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Hydraulic Properties and Their Dependence on Physico-chemical Properties of Soils: A Review

Seema[1*], Rita Dahiya[2], V. K. Phogat[1] and H. S. Sheoran[1]

[1]Department of Soil Science, CCS Haryana Agricultural University, Hisar -125004, India.
[2]Department of Physics, CCS Haryana Agricultural University, Hisar -125004, India.

Authors' contributions

This work was carried out in collaboration among all authors. Author Seema designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors RD and VKP managed the analyses of the study. Author HSS managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

In the present day context, the knowledge of the soil, water and its movement in the soil has key importance for optimum plant growth as well as having practical inferences in agricultural, hydrological and ecological situations. Hydraulic properties of soils play a significant role in the adoption of water management strategies capable of improving resource use efficiency and alleviating production constraints of soils worldwide. Hydraulic conductivity is the most important hydraulic parameter to regulate the flow and transport related phenomena in soil. Hence, there is a need for accurate and adequate information regarding the hydraulic properties in relation to soil physico-chemical properties. The aim of this paper is to extend the relationship between the hydraulic properties and other soil physico-chemical properties of soils. Many studies around the world reveal the effect of texture, soil organic carbon content, bulk density, pH, electrical conductivity, sodium adsorption ratio, aggregate stability index and soil water holding capacity on hydraulic properties of soils.

**Corresponding author: E-mail: seemasheoran25@gmail.com;*

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1. INTRODUCTION

Sustaining the agricultural productivity to meet the increasing demand of food and fiber for the world population from the limited land and water resources is the key issue in present scenario. Hence, there is a need to have adequate and accurate information about hydraulic properties of soils which play an important role in the adoption of appropriate water management practices capable of enhancing input use efficiency and alleviating production constraints of soils. Soil water has direct effects on plant growth and development through monitoring plant water status in soil and indirectly through its effect on aeration, temperature, nutrient transport, uptake and transformation [1,2]. Therefore, the knowledge of soil water status and its movement in soil is important for optimum plant growth and has practical inferences in agricultural, environmental and hydrological situations as well. Hydraulic properties of soils such as water infiltration, hydraulic conductivity, and water retention regulate the ability of the soil to capture and accumulate precipitation or irrigation water. Saturated hydraulic conductivity (Ksat) is one of the highly dynamic soil properties that determine the capacity of a soil to conduct water in soil. It is influenced by the properties of the fluid that is being transmitted and the porous medium. Soil hydraulic properties reflect the structure of the soil porous system consisting of pores of different geometry, sizes and connectivity [3,4]. Hydraulic conductivity is a very important soil property in solving environmental problems because it is one of the important soil physical properties that determine infiltration rate, irrigation and drainage practices and other hydrologic processes [5]. Well-developed soil structure hierarchy is important for crop production and for minimizing environmental pollution arising from preferential flow of water through soil matrix [6]. As the sand and silt content in soil texture increases generally soil bulk density increases and total porosity is decreased. Jarvis et al. [7] reported that Ksat in the topsoil (<30 cm) was found to be strongly dependent on soil bulk density and organic carbon content. Hence, saturated hydraulic conductivity (Ksat) of different soils under variable field conditions is still a matter of interest [8]. However, such findings are not consistent across soils and climates, therefore, many workers have suggested Singh et al. [9] the need for better understanding of hydraulic properties of soils in different regions under diverse climatic conditions.

Soil water retention is one of the major hydraulic properties that govern soil functions in the ecosystem and greatly affects soil management practices. The soil water retention curve plays a key role in soil and water management practices [10]. Several workers reported that by adopting appropriate agricultural management practices the soil moisture retention characteristics can be improved with an increase in soil aggregation, friability and improving soil structural stability [11]. The hydraulic properties also provide valuable information about land-use evaluation, estimation of drainage, chemical leaching and the impact of contamination on the subsurface environment [12]. Therefore, detailed information of soil hydraulic properties are required for assessing soil water movement and the status for developing the strategies for sustainable crop production. There is a need for much more extensive research on the subject.

2. REVIEW OF WORK DONE

The literature available on the assessment of soil hydraulic properties in relation to the physical and chemical properties of soils has been reviewed here.

2.1 Effect of Texture on Hydraulic Properties

Soil texture has greater influence on hydraulic properties, because the hydraulic conductivity of soil is the function of pore size, therefore, soils with large sized sand particles relatively have large pore spaces resulting in higher saturated hydraulic conductivity (Ksat). Soil texture has the dominant effect for saturation capacity, water holding capacity of soil and soil water characteristics [13,14]. Reynolds [15] recorded Ksat for sand of 29 cm h^{-1}, 4.1 cm h^{-1} for a loam and 0.091 cm h^{-1} for clay loam soils. He concluded that Ksat of the sand (having large sand fraction) was about 300 times higher than that of the clay loam (having small sand fraction) soil. Al-Qinna et al. [16] also stated significant relationship between texture and hydraulic properties of soils. Shwetha and Varija [17] observed that Ksat varies from 1.16 to 10.31cm/hr for sandy loam textured soils, 4.46 to 12.68 cm/hr in loamy sand textured soils; it ranges from 13.92 to 6.48 cm/hr for sandy soils.

