur—do—	7.10	6.65
10. Donga—do—	9.50	5.10
11. Ruderpur—do—	9.60	5.10
12. Khāлагаон—Rice harvested, soil puddled, extremely compact	2.05	0.75
<i>C-Forest Areas</i>		
13. Bidhauri—Sal forest with good leaf litter	8.95	5.90
14. Horawala—Sal forest with little leaf litter and compact surface	3.65	2.00
15. Amari, R.F.—Sal forest with little leaf litter and compact surface	4.55	2.45
16. Chandpur, R.F.—do—	4.85	2.55
17. Dholkot, R.F.—Sal forest with good leaf litter	7.35	6.00
<i>D-Forested Siwalik slope</i>		
18. Kargapani Fireline—Sal forest with little leaf litter and compact	5.35	2.30
19. Karawapani, R.F.—do—	2.80	1.15
20. Sabhawala Fireline—do—	3.70	2.70
21. Sabhawala Forest Chawki—Miscellaneous forest with compact surface	4.15	2.00

TABLE 11
INFILTRATION RATES OF CHURIA HILLS, NEPAL (KHYBRI, 1965)

Site**	Surface Cover	Stoniness	Initial* Moisture per cent	Infiltration rate (cm/hr)		
				1st hr	2nd hr	3rd hr
1. Near Archale	Grass turf	nil	16.5	1.01	1.11	1.09
2. Durbasa Khola watershed	Forest trees	Yes	5.6	12.19	7.25	6.64
3. Near measuring Weir site	Forest trees	Yes	5.5	5.65	3.02	2.6
4. Bhaber Zone	Sal Forest	Yes	20.1	5.54	4.92	4.12

* Moisture content of surface (0-8 cm) layer

- ** 1. Top of Durbasa watershed, surface-loam, and sub-surface-clay loam
 2. Midway between Phulbari and KR 19/27, surface sandy clay loam, and sub-surface-gravelly loam
 3. Bottom of Durbasa watershed, surface-gravelly sandy loam, and sub-surface gravel and rock fragments
 4. Near Colony area, surface-sandy loam, and sub-surface-sandy loam

TABLE 12
VEGETABLE COVER AND INFILTRATION RATES
(MISTRY AND CHATTERJEE, 1965)

Vegetal Cover	Infiltration Rate (cm/hr)			Total infiltration in 180 min (cm)
	0-15 Min	90-105 Min	165-180 Min	
A. Permanent vegetal (Upland)				
Forest land	51	24	20	81.3
Permanent grass	30	10	8	35.8
Grass plot two-year-old	26	8	6	30.5
Legume plot two-year-old	25	7	5	26.8
B. Arable crop (Upland)				
RAC Farm	22	5	1	21.25
Cultivators farm	20	3	2	14.30
Infrequent cultivated land	18	2	1	13.30
Slopy land with hard pan	10	2	1	10.80
Gullied land	12	2	1	11.30
C. Low land				
RAC farm (paddy)	18	4	2	17.3
Cultivators farm (paddy)	16	4	2	16.8

after two hours from 0.8 to 6.65 cm/hr for the soil under different management practices. The Himalayan foot-hills on the north side of the Doon Valley whether cultivated or under forest had considerably higher infiltration rates than the soils of cultivated valley or those of the southern slopes under highly grazed sal forest.

In the Churia hills and foothills of Nepal (Table 11), the initial infiltration rates were found to vary from 1.01 to 12.19 cm/hr, and the rates after three hours from 1.09 to 6.64 cm/hr, under different surface covers. The sites two and four having high infiltration rates were also found to have 2.6 per cent organic matter as compared with one per cent in sites one and three.

The soils under forest and permanent grass, having high amounts of organic matter, maintained much higher infiltration rates than the soils under arable crops (Table 12). The cumulative intake in three hours varied from 10.8 cm for the slopy land with hard pan to 81.3 cm for land under forest. The denuded forest soils were found to have lower infiltration rates when compared with the soil under natural sod and other vegetal covers (Table 13).

