Improving soil hydraulic properties for better agricultural water management and crop Production – A review

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***Abstract*— Soil hydraulic properties are the key indicators for movement of water and chemicals through the soil, the amount of water and solutes available for plant growth, and finally impact on agricultural productivity. This paper reviews the approaches and methods to improve the soil hydraulic properties (SHP) with a view to help to improve SHP under the prevailing conditions. Different soil hydraulic properties pertinent to water and nutrient management, the factors affecting soil hydraulic properties, and the available methods or management options to improve them are discussed. The improvement of soil hydraulic properties through site specific technologies will lead to efficient use of water and fertilizers and help in sustaining agricultural production at higher level.**

***Index Terms*— Sustainable agriculture, Soil hydraulic properties, water holding capacity, water transmission property, organic manuring, tillage, mulching**

I. INTRODUCTION

Sustaining the productivity at higher level 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 modern agriculture. Soil physical, chemical, biological and hydraulic quality must be maintained/restored at its optimum level to sustain productivity at higher levels in the long run. The role of soil in the soil-plant-atmosphere continuum is unique. Although soil is not essential for plant growth and indeed plants can be grown hydroponically (in a liquid culture), however, usually plants are grown in the soil, and soil properties directly affect the availability of water and nutrients to plants. Soil-water affects plant growth directly through its controlling effect on plant water status and indirectly through its effect on aeration, temperature, and nutrient transport, uptake and transformation.

The knowledge of soil-water status and its movement in soil is important and has practical implications in agricultural, environmental and hydrological situations (Ali, 2010a**;** Ali and Turral, 2001). Soil-water movement in the field depends on the hydraulic properties of the soil. The understanding of these properties is helpful in good irrigation design and management. Unless the soil hydraulic condition (water retention and transmission) is maintained at its optimum level, the genetic yield potential of a crop cannot be realized even when all other requirements are fulfilled. A knowledge of soil hydraulic properties is essential to allow application of existing soil physical theory to practical land management issues. Soil hydraulic properties like the movement of water to plant roots, the flow of water to drains and wells, water holding capacity, moisture release properties, solute transport and the evaporation of water from the soil are essentially required for developing irrigation scheduling for maximizing water use efficiency. Scientific management of irrigation system requires a thorough understanding of the hydraulic and drainage characteristics of soil of any command area. This facilitates prevention of water logging and salinization through adoption of preventive measures at proper time. Therefore, persistent efforts are needed to arrest further degradation of soil hydraulic properties, to alleviate soil hydraulic constraints, and also to understand the respective causal processes for the sake of holistic, safe and resilient agricultural production system.

This paper reviews the techniques to improve the soil hydraulic properties. Before going to detail discussion, concept and definition of different hydraulic properties are discussed first.

II. CONCEPT AND DEFINITION OF DIFFERENT SOIL HYDRAULIC PROPERTIES

Hydraulic properties of soil are generally categorized into water retention and water transmission properties. Water retention properties include saturation capacity, field capacity (or water holding capacity), wilting point, etc. Water transmission properties include permeability, hydraulic conductivity, infiltration capacity, etc.

A. *Saturation Capacity*

It is the moisture content of soil when all the pores are filled with water. In clayey soil, the porosity is highly variable as the soil alternatively swells and shrinks, aggregates and disperses, compacts and cracks. Since clayey soils swells

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upon wetting, the relative volume of water at saturation can exceed the porosity of the dry soil.

Irrigation water management at any level requires a thorough understanding of the relations between soil and water. These relations are governed by intermolecular forces and tensions which give rise to the 'capillary phenomenon'. These forces in unsaturated soils are influenced by soil texture and structure. Based on the soil texture and structure, water retention capacity or water holding capacity of the soil varies (Ali, 2010b).

B. Field Capacity

The soil is at field capacity when all the gravitational water has been drained and a vertical movement of water due to gravity is negligible. Further water removal for most of the soils will require at least 7 kPa (7 cbars) tension. Sometimes it is referred to as water holding capacity *or* water retention capacity.

