Soil physical quality of the Indo-Gangetic Plains and black soil region

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Understanding the physical quality of soil that influences its hydraulic behaviour helps in formulating appropriate water management strategies for sustainable crop production. Saturated hydraulic conductivity (K_s) is a key factor governing the hydraulic properties of soils. K_s can be estimated through various techniques. In the present article we have developed and validated the regression models to predict K_s of the soils of the Indo-Gangetic Plains (IGP) and the black soil regions (BSR) under different bioclimatic systems. While particle size distribution was found to be a key factor to predict K_s of the BSR soils, organic carbon was found useful for the IGP soils. Moreover, the models for K_s of both soils were strengthened by putting in $CaCO_3$ and exchangeable sodium percentage content. It seems there is ample scope to study the interaction process for revising K_s to desired levels through management practices in these two important food-growing zones. An index of soil physical quality, derived from the inflection points of the soil moisture characteristic curves could well explain the impact of management practices on soil physical quality.

Keywords: Index, management, saturated hydraulic conductivity, soil physical quality.

Introduction

INDIA is an agrarian country with diversified natural resources, but requires judicious soil and water management practices for sustainable crop production. Soil physical quality comprising hydro-physical properties of soil is as important as chemical and biological quality to maintain soil productivity. Water provides moisture, food, turgidity to the living things within and above the soil for plant growth, and physical quality of the soil governs the movement of water in soil. This requires modelling water transport to understand the process of hydrologic cycle. Availability of data on hydrological properties is limited as measurement of saturated hydraulic conductivity (K_s), an important soil hydraulic property, is difficult and time-consuming[1,2]. However, K_s can be predicted using theoretical methods[3–6]. Pedotransfer functions (PTFs) are mostly multiple regression equations or models, which correlate the soil properties with other easily available soil properties[7] and have been used successfully to determine hydrological, physical and chemical properties of soils[8,9].

The regression models have been developed using necessary soil database. The most suitable PTFs for use can

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be identified through testing[10]. Accuracy and reliability of PTFs[11] can be made through stratification, calibration and testing. To establish separate PTFs based on soil type and input information stratification is required. Stratification has been carried out based on soil horizons[12]; FAO soil classes[13], textural classes[14]; hydraulic-functional horizons[15]; great soil groups, temperature regime, moisture regime[16]; parent material and horizon morphology[17]; numerical soil classification[10] and management units[18] followed by testing.

Soil porosity plays a vital role in the movement of water in the soil[19]. There are two kinds of porosity, i.e. textural and structural, constituting micro- and macropores respectively[20]. Structural porosity comprises of microcracks, cracks, bio-pores and macrostructures which can get destroyed due to machine traffic or animal trampling[21] or soil tillage. Unlike the conventional one, connectivity between macropores increases under no-till system[22]. The textural porosity which occurs between the primary mineral particles is little affected by soil management practices, whereas the structural porosity produced by tillage is sensitive to management factors such as tillage, compaction and cropping[23]. Moisture retention curves provide accurate information about pore size distribution[24]. From these curves, it is possible to fit mathematical functions that allow the determination of the structural and textural porosity of soils, apart from obtaining information about the way in which they are modified due to structural degradation[25,26]. The structural porosity clearly influences the soil hydraulic conductivity[27].

An attempt was made to assess soil physical quality of the Indo-Gangetic Plains (IGP) and black soil regions (BSR) under rice–wheat and cotton-based cropping systems respectively, under different management practices. Deriving PTFs for K_s based on physical and chemical properties and soil physical quality index may help in understanding soil hydraulic behaviour and formulating appropriate water management strategies for sustainable crop production.

Study area

The hydrological, physical, chemical and biological characteristics of the soil deteriorate due to intensive cultivation, injudicious fertilizer application and rainfall distribution. The quality of soil and water is threatened in many regions where intensive agricultural activities are carried out. The IGP and BSR are vastly populated, covering an area of about 52.01 (in the Indian part of IGP) and 76.4 m ha respectively[28], and the agricultural lands are over exploited to meet the food crop (rice–wheat) and cash crop (cotton) demand of the increasing population.

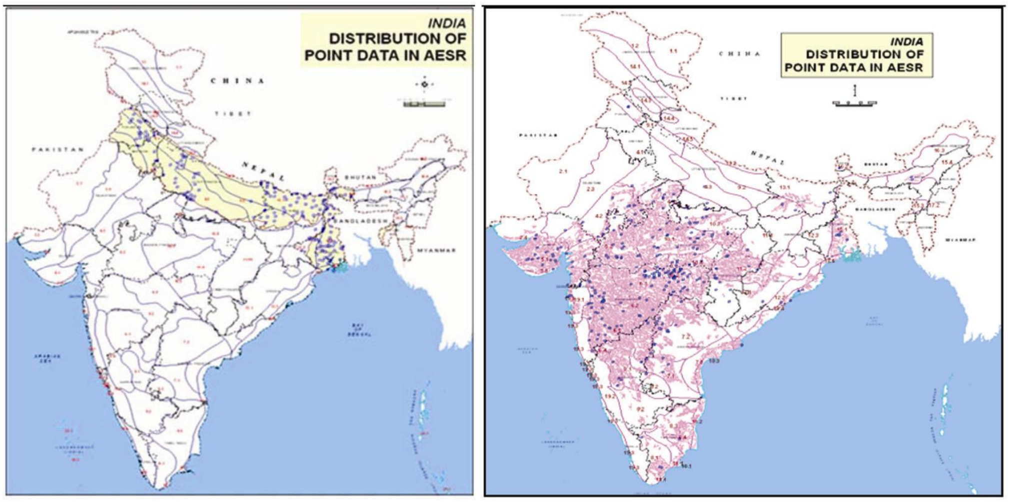
The IGP, also known as the Great Plains are large alluvial plains. They run parallel to the Himalayas, from Jammu and Kashmir in the west to Assam in the east, and drain most of northern and eastern India. The major rivers in this region are the Ganges, Indus and Brahmaputra along with their main tributaries – Yamuna, Chambal, Gomti, Ghaghara, Kosi, Sutlej, Ravi, Beas, Chenab and Tista – as well as the rivers of the Ganges Delta, such as the Meghna[29].