TABLE 13
VEGETAL COVER AND INFILTRATION RATES
(BONDE AND SUBRAMANYAM, 1968)

<i>Treatments</i>	<i>Infiltration rate (cm/hr)</i>		<i>Cumulative infiltration (cm/hr)</i>
	<i>Initial</i>	<i>Final</i>	
Fallow	7.07	0.74	6.77
Pea	9.17	0.76	7.25
Wheat	9.20	0.84	7.87
Natural sod	12.85	0.95	10.10
Denuded forest	6.17	0.74	6.06

The infiltration rates have been found to improve with the proper seed-bed preparation and soil-management practices. The green manuring of the standing sannhemp crop was found to increase infiltration rates by about 50 per cent (Tejwani *et al.* 1966).

The ploughing of the bare land has been found to increase the initial infiltration rates, by two to three folds and the cumulative intake by 1.5 fold (Table 14). Rege and Srinivasan (1959) reported that the initial infiltration rates were higher in the cultivated land when compared with the grassland, but the cumulative intake was greater in

the grassland. The deep ploughing of the light-textured soils have been found to improve their infiltration rates and the water-retention capacity (Tables 15, 16).

TABLE 14
EFFECT OF PLOUGHING ON INFILTRATION RATES
(RAY AND SUBRAMANYAM, 1958)

Time (min)	Infiltration Rates (hr)		Cumulative Intake (in.)	
	Bare	Ploughed	Bare	Ploughed
15	3.08	8.84	—	—
30	2.60	5.44	1.42	3.58
45	2.26	4.40	—	—
60	2.12	3.96	2.52	5.68
75	2.00	3.52	—	—
90	1.86	3.24	3.49	7.38
180	1.60	2.12	5.98	11.05
300	1.47	1.85	8.98	14.83
420	1.47	1.85	11.92	18.53

TABLE 15
EFFECT OF PLOUGHING ON SOIL MOISTURE
(TALLATI AND MEHTA, 1963)

Depth (cm)	Per cent Moisture		*Grain Yield kg/ha	
	Deep	Shallow	Deep	Shallow
0-12.70	14.55	11.90	529.0	248.0
12.70-25.40	15.34	13.93		
25.40-38.10	15.61	15.05		
38.10-60.90	15.65	15.40		
Mean	15.29	14.07		

* Pearl millet crop

TABLE 16

EFFECT OF SUB-SOILING ON SOIL MOISTURE (GUPTA, 1969)

DEPTH (cm)	TREATMENTS					
	Deep ploughing+ Mould-Board ploughing and Discing	Mould-Board Ploughing and Discing	Discing	Desi-hal Ploughing	Discing	Deep Ploughing+ Mould-Board Ploughing and discing
(a) Moisture content of soil on 29th September, 1967 in the normal rainfall year (g/g)						
	CROPPED (Maize)			FALLOW		
0.0-7.5	7.10	7.01	4.81	4.05	3.99	
7.5-15.0	9.58	8.54	5.94	5.94	10.11	
15.0-22.5	11.74	10.01	9.45	10.02	11.55	
22.5-30.0	11.93	11.47	11.19	10.74	11.92	
30.0-37.5	14.78	12.52	11.17	12.27	12.75	
37.5-45.0	14.58	12.65	12.34	12.80	13.65	
45.0-52.5	15.98	12.83	12.04	12.87	14.12	
52.5-60.0	15.31	12.82	11.60	13.18	14.83	
(b) Moisture content of the soil on 19th September, 1968 in deficit rainfall year (g/g)						
0.0-7.5	4.01	3.51	2.92	4.11	3.59	8.75
7.5-15.0	7.26	5.70	4.05	6.73	6.50	10.79
15.0-22.5	9.44	7.55	5.38	8.82	8.01	10.86
22.5-30.0	10.74	8.56	6.47	10.49	9.69	11.97
30.0-37.5	10.53	9.74	6.75	11.11	11.00	13.39
37.5-45.0	11.69	10.48	7.54	12.07	12.18	13.53
45.0-52.5	12.04	11.20	8.30	12.14	12.80	14.17
52.5-60.0	12.44	11.80	8.26	12.72	13.07	14.18

The mould-board ploughing of the Goradu sandy loam soil of Anand (30 to 40 cm deep) followed by discing was found to be conducive to greater retention of moisture in the soil than the shallow ploughing (10 to 12 cm deep) with desi hal and harrow (Table 15). The sub-soiling of the sandy loam soil of Delhi, up to the depth greater than 45 cm at 120 cm intervals, along with mould-board ploughing and discing, has been found to retain a higher amount of moisture in the soil profile, when compared with the other treatments (Table 16) both during the normal and deficit rainfall years. In the Kharif fallow plots, the land prepared by sub-soiling plus mould-board ploughing and discing conserved a higher amount of moisture in the soil than the land prepared by discing alone.