C. Permanent Wilting Point

The permanent wilting point is the point/situation where there is no more water available to the plant. The permanent wilting point depends on plant variety, but is usually around 1500 kPa (15 bars). This means that in order for plants to remove water from the soil, it must exert a tension of more than 1500 kPa (15 bars). This is the limit for most plants and beyond this they experience permanent wilting.

D. Available Moisture

Available soil moisture (ASM) is the moisture content between field capacity (FC) and wilting point (WP). i.e. ASM = FC – WP

E. Hydraulic Conductivity

Hydraulic conductivity is the soil property that describes the ability of the soil with which the soil pores permit water (not vapor).

F. Permeability

Permeability is a term used to describe the ability of a porous material to transmit fluid.

G. Infiltration

Infiltration rate is a measure of the rate at which a particular soil is able to absorb rainfall or irrigation. It is measured in inches per hour or millimeter per hour. The rate decreases as the soil becomes saturated. It is related to the saturated hydraulic conductivity of the near-surface soil. The maximum rate that water can enter a soil in a given condition is the infiltration capacity.

H. Drainability

Drainability refers to a soil's ability to get rid of excess water, or water in macro-pores, through downward movement by gravity.

III. FACTORS AFFECTING SOIL HYDRAULIC PROPERTIES

Various factors such as variability in the pore geometry, discontinuity, soil texture, soil structure (type and grade), organic matter content, shrinkage properties, mineralogy, etc. influence the soil hydraulic properties. Variation in morphological features may partially explain the variation in hydraulic properties. Water retention of soil is mainly controlled by the number of pore, pore-size distribution, and the specific surface area of soil. Other factors that affect the hydraulic properties are discussed below.

A. Soil Structure

Adequate water transmission properties are associated with good soil structure.

B. Soil Texture

Water is held within the soil matrix by adsorption at the surfaces of particles and by capillarity in the pores. The size, shape, and arrangement of the soil particles and the associated voids (pores) determine the ability of the soil to retain water. It is important to realize that large pores in the soil can conduct more water more rapidly than fine pores. In addition, removing water from large pores is easier and requires less energy than removing water from smaller pores.

Sandy soils consist mainly of large mineral particles with very small percentages of clay, silt, and organic matter. In sandy soils there are many more large pores than in clayey soils. In addition the total volume of pores in sandy soils is significantly smaller than in clayey soils (30 to 40% for sandy soils as compared to 40 to 60% for clayey soils). As a result, much less water can be stored in sandy soil than in the clayey soil. It is also important to realize that a significant number of the pores in sandy soils are large enough to drain within few hours (largely the first 24 hours) due to gravity and this portion of water is lost from the system before plants can use it. At higher tension close to wilting point (15 bar) nearly all pores are filled with air, and the surface area of the soil particles and the thickness of the water film around the particle determines the moisture retention. On the other hand, water retention of a sandy soil at field capacity can be increased by compaction.

C. Presence of Coarse Fragment

Presence of coarse fragment in soil layer may affect the soil hydraulic properties which in turn will affect the percolation rate, amount and distribution of water storage, routing of overland flow and seepage. If the non-permeable coarse fragment increases, the area available for water movement decreases, and overall water movement can be restricted. Al-Qinna et al. (2008) found strong relationship between gravel and soil matrix adherence with hydraulic properties, where if gravel is present in loose form, enhance the bypass flow at saturation. If the gravel is present in adherent form with soil particles, it may act as a barrier for water conductance at unsaturated condition. They also found that gravel and carbonate increased the saturated infiltration rate by 0.7 mm/hr and 3.1 mm/hr, respectively, and increase the hydraulic conductivity by 1.3 mm/hr and 5.2 mm/hr.

D. Soil Surface Features

Infiltration of water into the soil depends on soil surface features (initial infiltration rate) and the transmission properties of the underlying soil profiles (final *or* steady state infiltration rate).