Black soils are calcareous in nature with high cation exchange capacity and base saturation. These soils contain high amount of clay and low amount of organic carbon. The BSR covers Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka, Tamil Nadu, Karnataka, Rajasthan, Odisha and a few other states[30]. The soils under study are Vertisols[31]. They are sticky and plastic and have shrink–swell characteristics. Several researchers[32–42] have studied the morphological, physical and chemical properties of these soils.

Soil hydraulic properties are one of the key factors governing the soil quality and its function. Prediction of soil hydraulic properties from other easily measured soil properties through establishment of PTFs is of interest for vast areas like the IGP and BSR. Since it is not practical to collect data on physical properties from such a vast region (to be truely representative), limited number of samples was collected and regression models were developed for each region. A pre-requisite for deriving PTFs which can be applied is the availability of basic soil data and soil hydraulic properties from a wide range of soils. The database and its storage are described in the literature[30,31,43]. The georeferenced sampling sites – 64 spots – of both IGP and BSR are shown in Figure 1. A total of 366 of horizon-wise soil samples were collected after examining the profiles following standard procedures[31].

In IGP, 14 benchmark georeferenced sample sites were selected from arid, semi-arid, sub-humid and humid/perhumid bioclimates with mean annual rainfall (MAR) of < 550, 550–1000, 1000–1600 and 1600–2000/> 2000 mm respectively, covering seven states of Rajasthan, Punjab, Uttarakhand, Uttar Pradesh, Bihar, West Bengal and Tripura and 11 agro-ecological subregions (AESRs, 2.1, 4.1, 9.2, 4.3, 9.1, 12.3, 13.1, 18.5, 16.2, 15.3 and 17.2)[44]. All the soils are developed from weathering of alluvium covering the IGP (Table 1). Topography and slopes make these soils well drained to poorly drained. Rice-based cropping system dominates in these soils which are represented by Entisol, Inceptisol, Alfisol, Mollisol and Vertisols.

In BSR, 18 benchmark georeferenced sample sites were selected from arid, semi-arid, sub-humid dry and sub-humid moist bioclimates with MAR of < 550, 550–1000, 1000–1200 mm and 1200–1600 mm respectively, covering six states of Maharashtra, Gujarat, Madhya Pradesh, Andhra Pradesh, Karnataka and Tamil Nadu represented by 18 AERs (6.1, 5.1, 8.1, 3.0, 6.4, 7.1, 5.1, 8.3, 8.2, 4.4, 7.2, 6.2, 6.3, 5.2, 10.3, 10.2, 10.1 and 7.3). Most of these soils are developed from basaltic alluvium



Indo Gangetic Plains | Black soil region

Figure 1. Georeferenced location sites of BSR and IGP soils.

covering the Deccan plateau, whereas few soils occurring in lower piedmont plains or valleys or old flood plains are formed in the alluvium of other rock formations rich in plagioclase feldspar and ferromagnesian minerals (Table 2). The soils are moderately well drained to well drained, due to undulating topography with very gentle to moderate slopes. Cotton-based cropping is dominant in these regions followed by soybean. All the soils are Vertisols except at Siddalaghatta where Inceptisols occur.

Two representative soil pedons/profiles were selected under the same soil series, one under low management (LM) characterized by low NPK application, rarely applied manure, removal of residues and manure without any soil moisture conservation practices and the other under high management (HM) characterized by higher NPK application, regular application of organic matter, incorporation of residues and adoption of soil moisture conservation techniques like ridge furrows, bunding, broad bed furrow and amendments.

Materials and methods

The soil samples collected were air-dried, ground and then passed through 2 mm sieve for physical and chemical analysis. The particle size distribution was determined using the international pipette method after removal of organic matter. $CaCO_3$ and free Fe oxide[45,46]. Sand (2000–50 μm), silt (50–2 μm), total clay (< 2 μm) and fine clay (< 0.2 μm) fractions were separated through dispersion and wet-sieving method following the standard procedure[47]. The core bulk density (BD) was measured using standard methods[48].

By varying the soil suction and recording the changes in soil water content, a water retention function or curve was determined. Soil water content at the field capacity (FC) was measured, equilibrating soil moisture for 48 h at 33 kPa on a ceramic plate. Permanent wilting point (PWP) was measured equilibrating soil moisture for 72 h at 1500 kPa on a pressure plate apparatus. Saturated hydraulic conductivity (K_s) was measured using permeameter following the constant head method as described by Klute and Darksen[2]. The observations on time and constant head were used in the Darcy equation to find K_s (cm h^{-1}).

$$K_s = \frac{QL}{AhT},$$

where K_s is the hydraulic conductivity (cm/s), Q the outflow volume (cm^3), A the cross-sectional area of soil column (cm^2), T the time (h) and h is the head difference (cm). Electrical conductivity (EC), pH and organic carbon (OC) content of soils were measured using standard procedures[49]. Organic carbon was estimated using Walkley–Black procedure[50]. $CaCO_3$, cation exchange capacity (CEC) and exchangeable Na and K were determined on the total fine earth (< 2 mm) using standard procedures[51]. Exchangeable Ca and Mg were determined following the 1 N NaCl solution extraction method[52]. EC and soluble cations and anions in saturated extracts were determined using standard methods.