Capillary Rise

As early as 1939, A.N. Puri showed that the height to which the water would rise in a capillary tube depends upon the surface tension, viscosity and density of the liquid, and the radius of the tube. The maximum height (h) to which water would rise in a capillary tube of uniform radius could be expressed as :

$$h = \frac{2T \cos a}{rdg}$$

where T is the surface tension, a is the angle of contact between the water and walls of the tube, r is the radius of the tube, d is the density and g is the gravitational acceleration.

The height of the saturated soil or of closed capillary fringe, above the water table, would depend upon the radius of the largest pore in the soil, and that of the unsaturated soil or of open capillary fringe, upon the radius of the smallest pore in the soil. Ramdas and Mallik (1942) evaluated the influence of the soil texture on the capillary rise rates, and reported that the initial rate of ascent of water was more rapid in the mixtures of sand and black cotton soil than in pure sand and pure black-cotton-soil, and the rate increased with the decrease in the percentage of black-cotton soil up to 28.6 per cent. After eight hours, the maximum rate of ascent shifted gradually towards mixtures containing larger and larger proportions of black soil. In 30 hours, the maximum height of 53.3 cm was reached in the mixture consisting of 14.3 per cent sand and 85.7 per cent black-cotton soil (Table 17).

In another study, Ramdas and Mallik (1939) found that the rate of capillary rise in the normal alluvial soil of Punjab was

TABLE 17
 CAPILLARY RISE IN POONA BLACK SOIL AND SAND MIXTURES (CM)
 (RAMDAS AND MALLIK, 1942)

Time	Per cent Poona black soil							
	100	85.7	71.4	57.1	42.9	28.6	14.3	(All Sand)
10 min	2.7	6.8	8.3	11.7	12.5	15.3	13.3	6.3
20 "	5.8	10.0	11.9	16.1	16.9	19.5	15.9	6.7
30 "	8.0	12.9	14.8	19.4	20.0	22.3	16.9	6.8
45 "	10.7	15.7	17.6	22.3	23.4	25.3	18.5	6.9
8.0 hr	22.4	39.2	38.6	41.4	41.2	36.4	24.9	7.6
24.0 "	43.4	51.3	47.5	48.3	47.7	40.7	28.9	8.5
30.0 "	45.2	53.3	49.6	49.6	48.5	41.8	29.2	8.6

much higher than in the alkali soil (Table 18). In comparing black and alluvial soils, the alluvial soil was found to have a higher rate of capillary rise, especially when the depth of water table was greater than 60 cm.

TABLE 18
 EFFECT OF DEPTH OF WATER TABLE ON CAPILLARY RISE
 IN DIFFERENT SOILS
 (RAMDAS AND MALLIK, 1939)

	Depth of water table (cm)				
	15	30	45	60	90
	<i>Time taken (days) to rise water to soil surface</i>				
Poona Black Soil	1	2	6	15	Not wet
Punjab Alluvial Soil	1.5	3	5	10	21
Punjab Alkali Soil	3	Not wet up to 90 days			

Kothari and Auluck (1942) suggested that the upward movement of water in the experiments of Ramdas and Mallik (1942) could be calculated by the use of relationship written as :

$$t = \frac{nh_{\max}}{kgd} \left[\log \frac{h_{\max}}{h_{\max} - h} - \frac{h}{n_{\max}} \right]$$

where t is the time, n is the viscosity of the liquid and k is the permeability coefficient and is equal to $a^2/8$, where a is the radius of the capillary tube.