E. Organic Matter

The ability of soil to transmit water depends on the porosity and the arrangement of soil particles. Application of organic materials leads to an increase in soil porosity and aggregation of the soil. Thus, water retention capacity and hydraulic conductivity are expected to be greater in organic matter added soils. Hathaway-Jenkins et al. (2010) observed higher infiltration rate in organically managed grassland in comparison with conventional grassland. They also noted significant effect upon reducing peak runoff (by 29%) in organically dominated landscape compared to the conventionally dominated landscape. Hati et al. (2007) noted that the aggregate stability was positively correlated with the soil organic carbon content. In surface soil, organic matter is the principal binding material responsible for the water stability of soil aggregates with the formation of clay humus complex (Bandyopadhyay et al., 2009).

F. Tillage

Conventional tillage system significantly reduces macro-aggregates with a significantly redistribution of aggregates into micro-aggregates. Tillage affects the soil water status and the capacity of plans to utilize it. It also alters surface and subsurface soil conditions that govern infiltration, runoff and evaporation. Shallow tillage at tillable wetness after rain or irrigation reduces evaporation loss from the soil. Conservation tillage helps in conserving soil moisture. In addition, tillage increases the proportion of macro-pores in a tilled layer, thus facilitates drain out water rapidly after heavy rain or irrigation.

G. Mulching

Mulching (artificial application of mulch – a layer of dissimilar material separating the soil surface from the atmosphere) improves soil physical, chemical and biological activities of soil, and consequently alters water retention and release characteristics, retards erosion of soil. Mulching influences soil moisture regime by controlling evaporation.

H. Compost

Addition/incorporation of different forms of compost, straw, sawdust, etc. to soils generally increases the solid phase, and increases the water and gas phase. Therefore, the total porosity increases with the increase in incorporation rate. The increases in total porosity thereby have a positive effect on water retention and transmission characteristics. As we know that the water flow rate in soil pores (circular) is proportional to the second power of the radius, the saturated hydraulic conductivity will be much higher than the porosity expansion. Therefore, it is clear that incorporation of compost (or other form of organic matter) will have a positive effect on the hydraulic conductivity.

The effect of compost incorporation on changes in soil water retention behavior may be explained according to the Young-Laplace equation:

$$h_c = \frac{2\gamma Cos\alpha}{g(\rho_1 - \rho_2)r} \quad \ldots\ldots\ldots\ldots(1)$$

That is, the capillary pressure head in a capillary tube is proportional to the height h above the free water surface and inversely proportional to the capillary radius r. The incorporation effect of compost is reflected by porosity expansion (here, by r). Thus, from the equivalent capillary expansion, the capillary height (h_c) decreases, and reduces to surface adsorption. As a result, water retention characteristics improve.

IV. MEANS OR WAYS TO IMPROVE SOIL HYDRAULIC PROPERTIES

A. Improving through modifying/improving bulk density, porosity, soil aggregation
B. Tillage practices
C. Mulches application
D. Organic matter application
E. Application of sand in clayey soil

Improving through modifying/improving bulk density, porosity, soil aggregation

Schjonning et al. (1994) observed that farmyard manure or slurry significantly increased the volume of pores for <0.2 and 0.2 to 0.3 µm within 20 cm depth from the soil surface while they noted no effect on pores for >30 µm. Addition of animal manure has greater effect on macroporosity and conductivity (Schjonning et al., 2005). The increased soil organic matter improves the soil aggregation, and this improvement of soil structure increases the downward movement of soil water.

A. Tillage

Tillage practices change the initial state of soil to a new state, with changes in the physical, chemical and biological environment of soil. Tillage loosens the soil and changes its volume and mass relationship (i.e. bulk density). Loosening of soil decreases the bulk density, and its compaction increases the bulk density. A decrease in bulk density increases the total porosity and the proportion of macro-pores, which in turn increases water holding capacity.

The changes in total porosity, pore size distribution and particle-to-particle contact affect all (physical) state variables, which in turn, induce behavioural changes in soil properties and processes, modifying the edaphic environment.

