Modelling Root Water Extraction under Water and Osmotic Stress Conditions

Satendra Kumar[1], K. S. Hari Prasad[2*]

Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee – 247667, Uttarakhand, India. Email: skumar10@ce.iitr.ac.in.
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Abstract: Increasing demand for freshwater in various sectors has necessitated the use of marginal quality of water in agriculture sector in arid and semi-arid regions. Due to limited availability of freshwater resources, sewage treated water mixed with available freshwater is used to meet the irrigation demand of agricultural crops under water stress. This treated water has marginal amount of salts which are known to affect the soil properties and crop growth. Hence a scientific approach is necessary to incorporate the effects of soil salinity to model the water extraction by plant roots under varying water and osmotic stress conditions. A numerical model is developed, which solves the one-dimensional Richards equation for the simulation of moisture flow dynamics subjected to certain boundary conditions in variably saturated root zone. A non-linear root water extraction term is incorporated in the model as a sink term as per (Ojha and Rai 1996). Water stress in the root water extraction model is used as per (Feddes et al. 1978) and osmotic stress due to dissolved salts in soil-water is incorporated as per (Mass and Hoffman 1977) Mass and Hoffman (1977). Laboratory experiments were conducted to study the effect of salinity on water retention characteristics and saturated hydraulic conductivity. The analysis was carried on two contrast soils pertaining to textural classes silt and sand. Numerical experiments were performed for a 40 days growth period of winter wheat crop with four levels of soil-water salinity with 0.5, 15, 30 and 50 dS/m of electrical conductivity. Results of the numerical simulations show that roots extract water at maximum potential rate when there is no water and osmotic stress, and no water extraction when either or both of the water or osmotic stress reaches the threshold for permanent wilting point. Root water extraction reduces as the soil-water salinity reaches the threshold value for osmotic stress even in the absence of water stress. Hence multiple working combinations of water and osmotic stress based on the quality and availability of water can be worked out for the maximization of crop yield. The present numerical analysis finds application in the better management of available water resources for irrigation practices in crop production.

Keywords: Root water extraction; electrical conductivity; water stress; osmotic stress.

1. Introduction

Soil-water retention and hydraulic properties impact the processes of movement of water and solutes in vadose zone. These hydraulic properties are used in modelling of water movement and solute transport. Physical simulation of these processes is governed by Richards equation which is done by solving the one dimensional Richards equation for variably saturated flow. Water movement in unsaturated zone is governed by Richard's equation. Soil-water characteristic properties used in numerically solving this equation are required in terms of functional relationships. Hydraulic conductivity and retention water content as a function of soil-water pressure head or as a function of soil-water content. These characteristics primarily depend on the soil texture, particle size distribution and other physical properties of the soils (Ahuja et al. 1985; Kosugi 1999; Leij et al. 1997). It has been observed that salinity also affects these characteristics significantly. Soil hydraulic properties are also known to be influenced by salinity. Some cases show that with the salinization hydraulic processes such as infiltration rates increases, and unsaturated hydraulic conductivity also increases (Chawla et al. 1983). Another study (Singh et al. 2011) shows that soil-water content is lesser in the soils with higher soil-water salinity than that with the low soil-water salinity at the same pressure head. As far as yield and growth of crops is concerned soil-water salinity in root zone adversely affects the moisture extraction by plant roots, because of increased osmotic potential in soil-water in the presence of soluble salts. In other words availability of soil-water reduces (Lamsal et al. 1999). In the present work effect of salinity on soil-water retention characteristics is studied by conducting the pressure plate apparatus experiments and effect on saturated hydraulic conductivity is studied by performing permeameter experiments with salt solutions of varying salt concentrations. Numerical model is developed for conducting numerical experiments for the simulation of moisture flow properties and root water uptake. The experiments were performed by incorporating the effects of salinity on soil-water retention parameters and hydraulic properties. Root water uptake is modelled as a sink term in the Richards equation. A macroscopic nonlinear root water uptake model of (Ojha and Rai 1996) is used in the modelling of water extraction by plants. Water stress and salinity stress are incorporated in the model as stress response functions as defined by (Feddes et al. 1978) and (Mass and Hoffman 1977). Thus the main objective of this paper is to quantify the effect of salinity on water retention and hydraulic properties of soil and consequent effects on root water extraction properties.