There is no single soil parameter to assess soil physical quality[45]. It thus demands integration of a group of soil physical parameters for proper assessment of the physical quality of soils[53]. Soil physical quality, S is proposed as an index that can be easily measured from the soil moisture characteristics curve. The soil moisture characteristics curve has a characteristic inflection point where the curvature is zero. The significance of the inflection point as soil physical quality has been well discussed by Dexter and Bird[54]. The soil physical quality is the slope of the inflection point and is calculated as $S = d\theta/d \log(h)$. This

Table 1. Description of soils of the Indo-Gangetic Plains under study

Sampling site	Soil classification	Physiography/topograohy	Drainage	Parent material	Land use
Arid (A) (MAR < 550 mm)					
Mashitawali Hanumangarh, Rajasthan	Coarse-loamy, mixed hyperthermic, Aridic Haplustepts	Interdunal plain/nearly level plain, 0–1% (> 600 m in length)	Well drained	Alluvium	Cotton-wheat/mustard/gram
Sakhi Ganganagar, Rajasthan	Coarse-loamy, mixed hyperthermic, Aridic Haplustepts	Interdunal Ghaghar plain/nearly level sloping plain, 0–1% (> 600 m length)	Well drained	Alluvium	Cotton-wheat/mustard
Semi-arid (SA) (MAR 550–1000 mm)					
Zarifa Viran Karnal, Haryana	Fine-loamy mixed hyperthermic, Vertic Natrustalfs	Old alluvial plain/plain sloping, 1–0% (50–300 m)	Moderately well drained	Alluvium	Wheat Rice–wheat
Sakit Itah, Uttar Pradesh	Fine-loamy, mixed hyperthermic, Typic Natrustalfs	Old alluvial plain Nearly level to very gently sloping, 0–1% (50–150 m length)	Poorly drained	Alluvium	
Itwa Chandhi, Uttar Pradesh	Fine, mixed hyperthermic, Vertic Natraqualfs	Plain land/concave relief, 0–1% (150–300 m length)	Imperfectly drained	Alluvium	Rice–wheat/barley/gram
Sub-humid (SH) (MAR 1000–1600 mm)					
Fatepur Ludhiana, Punjab	Coarse-loamy, mixed hyperthermic, Typic Haplustepts	Upper Indo-Gangetic Plain nearly level 0–1% (150–500 m length)	Well drained	Alluvium	Rice–wheat/bajra/mustard/ pigeonpea/soybean/gram
Haldi Udham Singh Nagar, Uttarakhand	Coarse-loamy, mixed hyperthermic, Typic Hapludalfs	Plain/sub-montain (Tarai), 0–1% (50–150 in length)	Well drained	Alluvium	Tiger grass, rue grass
Madhpur Nishigram, West Bengal	Fine mixed hyperthermic, Vertic Endoaqualfs	Indo-Gangetic Alluvial Plain/almost level to very gently sloping, 0–3% (50–150 m length)	Moderately well drained	Alluvium	Rice–mustard/potato
Gopalpur Birbhum, West Bengal	Fine, smectitic, hyperthermic, Chromic Endoaquerts	Alluvial Plain/almost level to very gently sloping plain, 0–3% (50–150 m length)	Imperfectly drained	Alluvium	Rice–potato/lentil/ groundnut
Ekchari Bhagalpur, Bihar	Fine, smectitic hyperthermic, Vertic Endoaqualfs	Very gently sloping land, 1–3% (300–600 m length)	Imperfectly drained	Alluvium	Rice–maize/wheat
Humid/per humid					
Sagar Narendrapur, West Bengal	Fine, mixed isohyperthermic, Vertic Endoaqualfs	Deltaic alluvial plain/sloping plain, 0–1% (150–300 m length)	Imperfectly drained	Alluvium	Rice
Seoragiri Coochbehar, West Bengal	Clayey over loamy, mixed isohyperthermic, Typic Endoaqualfs	Flood plain/nearly level, 0–1% (50–150 m length)	Moderately well drained	Alluvium	Rice
Singhbhita Dayaling, West Bengal	Fine-loamy, mixed thermic, Umbric Endoaqualfs	Alluvial plain/nearly level, 0–1% (50–150 m length)	Poorly drained	Alluvium	Rice
Nayanpur West Tripura, Tripura	Fine loamy, mixed hyperthermic, Typic Endoaqualfs	Plain land/nearly level, 0–1% (50–150 m in length)	Moderately well drained	Alluvium	Bamboo. Sirish, *Acacia*, korui

MAR, Mean annual rainfall.