The rate of the capillary rise has also been found to be influenced by the presence of salts in the water and soil. Asghar and Dhawan (1948) reported that the maximum height to which a one per cent salt solution could rise in 120 days, varied from 75 cm for sodium sulphate solution to 170 cm for sodium chloride solution (Fig. 5).

In case when the soils containing the above salts in the same concentration (one per cent) were packed in columns ; the maximum

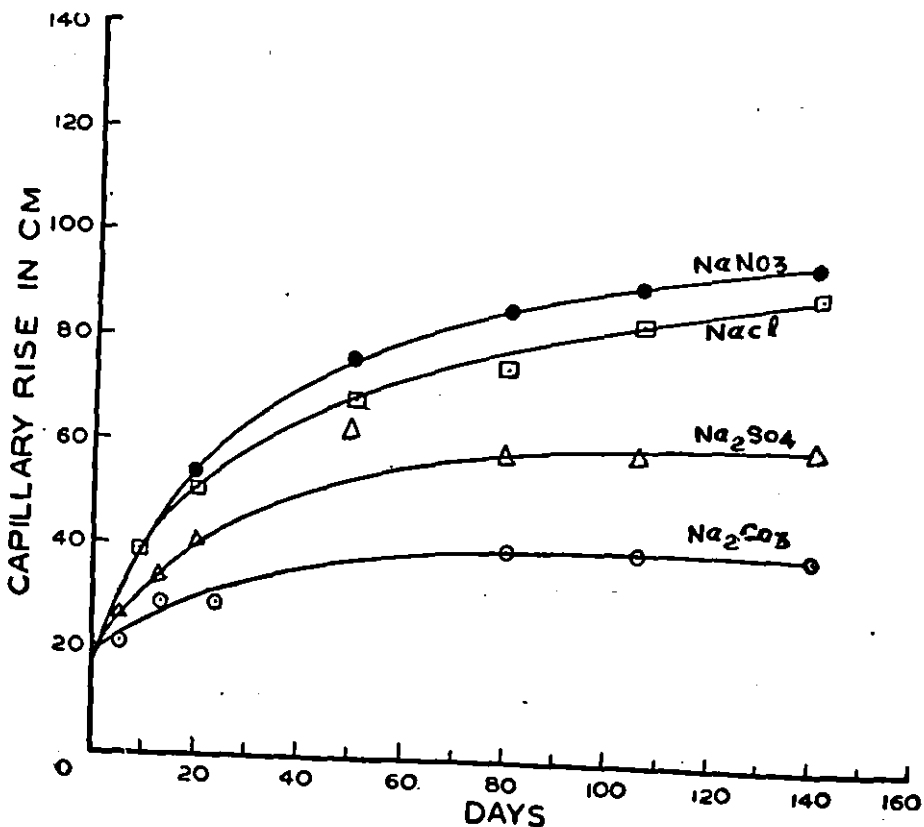


Fig. 5. Capillary rise of 1 per cent salt solution (Asghar and Dhawan, 1948)

height to which the salt-free water could rise in 140 days was found to vary from 40 cm for sodium carbonate to 95 cm for sodium nitrate salts (Fig. 6).

