Water management in agricultural soils of the Indus River valley under an arid climate

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Abstract

The behavior of agricultural soils is governed by the presence or absence of water that, in turn, is primarily derived from the prevalent atmospheric conditions causing precipitation and evaporation. Farming practices of irrigation and transpiration also affect soil behavior and eventually crop yield. The main objective of this paper is to understand the significance of water storage and release under saturated and unsaturated states. The concepts of water retention and hydraulic conductivity are presented, based on flow through porous media. The significance of these relationships for water management in soils under arid climatic zones, such as those in the Indus River valley, is highlighted.

Keywords: Water retention, Hydraulic conductivity, Agricultural soils

1. Introduction

Arid climate regions have a net water deficit between precipitation and evaporation. Although water can be stored in natural lakes or man-made reservoirs, water loss from such containment facilities can be large because water is readily available for evaporation from exposed surfaces (Suchan and Azam, 2021). Furthermore, seasonal weather variations in meteorological conditions (air temperature, relative humidity, wind speed, and net radiation) result in fluctuating water levels available for storage. Soils can serve as a water storage tank because water is held in the pore network through capillary forces and, as such, it is not freely available for evaporation.

Pakistan mostly falls under an arid climate zone. Seasonal weather patterns, which were previously predictable, have been severely disrupted in the country due to the global rise in temperature. The impact of climate change is routinely observed in the form of extended drought periods with sporadic and scanty rainfall and excessive monsoon rains to cause flash floods. In both cases, surface water storage is not adequate to adapt to the adverse effects of climate change. Sustainable

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agriculture in the Indus River valley (about 520,000 km^2) requires a clear understanding of soil-atmosphere interactions.

Generally, the gentle gradient of the Indus River valley (about 2% from the Himalayan foothills to the Arabian Sea) ensures that water from rain or canal systems adequately infiltrates into the soils. This is mostly the case under steady-state conditions, that is when there are no floods. Perennial flooding in the Kabul River (tributary to the Indus River) occurs due to snowmelt in spring and in the Indus River due to heavy rainfall in late summer (Azam, 2022). During these events, the rate of water received is significantly higher than the rate of infiltration into the soil. This means that more water is available to overflow on the surface. Furthermore, the variation of soil texture (cohesive soils versus cohesionless soils) throughout the surficial alluvial deposits has a significant effect on water flow within and above agricultural lands in the valley. Therefore, there is a need for a conceptual understanding of the factors affecting water management in the Indus River valley.

The main objective of this study is to present information on water migration and retention through porous media under saturated and unsaturated conditions. The water retention curve (WRC) and the hydraulic conductivity curve (HCC) are used to understand the inflow and outflow processes in surface soils. The significance of these fundamental curves for water management in agricultural soils of the Indus River valley (cohesive soils such as clayey loams to silty clays and cohesionless soils such as sandy loams to silty sands) under arid zones is highlighted.

2. Water Retention Curve

Water storage and release in the soil is governed by the difference between air pressure (ua) and pore water pressure (uw), which is called the matric suction or water potential (ψ) (van Genuchten, 1980). Fig. 1 shows the WRC by plotting the volumetric water content (θ, which is the ratio of water volume to the total soil volume) concerning matric suction. Generally presented on a semi-logarithmic scale, the WRC defines the amount of water in a soil using three straight-line portions, namely: no change in volumetric water content up to the air entry value (AEV) of suction; rapid decrease in volumetric water content from AEV to the residual suction value (RSV); and slow change in volumetric water content from RSV to a dry state.

The WRC is the thumb impression of surficial soil and is based on inherent material properties and anthropogenic activities. Generally, cohesive soils such as clayey loams to silty clays are characterized by high AEV (100 kPa to 1000 kPa) and high water storage owing to their finer grain sizes (high capillarity due to smaller pore sizes) and the water adsorption capability of the clay minerals (Khan and Azam, 2015). Conversely, cohesionless soils such as sandy loams to silty sands have a relatively low AEV (1 kPa to 100 kPa) and low water storage because these materials contain coarser and inert particles (Lu and Likos, 2004). The actual shape of WRC for a soil is governed by the grain size distribution curve because the latter curve corresponds to the volume of soil particles in the total volume; the remainder is the pore volume through which water can migrate (Hernandez, 2011).