Table 2. Description of soils of black soil regions under study

Sampling site	Soil classification	Physiography/topography	Drainage	Parent material	Land use
Arid (A) (MAR < 550 mm)					
Nimone, Ahmednagar, Maharashtra	Very fine, smectitic, isohyperthermic Sodic Haplusterts	Level to very gently sloping, 0–3% (50–150 m length)	Moderately well drained	Basaltic alluvium	Soybean–wheat/ gram/sorghum/sugarcane
Sokhda, Rajkot, Gujarat	Fine, smectitc (calc), hyperthermic Leptic Haplusterts	Plain/nearly level to very gently sloping, 0–1% (150–300 m length)	Moderately well drained	Alluvium	Cotton–pearl millet/sorghum/ castor/groundnut
Semi-arid (SA) (MAR 550–1000 mm)					
Vasmat, Hingoli, Maharashtra	Very fine, smectitic, hyperthermic Typic Haplusterts	Middle Maharashtra Plateau/almost level to very gently sloping, 0–3% (50–150 m)	Imperfectly drained to moderately well drained	Basaltic alluvium	Sugarcane/sorghum, safflower
Paral, Akola, Maharashtra	Very fine, smectitic, hyperthermic Sodic Haplusterts	Undulating/nearly level land, very gentle slopping, 0–1% (50–150 cm)	Imperfectly drained	Basaltic alluvium	Cotton–soybean/pigeon pea
Kassireddipalli, Medak, Andhra Pradesh	Fine, smectitic, isohyperthermic Typic Haplusterts	Undulating/very gently sloping, 1–3% (50–150 m)	Moderately well drained	Basaltic alluvium	Soybean–pigeon pea/maize/ safflower
Singpura, Moraina, Madhya Pradesh	Fine-loamy, mixed, hyperthermic Vertic Haplustalfs	Almost level to very gently sloping, 1–3% (50–150 m)	Well drained	Alluvium	Bajra/wheat/mustard/gram/ urad
Bhola, Rajkot, Gujarat	Fine, smectitic, hyperthermic VerticHaplustepts	Old flood plain/very gently sloping, 1–3% (150–300 m)	Moderately well drained	Alluvium	Cotton–wheat/coriander
Kovilpatti, Thoothukkudi, Tamil Nadu	Very fine, smectitic, isohyperthermic Gypsic Haplusterts	Plain/nearly level, 1–3% (300–600 m)	Well drained	Alluvium	Cotton–blackgram
Coimbatore, Tamil Nadu	Very fine, smectitic, isohyperthermic Typic Haplusterts	Plain/nearly level, 1–3% (150–300 m length)	Moderately well drained	Alluvium	Cotton–sorghum/pigeon pea/ rice–sugarcane
Siddlaghatta, Chikkaballapur, Karnataka	Fine, smectitic, isohyperthermic Vertic Haplustepts	Upland/nearly level, 1–3% (150–300 m)	Well drained	Granitic alluvium	Rice–sugarcane/vegetables
Nandyal, Kurnool, Andhra Pradesh	Fine, smectitic, isohyperthermic Sodic Haplusterts	Upland/gentle slope, 1–3% (300–600 m)	Well drained	Basalt	Cotton–sorghum/bajra/ rice–groundnut/red gram
Telgi, Bellary, Karnataka	Fine, smectitic, isohyperthermic Sodic Haplusterts	Very gently sloping plain/nearly level, 1–3% (150–300 m)	Moderately well drained	Basaltic alluvium	Cotton–sorghum/pigeon pea/ tobacco/paddy
Achamatti, Dharwar, Karnataka		Very gently sloping upland/nearly level, 0–1% (0–50 m)	Well drained	Basalt	Maize/redgram/cotton–pigeon pea
Sub-humid dry (SHd) (MAR 1000–1200 mm)					
Sarol, Indore, Madhya Pradesh	Fine, smectitic, hyperthermic Typic Haplusterts	Malwa plateau/almost level to very gently sloping 0–3% (50–150 m)	Moderately well drained	Basaltic alluvium	Soybean–wheat
Gulguli, Umeria, Madhya Pradesh	Fine, smectitic, hyperthermic Typic Haplusterts	Eastern Baghelkand plateau/ undulating, gently to moderately sloping 3–5% (50–150 m)	Well drained	Sandstone alluvium	Rice–wheat/gram
Sub-humid, moist (SHm) (MAR 1200–1600 mm)					
Nabibagh, Bhopal, Madhya Pradesh	Fine, smectitic, hyperthermic Typic Haplusterts	Central Highland, Vidhyan Range/ level to very gentle sloping, 1–3% (50–150 m)	Moderately well drained	Basaltic alluvium	Soybean–wheat
Tenali, East Godavari, Andhra Pradesh	Very fine, smectitic, isohyperthermic Sodic Haplusterts	Low land/very gently sloping, 1–3% (150–300 m)	Moderately well drained	Deltaic alluvium	Cotton
Panjari, Nagpur, Maharashtra	Very fine, smectitic hyperthermic Typic Haplusterts	Lower Maharashtra Plateau/very gently sloping, 1–3% (50–150 m)	Moderately well drained	Basaltic alluvium	Cotton

MAR, Mean annual rainfall.

Table 3. Hydro-physical characteristics of the IGP soils under different bioclimates

Parameters	Minimum	Maximum	Mean	Standard deviation
Arid				
Sand (%)	50.50	88.60	70.17	10.94
Silt (%)	1.30	18.50	9.45	5.01
Clay (%)	9.50	34.40	20.38	6.79
BD (Mg/m^3)	1.48	1.82	1.65	0.11
FC (m^3/m^3)	0.05	0.37	0.22	0.08
PWP (m^3/m^3)	0.01	0.13	0.07	0.04
AWC (m^3/m^3)	0.03	0.24	0.14	0.06
K_s (cm/h)	0.12	1.10	0.50	0.34
Semi-arid				
Sand (%)	33.35	79.70	50.24	12.90
Silt (%)	3.70	29.75	18.85	6.38
Clay (%)	7.20	43.35	30.91	8.64
BD (Mg/m^3)	1.18	1.78	1.53	0.13
FC (m^3/m^3)	0.15	0.56	0.33	0.10
PWP (m^3/m^3)	0.03	0.23	0.10	0.05
AWC (m^3/m^3)	0.08	0.49	0.23	0.09
K_s (cm/h)	0.00	8.40	1.22	2.34
Sub-humid				
Sand (%)	10.80	89.80	43.10	22.22
Silt (%)	2.15	33.60	21.31	7.50
Clay (%)	4.50	60.80	35.58	16.98
BD (Mg/m^3)	1.24	1.77	1.49	0.12
FC (m^3/m^3)	0.02	0.49	0.33	0.12
PWP (m^3/m^3)	0.01	0.25	0.15	0.08
AWC (m^3/m^3)	0.01	0.32	0.18	0.07
K_s (cm/h)	0.15	6.55	1.69	1.87
Humid/per-humid				
Sand (%)	2.80	57.80	25.05	17.99
Silt (%)	13.90	54.80	37.30	11.66
Clay (%)	16.60	55.60	37.65	11.50
BD (Mg/m^3)	0.00	1.61	0.34	0.62
FC (m^3/m^3)	0.19	0.56	0.40	0.07
PWP (m^3/m^3)	0.04	0.27	0.15	0.06
AWC (m^3/m^3)	0.09	0.45	0.25	0.08
K_s (cm/h)	0.08	1.71	0.42	0.40