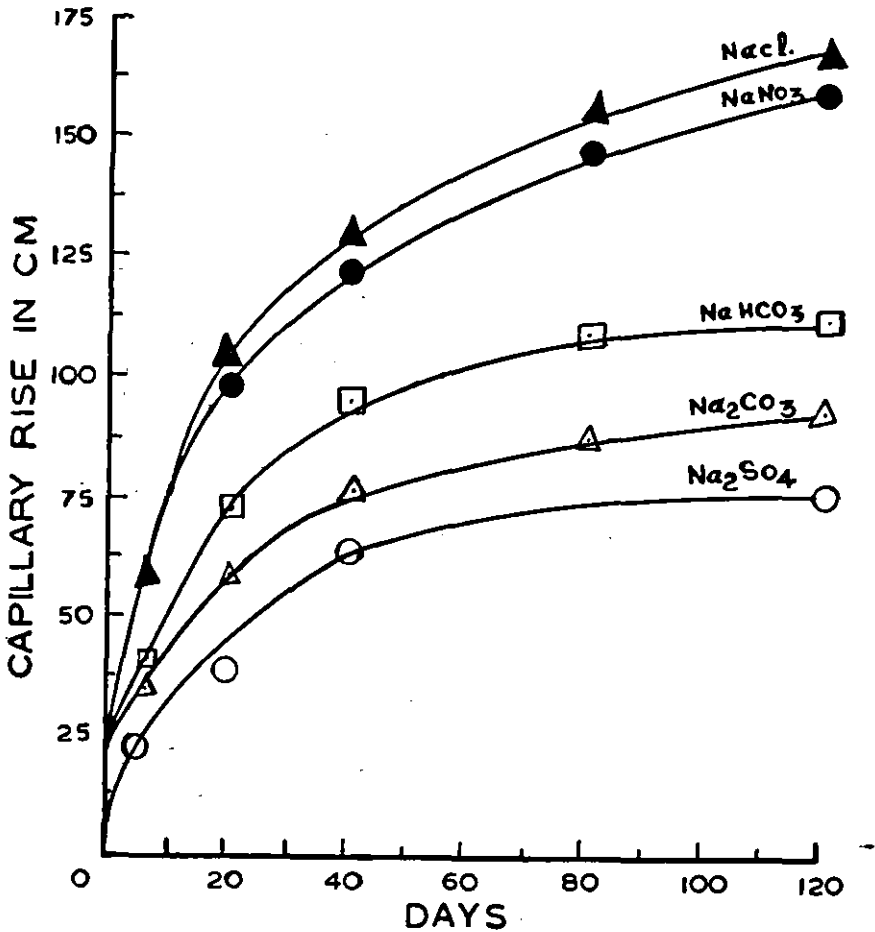


Fig. 6. Capillary rise in soil containing 1 per cent salt (Asghar and Dhawan, 1948)

The authors were also able to calculate the rates of capillary rise from the empirical relationship written as :

$$h = h_{\max} (1 - b)^{ta}$$

where $h_{\max} = 1.792/d^{0.89}$ a and b are constants varying with the size of soil particles, and d is the diameter of the soil particles.

Evaporation and Redistribution of Soil Moisture

The water stored in the soil is used by the plants for their growth

and metabolic processes, and is lost by evaporation and deep percolation. The distribution of moisture in the soil profile is influenced by rainfall and other meteorological parameters, so the moisture in the soil remains in dynamic equilibrium for most of the period, especially in the surface layer. It has been of considerable interest in India to study the loss of water by evaporation from the different soil profiles.

Ramdas and Mallik (1939) reported that the amount of water lost by evaporation decreased with the increase in the depth of water table in all the three soils (Table 19). The maximum loss of water occurred when the water table was within 30 cm of soil surface. The rate of evaporation was essentially the same for Alluvial soil and Black soil, but was much higher than that of Alkali soil. The evaporation from a Piche evaporimeter located at 120 cm above ground level was found to be 50 per cent higher than the loss of water from the soil having water table at 15 cm.

TABLE 19
EFFECT OF DEPTH OF WATER TABLE ON EVAPORATION
(RAMDAS AND MALLIK, 1939)

Soil	Month	Depth of water table (cm)					*Piche Evaporimeter
		15	30	45	60	90	
	January						0.45
Poona Black		0.30	0.27	0.13	0.12	0.01	
Punjab Alluvial		0.29	0.23	0.21	0.18	0.09	
Punjab Alkali		0.05	0.02	0.02	0.01	0.01	
	February						0.56
Poona Black		0.38	0.34	0.22	0.15	0.02	
Punjab Alluvial		0.37	0.26	0.22	0.18	0.09	
Punjab Alkali		0.06	0.02	0.02	0.02	0.01	
	March						0.21
Poona Black		0.48	0.41	0.23	0.16	0.02	
Punjab Alluvial		0.43	0.30	0.21	0.17	0.08	
Punjab Alkali		0.05	0.03	0.03	0.02	0.01	

* Located at 120 cm above soil surface.