[10] found a significant negative and exponential relationship between silt + clay and Ksat of the soils with correlation coefficient (R^2) of 0.90 at two different depths. Coarse-textured and well-aggregated soils are more conductive than clayey soils because of the large pore spaces [18].

Water retaining capacity of soil is strongly related to the size of the soil particles. Water molecules held more tightly to the fine particles of a clay soil than to coarser particles of a sandy soil, therefore, clay soils retain more water than the sandy soils [19]. Olorunfemi and Fasinmirin [20] observed the highest water holding capacity (36.69%) in sandy clay loam soils than the sandy loam (25.15%) and loam soils (31.98%) and concluded that as the finer fraction of the soil increases, the correlation between the water holding capacity and soil texture also increases. At low potentials soil texture controls water retention while the role of soil structure predominates at higher potentials [21]. The soil moisture retention capacity was reported higher for the soils having large amounts of clay and organic carbon content [22]. Viji and Prasanna [23] conducted a study on the three textural soils i.e., sandy loam, silty clay and clay loam and among all textural classes, highest water holding capacity was observed in clay loam (30.69%), which may be due to high clay content of the solid fraction of soil.

2.2 Effect of Soil Organic Carbon on Hydraulic Properties

Soil water retention and transmission properties are affected by the organic carbon contents as it plays a significant role in pore size distribution because soil organic matter strongly influences soil aggregation and aggregate stability. Therefore, many scientific studies have revealed that the organic carbon content and hydraulic conductivity has a positive significant relationship with one another. In most of the agricultural soils, soil organic carbon enhances the hydraulic conductivity by improving soil aggregation and porosity [24,25,26]. Nemes et al. [27] studied the complex effect of organic matter on soil hydraulic conditions, as it enhances hydraulic conductivity by creating larger pore sizes in the soil and also reduces the conductivity by retaining more water as soil organic matter affects the pore-size distribution of the soil through soil structure development. The modification of soil structure with the increase of organic matter content may convert larger cracks and clods with more aggregated material with more tortuous and thin pathways for water to go. The extent of these effects may vary for different textured soils. Addition of organic matter improves aggregate stability and soil porosity which in turn promotes storage and movement of water through soil [28].

Yazdanpanah et al. [29] reported greater hydraulic conductivity of soils with higher organic carbon content as compared to the soils with lower soil organic carbon due to more macro pore fraction. Increases in organic carbon content led to increased water retention in sandy soils, and a decrease of water retention in fine-textured soils. However, at high organic carbon values, there was an increase in water retention in coarse as well as in fine textured soils with the largest increase in sandy and silty soils [30]. The effect of organic matter on water retention at field capacity was observed to a larger extent than at permanent wilting point [31]. Hugar et al. [32] reported increased organic carbon in Red soils, where it acted as a fine medium of sorption to hold water as well as improved the soil aggregation. The increase in water holding capacity of the soils is due to higher total porosity of soils with higher SOC. It was reported that in certain types of soil, organic matter can hold up water up to 20 times of their weight [33].

2.3 Effect of Bulk Density on Hydraulic Properties

Bulk density is one of the significant soil physical properties used extensively for assessing soil looseness or compactness. Thus, bulk density of soil also affects the soil hydraulic properties. The bulk density of soil is highly dynamic in nature and varies with inherent soil properties as well as with soil management practices. Hence, any alteration in bulk density due to texture, structure, organic matter or agricultural management practices, etc. would result in variation of hydraulic properties. The effect of sand content on bulk density was found more dominant as compared to other soil properties which have direct effect on hydraulic properties [34]. Singh et al. [35] in their study observed a decrease in saturated hydraulic conductivity with an increase in soil bulk density due to the reduction of non-capillary pores.

Dec et al. [36] reported similar results of decreasing Ksat with increasing bulk density of soil due to a smaller volume of large sized pores in the soil. Bulk density and hydraulic conductivity was found to have a high correlation coefficient of r = 0.94 of different textured soils of Abekuta at p <0.05 [20]. Seema and Phogat [10] studied water transmission under laboratory conditions of texturally different soils and found positive correlation between bulk density and hydraulic conductivity with correlation coefficient R^2 value of 0.61. The results from numerous scientific studies specify that an increase in bulk density is attributed to an increase in coarser fraction (sand) which consequently resulted in an increase in the mean pore size and contributed to an increase in hydraulic conductivity of soils.