BD, Bulk density; FC, Field capacity; PWP, Permanent wilting point; AWC, Available water content; K_s, Saturated hydraulic conductivity.

is measured directly from the curve manually and its value is always negative. However, the modulus of S requires further discussion. The pores that are drain at the inflection point of the water retention curve can mostly be classified as structural pores or micro-cracks which can be seen as elongated pores in two-dimensional sections. To a first approximation, it is possible to conclude that for soil drying between saturation and the inflection point, it is mainly structural pores that are emptying. However, for soil draining below the inflection point, it is mainly textural pores that are emptying. The database generated was statistically analysed using Statistical Analysis System SAS.

Results and discussion

Particle size distribution

The Indo-Gangetic Plains: The soils vary from sandy clay loam to loam, with a few soils having sandy or clayey texture prevailing under arid and humid bioclimates respectively (Table 3). The soils are, in general, acidic to neutral in humid/perhumid regions; slightly acidic to slightly alkaline in sub-humid environment; slightly alkaline to strongly alkaline in semi-arid environment and strongly alkaline in arid environment. This may be attributed to the fact that, with increase in rainfall, more soluble bases are lost from the soil due to runoff and leaching, resulting in acidic reaction. The pH and $CaCO_3$ generally increase as the rainfall decreases from sub-humid to arid climates (Table 4). The exchangeable sodium percentage (ESP) increases with decrease in rainfall. Increased rainfall enhances the rate of decomposition of organic matter. As a result, the organic carbon content increases significantly from arid to humid/perhumid environment. Ca^{2+} is the dominant exchangeable cation, followed by Mg^{2+}, Na^+ and K^+ in almost all soils. However, in soils of semi-arid climate, Na^+ content is more in strongly alkaline soils of Sakit and Zarifa Viran.

Table 4. Some chemical characteristics of the IGP soils under different bioclimates

Parameters	Minimum	Maximum	Mean	Standard deviation
Arid				
pH (water)	8.53	9.39	9.02	0.24
OC (%)	0.04	0.39	0.14	0.13
$CaCO_3$ (%)	3.10	23.76	11.10	7.89
ESP (%)	8.11	53.90	30.30	15.40
EMP (%)	3.01	41.46	17.44	10.50
Ca/Mg	1.51	20.61	5.27	4.91
Semi-arid				
pH (water)	7.49	10.44	9.07	0.94
OC (%)	0.04	0.95	0.26	0.22
$CaCO_3$ (%)	0.22	23.04	4.84	7.23
ESP (%)	0.05	96.71	39.50	36.25
EMP (%)	0.00	53.80	15.07	16.09
Ca/Mg	0.00	17.25	3.87	3.25
Sub-humid				
pH (water)	5.90	8.62	7.88	0.64
OC (%)	0.01	1.26	0.42	0.41
$CaCO_3$ (%)	0.24	3.80	1.78	0.98
ESP (%)	1.28	8.20	2.64	1.66
EMP (%)	6.10	52.13	22.75	8.19
Ca/Mg	1.59	7.60	3.27	1.20
Humid				
pH (water)	4.87	8.56	6.17	0.95
OC (%)	0.03	1.65	0.51	0.34
$CaCO_3$ (%)	0.23	2.83	1.38	0.56
ESP (%)	0.75	60.39	7.65	14.08
EMP (%)	2.20	72.78	26.75	22.35
Ca/Mg	0.32	6.10	1.93	1.57

OC, Organic carbon; ESP, Exchangeable sodium percentage; EMP, Exchangeable magnesium percentage.

Black soil regions: The soils are clayey; clay and silt constitute > 50% of the total fraction (Table 5). The soils are, in general, neutral to slightly alkaline; they are strongly alkaline when they occur in semi-arid and arid environments (< 900 mm MAR). The pH and $CaCO_3$ generally increase as the rainfall decreases from sub-humid to arid climates (Table 6). The soils are impoverished in organic carbon (< 1%)[35]; Ca^{2+} is the dominant exchangeable cation, followed by Mg^{2+}, Na^{+} and K^{+} in almost all soils. However, in soils of semi-arid and arid climates, Mg^{2+} ion tends to dominate the exchange sites.

The results of chemical analysis are in good agreement with those of Srivastava *et al.*[55].

Hydrological properties

IGP soils: The average and range of field capacity (FC determined at 33 kPa) and permanent wilting point (PWP determined at 1500 kPa), the two boundary constants of plant available water content (AWC) in IGP and BSR soils are summarized under different bioclimates (Table 3). AWC varied under different bioclimates and was lowest in soils under arid bioclimate, which suggests that frequent irrigation is required to meet the crop water requirement. AWC ranges from 20% to 24% in soils of Uttar Pradesh and Bihar represented by fine, smectitic, hyperthermic Vertic Endoaqualfs.