B. Mulches

Mulching improves infiltration and soil moisture retention. Mulching improves moisture retention properties of soil through its effect on pore size distribution and soil structure. Soil moisture retention at lower suction is increased due to higher mulch rate (Lal, 1987) due to increase in macro-pores and inter aggregate pores caused by enhanced soil organic matter content and higher activity of soil fauna such as earthworms and termites in mulched plots. Deep tillage increases soil saturated hydraulic conductivity (Khan et al., 2010).

Stones and gravel mulches facilitate lateral movement of heat and vapor, which could in turn collect water under the stones due to condensation of vapor at night, in amounts sufficient enough to serve as the source of water for some species of desert plants and soil fauna. Organic mulching enhances the soil temperature at night and early morning hours, but it decreases the daytime temperature as compared to unmulched plots. Mulching also improves soil structural properties directly and indirectly by promoting the biological activity.

C. Organic Matter Application

Application of organic manures such as compost, farmyard manure, and green manure improve soil physical properties through improvement of soil organic matter. Increasing soil organic matter content characteristically leads to a decrease in bulk density and surface crusting, and an increase in macroporosity, water holding capacity, infiltration capacity, and hydraulic conductivity. Specially for sandy soil, manure application increases water holding capacity, and the structure of the soil is improved.

Organic manure improves the initial and steady state infiltration rate due to increase in water stability of soil aggregates, reduction in crust formation, and consequent increase in hydraulic conductivity (Acharya et al., 1998). Addition of organic matter leads to an increase in total pore volume of the soil, in addition to changes in pore size distribution. Organic matter addition through sludge and compost increases the transmission (50-500 μm) and storage (0.5 -50 μm) pores while reduces the percentage of fissure (>500 μm) (Metzer and Yaron, 1987). Application of organic matter in soil increases water holding capacity as well as portion of water available for plant growth (Sial et al., 2007; Bolan et al., 2004; Korentajer, 1991; Pagliai et al., 1981). Eusufzai et al. (2007) found that addition of compost, sawdust and straw were potential for improvement of surface soil physical and hydraulic properties. They also found that the effectiveness was partly depended on amendment type and application rate. The saturated hydraulic conductivity generally increased at any level of compost and straw incorporation (Eusufzai et al., 2007). They also noted that soil water content was relatively high at higher suction for compost amended soils, while improvement in soil water content was limited at lower suction for strawdust, and gradually increased from low to high suction for straw amended soils, respectively.

As the water transmission properties of soil are associated with good soil structure, it can be inferred as a thumb rule that application of organic matter (any form of organic manure) will generally also improve the water transmission properties. Soil permeability is a function of effective pore volume. As the addition of organic matter increases effective and total pore volume (specially for coarse textured soils), and pore-size distribution is altered and relative number of small pores is increased, it eventually increases water holding capacity (or water retention capacity), permeability and saturated hydraulic conductivity (Rawls et al., 2003; Miller et al., 2002; Hudson, 1994). As the organic matter increases specific surface area of soil, it eventually increases water holding capacity at higher tensions. Organic matter also improves soil fauna such as earth-warms and termites, which in turn improves porosity and eventually improves soil hydraulic properties. Bandyopadhyay et al. (2009) noted increased soil hydraulic conductivity of a vertisol with combined application of organic and inorganic fertilizer in a soybean-wheat system.

D. Application of Sand In Clayey Soil

The physical as well as hydraulic properties of heavy clay soil can be improved through the application of sand (Ali, 2010b).

V. CONCLUSION

Sustaining the agricultural productivity at higher level is essential to feed the growing world population. This calls for restoration/improvement of physical, chemical, biological and hydraulic properties of soil. From the review, it is apparent that there are many factors affecting the soil-water retention and transmission properties, and also there are a range of options to improve these properties. However, the most appropriate option(s) may vary from site to site, and country to country, and also on socio-economic conditions of the farmers. The improvement of soil hydraulic properties through site specific technologies will lead to efficient use of water and fertilizers and help in sustaining agricultural production at higher level.

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