Cabery and Chakladhar (1936) reported that the maximum loss of water by evaporation occurred from the surface (7.5 cm) soil layer during the dry season at Dacca farm. The loss of soil moisture from different depths in the soil profile, was expressed by the relationships written as :

$$\log (V-H)=K_1t+\log K_2$$

where (V-H) is the volume of water which is mobile, K_1 , the coefficient of evaporation and K_2 , an arbitrary constant. K_1 was found to decrease and K_2 increased with the increase in soil depth. Abichandani *et al.* (1967) reported that the total evaporation from a bare coarse textured soil in arid zone of western Rajasthan, was 6.7 cm during September to June. The maximum loss of 3.5 cm occurred from the top 15 cm soil layer. The loss of moisture from 15 to 30 cm soil layer, 30 to 45 cm soil layer and 45 to 100 cm soil layer was 1.9

TABLE 20

DISTRIBUTION OF MOISTURE IN THE SOIL
(JAYARAMAN AND BALASUBRAMANIAM, 1959)

Year	Mean per cent of moisture in soil (g/g)					Mean Max. Temp.F°	Mean Rainfall for the week (cm)
	Depth (cm) 7.5	14	30	45	60		
1948	14 (.787)	17 (.516)	18 (.328)*	17	17	87.3	1.3
1949	10 (.660)	14 (.404)	16 (.193)*	15	15	89.8	.7
1950	12 (.731)	15 (.588)	17 (.308)*	15	14	89.9	.98
1951	6 (.693)	9 (.370)	11 (.0183)*	13	14	89.9	.93
1952	6 (.617)	9 (.184)	13 (.029)*	15	15	90.2	.60
1953	9 (.612)	11 (.317)	14 (.247)*	16	15	89.2	1.54
1954	8 (.525)	11 (.285)	16 (.187)*	16	15	88.5	1.40
1955	8 (.540)	10 (.364)	14 (.152)*	14	14	90.2	.89

The figures in parenthesis refer to the coefficients of correlation between rainfall and per cent of moisture in the soil layer.

Non-significant, all others are significant.

cm, 1.1 cm, and 0.5 cm respectively. The presence of vegetation was found to dry the soil completely by the end of February. During hot summer months, April to June, moisture in 30 to 100 cm layer increased by 1.5 cm most probably owing to the redistribution of moisture under thermal gradients.

Jayaraman and Balasubramaniam (1959) reported that the rainfall received during a week had a positive and significant correlation with soil moisture in the surface (7.5 cm) soil layer, indicating that it was the moisture content of the surface layer which was highly influenced by the rainfall (Table 20). There was a gradual reduction in the correlation coefficient with the increase in soil.

SOIL-WATER AND TEMPERATURE

Moisture content of the soil is influenced by the daily and seasonal temperature changes. It may increase owing to the condensation of water vapour from the atmosphere during night or because of the movement of moisture under thermal gradients in the soil. Ramdas and Katti (1934, 1936) reported that the black-cotton soil undergoes maximum diurnal variation of 2.05 per cent of soil moisture, owing to the loss of water by evaporation during the day and again by absorption from the air during the night (Table 21). The brown and red soils came next, the Alluvial soil had only 1/5th of variation of that of black soil, and the quartz powder showed no diurnal variation. The variation of the air temperature and humidity percentage rather than the soil surface temperature was in phase with the variation of moisture content of the soil.

Jayaraman and Balasubramaniam (1959) reported that the maximum temperature in shade had a negative and significant correlation with the soil moisture at all depths (Table 22), indicating that the increase in temperature decreased the moisture content even at 60 cm depth.

TABLE 21

DIURNAL CHANGE IN MOISTURE CONTENT OF SOIL
(RAMDAS AND KATTI, 1936)

<i>Soil</i>	<i>Max. wt (g)</i>	<i>Min. wt (g)</i>	<i>Change in moisture</i>	<i>Per cent variation in moisture</i>
Quartz	60.610	60.610	0.00	0.00
Alluvial	60.575	60.160	0.415	0.83
Red	61.080	59.390	1.690	3.38
Laterite	61.080	59.390	1.690	3.38
Black	61.400	59.350	2.050	4.10

TABLE 22

COEFFICIENTS OF CORRELATION BETWEEN MAXIMUM TEMPERATURE
AND SOIL MOISTURE AT VARIOUS DEPTHS
(JAYARAMAN AND BALASUBRAMANIAM, 1959)