The K_s varied from negligible in Zarifa Viran soils to 8.39 cm/h in Fatehpur soils (Table 3). Majority of the soils have K_s 0–1 cm/h and such soils cover Bihar, West Bengal and Uttar Pradesh (Figure 2). It has been observed that K_s increases significantly with increase in sand ($r = 0.63^{**}$) and OC content ($r = 0.25^{**}$) and decreases significantly with increase in silt ($r = –0.52^{**}$), clay ($r = –0.53^{**}$), FC ($r = –0.40^{**}$), PWP ($r = –0.38^{**}$), $CaCO_3$ ($r = –0.22^{**}$) and exchangeable sodium percentage ESP ($r = –0.33^{**}$) content in the soil. Higher ESP content is observed in soil control section (SCS) of Natrustalfs (> 25–100) and lower in Haplustalfs (< 15) and the results are well supported[56–60]. Presence of calcium carbonate ($CaCO_3$) in soils of arid and semi-arid climates has been reported in the IGP[61] and also elsewhere[62–68]. The results depict that apart from particle size distribution, organic carbon content, $CaCO_3$ and ESP influence K_s of the IGP soils.

Pedotransfer relations through multiple regression models were developed for K_s with physical and chemical parameters using backward elimination procedure of statistical analysis software (SAS 9.2). A significant model

Table 5. Hydro-physical characteristics of black soil regions under different bioclimates

Parameters	Minimum	Maximum	Mean	Standard deviation
Arid				
Sand (%)	4.4	48.3	24.3	13.6
Silt (%)	14.6	30.2	21.2	5.5
Clay (%)	35.2	75.2	54.5	12.4
BD (Mg/m^3)	1.16	1.78	1.49	0.18
FC (m^3/m^3)	0.20	0.76	0.44	0.15
PWP (m^3/m^3)	0.05	0.38	0.19	0.12
AWC (m^3/m^3)	0.13	0.40	0.24	0.08
K_s (cm/h)	0.09	6.52	1.09	1.59
Semi-arid				
Sand (%)	1.6	48.5	19.5	12.4
Silt (%)	8.3	53.9	20.2	8.1
Clay (%)	24.1	79.4	60.3	13.7
BD (Mg/m^3)	1.12	2.05	1.72	0.21
FC (m^3/m^3)	0.30	1.00	0.56	0.15
PWP (m^3/m^3)	0.12	0.58	0.31	0.11
AWC (m^3/m^3)	0.13	0.54	0.25	0.09
K_s (cm/h)	0.03	3.01	0.31	0.37
Sub-humid dry				
Sand (%)	11.0	30.1	17.0	6.3
Silt (%)	14.1	28.3	20.4	4.0
Clay (%)	49.8	74.3	62.6	8.4
BD (Mg/m^3)	1.48	2.03	1.83	0.16
FC (m^3/m^3)	0.43	0.74	0.57	0.10
PWP (m^3/m^3)	0.10	0.38	0.29	0.08
AWC (m^3/m^3)	0.14	0.56	0.28	0.14
K_s (cm/h)	0.03	0.51	0.20	0.14
Sub-humid moist				
Sand (%)	2.0	24.1	6.6	5.1
Silt (%)	14.8	47.6	30.3	10.7
Clay (%)	36.2	80.0	63.1	10.4
BD (Mg/m^3)	1.24	1.97	1.75	0.15
FC (m^3/m^3)	0.51	0.87	0.68	0.09
PWP (m^3/m^3)	0.22	0.57	0.39	0.10
AWC (m^3/m^3)	0.05	0.46	0.30	0.10
K_s (cm/h)	0.07	0.75	0.25	0.15

with sand and OC content was observed when only physical properties along with carbon were used as input. A better model was obtained using chemical parameters showing contribution of $CaCO_3$ content, ESP and Ca/Mg ratio towards K_s (Figure 3).

Black soil regions: AWC does not vary much under different bioclimates (Table 5) represented by soils with high clay and silt content in most of the soils studied. Vertisols of sub-humid climate are dominated by Ca^{2+} ions throughout that increases the moisture content resulting in higher FC and PWP of soils, whereas under arid and semi-arid climates, Mg^{2+} ion dominates in the exchange complex. The distribution of AWC shows that majority of the soils have 16–20% AWC covering mainly Maharashtra with very fine smectitic hyperthermic sodic Haplusterts. The K_s varies from 0.027 cm/h in Vasmat soils to 6.521 cm/h in Sokhda soils (Table 5). Majority of the soils of this region have $K_s < 0.25$ cm/h covering Maharashtra, Karnataka and Tamil Nadu (Figure 4). K_s increases significantly with increase in sand ($r = 0.25^{**}$), clay CEC ($r = 0.27^{**}$) and $CaCO_3$ ($r = 0.46^{**}$) content and decreases significantly with increase in clay ($r = -0.21^{**}$), ESP ($r = -0.16^{*}$), EMP ($r = -0.22^{*}$) content and also with BD ($r = -0.17^{*}$) of the soil. The results depict that apart from particle size distribution, K_s of these soils is also governed by $CaCO_3$, ESP and EMP content in the soil and compactness of the soil. More compact the soil, less is the K_s value.