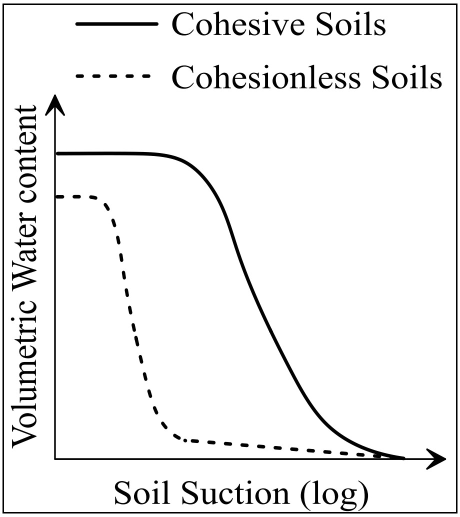

Figure 1. Water retention curve for typical agricultural soils.

At the farm level, the soil can densify over time. This results in an overall reduction in the sizes of individual pores as well as a re-distribution of the entire pore network. Therefore, a high AEV and RSV are observed for denser soils when compared with the corresponding looser state of the same soil. To facilitate water migration for plant growth, the soil is brought back to its original state through tillage. Mechanical agitation through digging, stirring and overturning breaks down the soil chunks and aerates the soil by increasing the bulk volume of pores. The ideal condition for plant growth falls between the field capacity and the wilting point. Field capacity is the volumetric water content retained after excess water has drained away or evaporated from the soil. This generally occurs after a few days of rainfall or irrigation at $\psi \approx 33$ kPa (Israelsen and West, 1922). Likewise, the wilting point is defined as the minimum amount of volumetric water in the soil that the plant requires to survive. This state of soil occurs after excessively dry conditions and is conventionally considered to occur at ψ ≈ 1500 kPa (Veihmeyer and Hendrickson, 1928).

3. Hydraulic Conductivity Curve

Water flows through the soil over the entire range of saturation and desaturation is based on HCC. Fig. 2 gives the HCC in the form of a log-log plot between hydraulic conductivity (k) and soil suction. This plot shows that all soils have a single value of hydraulic conductivity up to the AEV beyond which it varies by several orders of magnitude with an increase in soil suction up to the RSV where liquid flow changes to vapor flow at $k = 10^{-14}$ m/s (Ebrahimi, 2012).

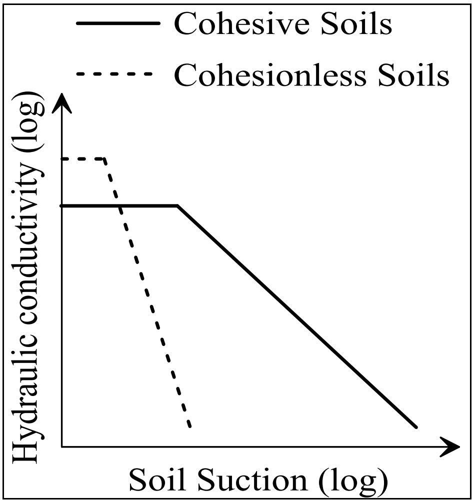

Figure 2. Hydraulic conductivity curve for typical agricultural soils.

Generally, the saturated hydraulic conductivity (ksat) of cohesive soils (10^{-8} m/s to 10^{-12} m/s) is lower than that of cohesionless soils (10^{-2} m/s to 10^{-8} m/s) because of the presence of a larger amount of connected water filled voids in the latter type of materials. Furthermore, ksat varies by up to one order of magnitude for volume-changing soils such as expansive clays (Parent et al., 2004). The plot indicates that the loss of effective water passages after the AEV results in a reduction in flow capacity for both types of soils and the rate of decrease in hydraulic conductivity is more pronounced for cohesionless soils.

At the farm level, the soil can densify, thereby resulting in a decrease in dead-ended pores and an increase in pore tortuosity. This means that a denser soil retains water whereas the same soil in a looser state drains water. Through tillage, the broken-down surface of the soil can develop dual porosity along with macroporous drainage that precedes micro-porous drainage (Ito and Azam, 2020). An irrigation system for arid regions can be designed by utilizing the top soil as a store-and-release cover (Hartzell et al., 2017). This can ensure an innate balance of moisture flux at the soil-atmosphere interface, that is, between water influx (precipitation, irrigation) and water efflux (evaporation, transpiration, surface runoff, and deep drainage).

4. Conclusion

Agricultural soils can be effectively used to store and release water in arid regions. The fundamental concepts of WRC and HCC are useful in improving farming practices to optimize water usage. Based on theory, a framework of soil improvement can be developed to ensure adequate water storage and/or release during inconsistent climatic events. This theoretical context is useful for determining the amount of water in soils at the regional scale (Zare et al., 2022a) as well as for predicting future trends under the impact of climate change (Zare et al., 2022b).

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