Year	Depth (cm)				
	7.5	15	30	45	60
1948	-.536	-.506	-.511	-.506	-.464
1949	-.388	-.550	-.570	-.582	-.543
1950	-.383	-.387	-.407	-.195	-.137*
1951	-.445	-.651	-.621	-.505	-.176
1952	-.505	-.505	-.259	-.239*	-.102*
1953	-.555	-.767	-.638	-.662	-.638
1954	-.553	-.693	-.443	-.297	-.168*
1955	-.644	-.711	-.533	-.727	-.565

* Non-significant and all others are significant.

SUMMARY AND FUTURE LINES OF WORK

The water being a dipole liquid, is oriented by the negatively charged clay particles with the positive pole towards the clay surface and the negative pole away from it, and is held by the short range adhesion and cohesion forces on the soil surface and by the pressure difference (soil moisture tension) across the air-water interface in the soil pore against the external forces including that of gravity. The amount of water held in the soil decreases with the increase in soil moisture tension, irrespective of the soil type. However the rate of decrease is dependent on the latter. An increase in tension from zero to $1/3$ atmosphere releases more than 75 per cent of water in light-textured soils, but less than 50 per cent in heavy-textured soils. The amount of available moisture ($1/3$ to 15 atmospheric percentage) varies from 6 per cent in light-textured soils to 15 per cent in heavy-textured soils. The soils having montmorillonitic-type of clay holds higher amounts of available water than the soils having illitic and kaolinitic-type of clay. The soils having high amounts of exchangeable sodium have higher water holding capacity than the normal soils. The application of phosphatic fertilizers and farmyard manure improves the water retention capacity of the soil, especially at low tension.

The water moves in the soil, both by mass flow and diffusion, in response to the soil moisture potential gradients. The rate of movement is evaluated in terms of the transmission coefficients such as hydraulic conductivity and infiltration rate.

The replacement of calcium by sodium, ammonium and potassium ions on the soil complex reduces the rate of percolation in the order of increasing ionic radius and valency. The hydraulic conductivity decreases more than 100-fold with about 25 per cent increase in the bulk density of the soil. The hydraulic conductivity and diffusivity coefficients decrease in their magnitude with the decrease in the moisture content of the soil.

The infiltration rates decreases as the movement of water through the soil continues, however the soils under forest and permanent grass maintain much higher infiltration rates than the soil under arable crops. The ploughing of the soil up to a depth greater than 30 cm improves both the initial and final infiltration rate, and the water-holding capacity of the soil.

The rate of capillary rise is more rapid in the mixture of sand and black-cotton soil than in pure sand and pure black-cotton soil, and

is more in normal soil than in the soils containing the sodium salts. The amount of water lost by evaporation decreases with the increase in the depth of water table.

The moisture content of the soil is influenced by the daily and seasonal temperature changes. The black-cotton soil undergoes maximum diurnal variation of 2.05 per cent of soil moisture.

Water and soil are the most important and complex materials in engineering and biological systems. A proper understanding of soil-water-plant relationships is essential to make the best use of available water resources in the country for the production of agricultural crops. An intensive research on the following lines would greatly help in analysing the complexity of the problem:

- (i) The influence of the surface properties of the colloidal materials in the soil on the properties of water held at different soil moisture tensions must be known before any real understanding can be obtained on the availability and migration of nutrients through the soil.
- (ii) The influence of the physical properties of the soil on the transmission of water through an unsaturated soil must be known and understood to obtain the maximum benefit from a unit volume of water stored in the soil.
- (iii) The relationship between the physical properties of the soil and the phenomenon of hysteresis must be studied in detail to know the amount of water available for the growth of plants.
- (iv) The response of the soil to the movement of water through it must be studied in detail to evaluate the long-term effects of the application of irrigation water to the rainfed soils, and draining of water from the waterlogged soils.
- (v) The mechanism of transmission of water through soil under thermal gradients must be known to evaluate the losses of water during dry season.
- (vi) The influence of the surface cover and crop canopy on the temperature of the soil must be studied to evaluate the supply of water to the crop through the phenomena of condensation and redistribution.

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