Pedotransfer relations through multiple regression models are developed for K_s putting in physical and chemical parameters, viz. sand, silt, clay and BD and chemical parameters, viz. pH, OC, $CaCO_3$ content, EMP, ESP, base saturation (BS), clay CEC and Ca/Mg using backward elimination procedure of SAS 9.2 software (Table 7). A significant model with sand content and BD is obtained when only physical properties are used as input. A better model is obtained using chemical

Table 6. Some chemical characteristics of BSR under different bioclimates

Parameters	Minimum	Maximum	Mean	Standard deviation
Arid				
pH (water)	8.26	9.79	8.72	0.44
OC (g kg^{-1})	0.7	7.7	4.5	2.1
$CaCO_3$ (%)	10.80	21.72	16.29	3.78
ESP (%)	1.58	99.20	18.97	22.00
EMP (%)	10.08	38.07	26.31	8.36
Ca/Mg	0.48	5.22	2.55	1.57
Semi-arid				
pH (water)	7.83	9.34	8.59	0.36
OC (g kg^{-1})	0.7	11.6	4.3	2.1
$CaCO_3$	1.68	21.50	8.08	4.15
ESP (%)	0.84	52.30	11.72	10.16
EMP (%)	7.56	94.30	30.99	14.95
Ca/Mg	0.34	19.07	3.31	2.83
Sub-humid dry				
pH (water)	6.81	8.64	7.94	0.70
OC (g kg^{-1})	0.19	1.00	0.49	0.23
$CaCO_3$ (%)	0.11	5.34	3.06	1.96
ESP (%)	1.22	5.17	2.31	0.89
EMP (%)	21.37	46.77	31.52	6.43
Ca/Mg	1.38	3.21	2.34	0.53
Sub-humid moist				
pH (water)	7.43	9.03	8.34	0.31
OC (g kg^{-1})	0.04	1.30	0.45	0.28
$CaCO_3$ (%)	0.50	17.80	4.33	3.41
ESP (%)	1.03	24.96	11.48	8.79
EMP (%)	16.73	40.44	27.57	6.78
Ca/Mg	1.22	4.73	2.70	0.88

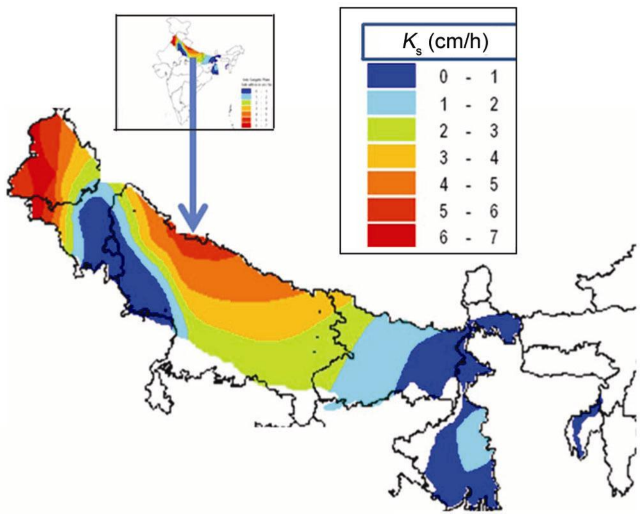


Figure 2. Distribution of saturated hydraulic conductivity (K_s) in the IGP soils.

parameters showing contribution of $CaCO_3$ content and ESP to K_s. A better model has been obtained when clay CEC (%) and BS (%) are included as input parameters (Table 7). R^2 value improves to 0.6224 with the inclusion of chemical parameters and K_s can be more precisely expressed in terms of clay (%), clay CEC (%), BS (%), ESP (%), EMP (%), $CaCO_3$ and Ca/Mg (Figure 5). This is because the presence of pedogenic $CaCO_3$ and exchangeable sodium content highly influence the soil hydrological behaviour. Soils with ESP > 15 exhibit large swelling and shrinkage as they wet and dry and also get dispersed completely in the presence of water.

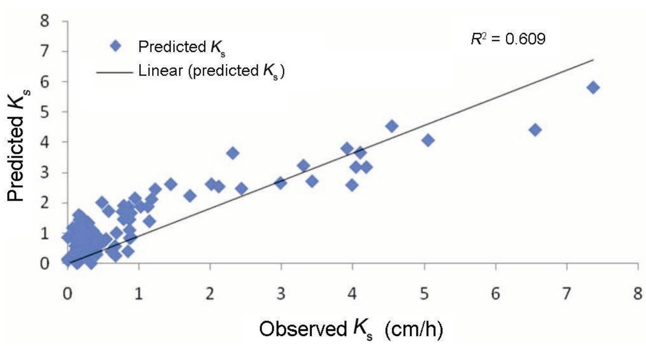


Figure 3. Validation of regression model no. 2 for K_s (cm/h) of the IGP soils.

Soil physical quality

Soil physical quality governs the hydrological behaviour of soil and depends on textural and structural porosity[20].

Table 7. Pedotransfer functions for K_s of the IGP and BSR soils

Model	R^2	N	RMSE
IGP			
$K_s = -1.25 + 0.05$ sand (%) $+ 0.76$ OC (%)	0.414	156	2.14
$K_s = -1.06 + 0.055$ sand (%) $- 0.074$ $CaCO_3$ (%) $- 0.011$ Ca/Mg	0.578	133	1.55
BSR			
K_s (cm/h) $= 1.03 + 0.013$ sand (%) $+ 0.52$ BD (Mg/m^3)	0.088	194	0.136
K_s (cm/h) $= 1.15 + 0.015$ silt (%) $- 0.028$ ESP (%) $+ 0.087$ $CaCO_3$ (%) $- 0.629$ BD (Mg/m^3) $+ 0.0726$ Ca/Mg	0.30	194	0.063
K_s (cm/h) $= -0.134 - 0.00631$ clay (%) $+ 0.008$ clay CEC (%) $+ 0.0039$ BS (%) $- 0.0146$ ESP (%) $- 0.0124$ EMP (%) $+ 0.037$ $CaCO_3$ (%) $- 0.045$ Ca/Mg	0.62	194	0.029

BS, Base saturation.