2.4 Effect of Aggregate Size and Stability Index on Hydraulic Properties

Aggregate size analysis determines the distribution of water stable aggregates according to their size, which has greater impact on the pore size distribution in soil and consequently on soil hydraulic properties. Larger inter-aggregate pores favour higher infiltration rates, improved hydraulic conductivity and adequate aeration for plant growth. The extent of disintegration of aggregate by wetting depends on aggregate stability which is directly related to organic matter and clay content of soil [37,38]. Generally, aggregate stability is commonly measured as the percentage of water aggregates with a diameter >2 mm, a parameter which is relatively easy and faster to measure mean weight diameter (MWD). Many authors reported that the soil aggregate stability was controlled by several soil primary characteristics, such as soil texture, clay mineralogy, organic matter contents and calcium carbonate which directly or indirectly improves the water retention capacity of soil [39]. Benjamin et al. [40] reported that increasing organic carbon due to incorporation of crop residue might not instantly result in enhancing soil aggregation in a semi-arid climate. However, gradually due to increased biological activities, addition of crop residues would increase the formation of stable aggregates and soil pore space resulting in better water conducting characteristics of soil. Lado et al. [41] observed that saturated hydraulic conductivity of soils with high organic matter content and aggregates size ranging from 2 to 4 mm was significantly higher than that of soil of low organic matter.

Yazdanpanah et al. [29] reported that soils with lower soil organic carbon compared to those with higher organic carbon resulted in higher percent of water stable aggregates and more macro pore fraction leading to higher hydraulic conductivity. Aziz and Karim [42] found that aggregates of 0.75 - 0.125 mm were positively correlated to fine, very fine sand and silt fractions and to organic matter. Stability of aggregates showed a positive correlation with clay content (r =0.94) and organic matter content. Eneje [43] found a positive and significant relation between Ksat and WSA at shallow depth (0-15cm) and he concluded that Ksat of soil increases with an increase in water stable aggregate (WSA). More stability soil macro-aggregates reduces swelling and slaking of the soil aggregates under saturated conditions as well as resulted in higher saturated hydraulic conductivity [41].

2.5 Effect of pH, EC and SAR on Hydraulic Properties

The soil pH states as soil reaction of the soil solution, the EC measures the soluble salt concentrations in the soil and SAR represents the concentration of sodium in soil as compared to calcium and magnesium. Dissolution of salts in water leads to changes in various physico-chemical properties and may influence the hydraulic properties of soils due to its effect on the attractive forces of soil water. Singh et al. [44] conducted a trial to study the effect of soluble salts on hydraulic properties of soil, and observed that Mg ion concentration did not show any effect on hydraulic properties; however, the presence of higher sodium ion concentration resulted in reduced Ksat of soil during leaching. Brady and Weil [45] reported that due to low salt levels and high sodium content, sodic soils have extremely poor physical properties manifested in degradation of aggregate stability structure, reduction of macro porosity, leading to restricted water and air movement within the soil. Bagarello et al. [46] also concluded that in the sandy loam soil, Ksat decreased with increasing of sodicity of soil. This decrease in Ksat might be due to aggregate slaking and partial blocking of soil pores by dispersed clay particles. Xiaomin et al. [47] conducted a study on salt affected soils and observed that saturated hydraulic conductivity values for 0-20, 20-30 and 30-70 cm soil layer depths were 141.26, 135.64 and 128.66 cm/day and available water content of these layers were 0.21, 0.20 and 0.19 cm^3/cm^3, respectively indicating that available water content of soil decreased with increasing depth along with salt concentration. Presence of excess amount of soluble salts and exchangeable sodium affect soil structure through slaking of aggregates and clay dispersion, which results in water logging, surface crust formation and leads to poor infiltration rate and decline in hydraulic movement, and drainage [48,49]. Mamedov [50] studied that the role of electrolyte concentration of the soil solution in resistance of soil aggregates to wetting and determining soil physico-hydrological properties. Therefore, concluded that the EC of the soil had considerable more effect on the stability of aggregates and hence on shape of the water retention curves.

3. CONCLUSION

The hydraulic properties of soils play a significant role in the development of efficient water management practices for enhancing input use efficiency. From the review, it is apparent that there are several factors affecting the water transmission and water retention properties of soils, and here we have illustrated some of the important properties which have significant influence on the water movement.

The results presented here show that hydraulic properties are influenced mainly by soil texture; soil organic matter, bulk density, water stable aggregates, electrical conductivity and SAR of soils, therefore, water management practices in the present scenario of limited water resources might be developed taking into consideration thorough knowledge of hydraulic properties in relation to the soil physico-chemical properties.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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