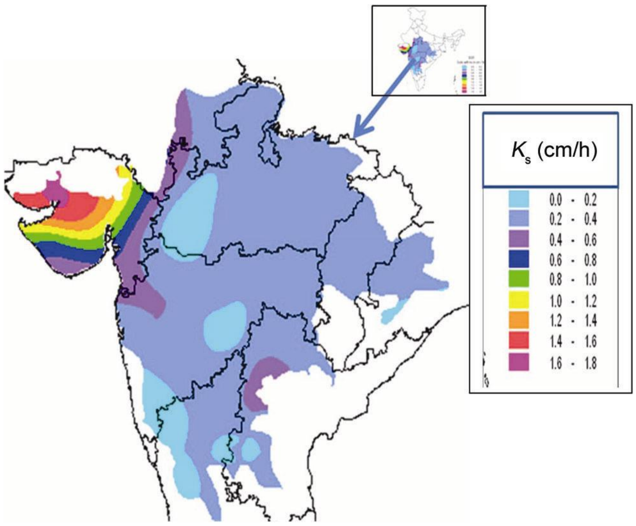


Figure 4. Distribution of saturated hydraulic conductivity (K_s) in the BSR soils.

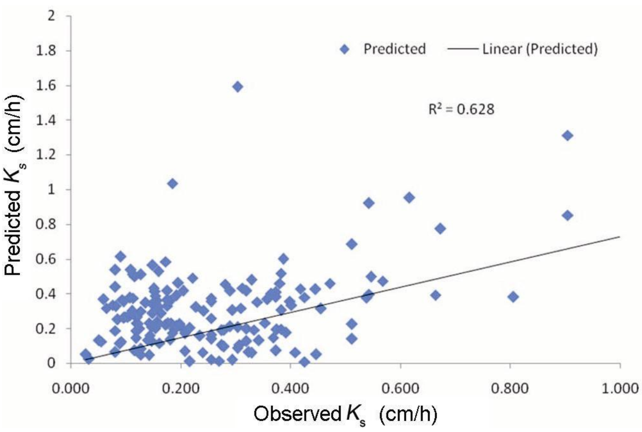


Figure 5. Validation of regression model no. 3 for K_s (cm/h) of BSR soils.

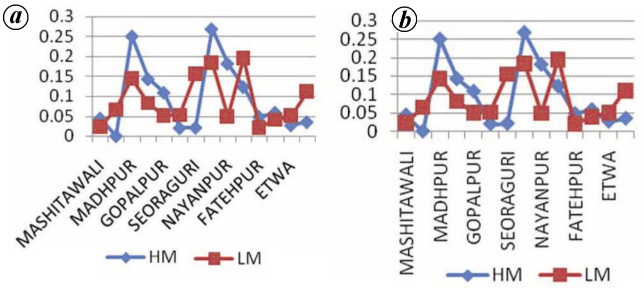


Figure 6. Soil physical quality (S) of the IGP surface soils (***a***) and sub-surface soils (***b***).

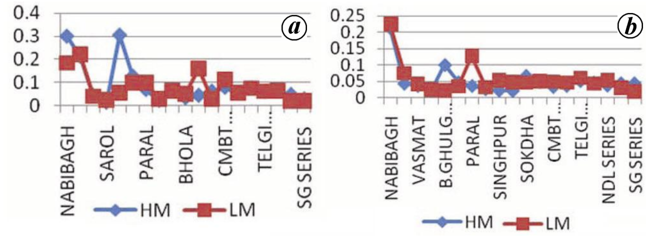


Figure 7. Soil physical quality (S) of BSR surface soils (***a***) and sub-surface soils (***b***).

It has been observed that BSR soils with higher clay content have higher textural porosity that occurs between the primary mineral particles, whereas IGP soils have higher structural porosity comprising microcracks, cracks, bio-pores and macrostructures produced by tillage. The surface (Figure 6 *a*) and subsurface (Figure 6 *b*) soils of IGP are found to be sensitive to management factors such as tillage, compaction and cropping due to high structural porosity, whereas the surface (Figure 7 *a*) and subsurface (Figure 7 *b*) soils of the BSR are little affected by soil management practices because of high textural porosity. The slope, S, of the water retention curve at the inflection point is mostly due to microstructural porosity that directly governs many of the principal soil physical properties[24]. Soil with only textural or structural porosity is compacted or loose and shows poor physical quality. Therefore, the presence of considerable amount of structural and textural pores and a corresponding large value of S are essential for good soil quality.

In IGP, incorporation of organic matter in soils has destroyed the structural porosity but improved textural porosity, which in turn improved the soil physical quality.

The results are in good agreement with the findings of Richards *et al.*[69] and support the use of the inflection point of the curve of the logarithm of h against θ for measuring S. In BSR soils, textural pores dominate and the management practices adopted have little effect on improving the structural porosity of the soils.

Conclusion

Saturated hydraulic conductivity (K_s), which is a key soil physical quality, is governed not only by the hydro-physical properties of the soil, but also by the chemical characteristics. In sandy-textural soils, organic carbon contributes significantly towards saturated hydraulic conductivity, whereas in the clayey soils BD as the measure of compaction is more meaningful in assessing physical quality of soils. Soil physical quality index (S) suggests that there is immense scope to improve the soil physical quality through management practices in the IGP and BSR, for better water management and increased crop production.

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