2. Materials and Methods

Soil Characteristics

Soil sample A was collected from the agricultural fields ($29°46'37.5''N;\ 77°59'14''E$) in the vicinity of river Solani and soil sample B was collected from the irrigation research field facility($29°51'42''N;\ 77°54'00''E$) of Indian Institute of Technology Roorkee, Uttarakhand India, which is located at about 274 m above mean sea level. The area is irrigated with groundwater by the means of tube wells. Major crops grown in the area are wheat (Triticum Aestivum), rice (Oryza Sativa), mustard (Brassica Compestris) and sugar cane (Saccharum Officinarum). Major income for local farmers come from the sugar cane as main cash crop.
Soil physical properties were determined by performing the laboratory experiments. Oven dried soil samples were used for the determination of dry bulk density of soil samples as per Indian standards (IS:2720-7 1980). Textural analysis of the soil samples was done following the standard procedures as per IS Standards (IS:2720-4 1985). In which air dried soil samples were sieved through a standard sieve set, and soil particles passing through 75 micron sieve and retaining on pan were used for hydrometer analysis. Fig. 1 shows the obtained particle size distribution for the soil samples.

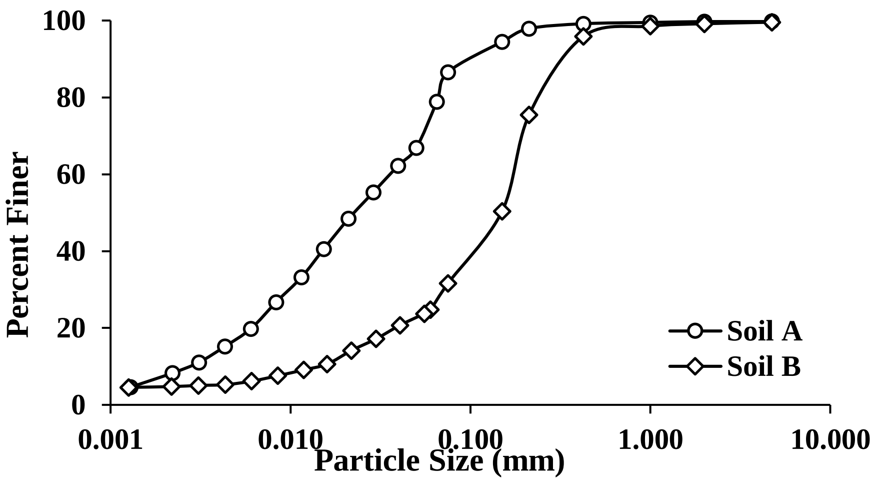

Figure 1. Particle size distribution of the collected soil samples.

Soils were classified as per USDA soil classification (Natural Resources Conservation Service

Soils, United States Department of Agriculture). Table 1 presents the textural information of soils examined.

Table 1. Texture and physical properties of soil samples.

Sample	Sand %	Silt %	Clay %	Texture	Bulk Density (g cm^{-3})
A	10	81	9	Silt	1.53
B	68	27	5	Sandy Loam	1.68

Experimental Design

Pressure plate experiments for the determination of soil water retention with varying matric potential were carried out following the operating instructions (Soil Moisture Equipment Corp. Santa Barbara, CA, USA). Four sodicity treatments and nine pressure treatments (corresponding to negative matric potentials) for the soil samples were arranged in a complete factorial of 36 treatments with three replicates. Tap water with an initial electrical conductivity of 0.5 dS/m was used for the preparation of salt solutions with NaCl salt having electrical conductivities 15 (0.83 %), 30 (1.8 %) and 50 dS/m (3.0 %). Four sodic treatments with an EC of 0.5, 15, 30 and 50 dS/m were applied for conducting the experiments. Air dried soil samples passing through 2 mm sieve were used for the experiments. Ceramic pressure plates were kept submerged for 24 hours in sodic solutions prior to the experimental run. Soil samples were placed in retainer rings of 5 cm diameter and 1 cm height on ceramic plate. Sodic solution treatments were applied directly to the porous plates until the soil samples were saturated. Samples were left for overnight to allow the sodic solution and soil interaction, and were rewetted again to ensure the saturation. Same procedure was repeated for each sodic and pressure treatments, separate apparti were used to equilibrate at nine matric potentials. Pressure was then applied to the pressure plate apparatus connected via PVC tube to an air compressor. Applied pressure was maintained by a pressure regulator valve arrangement fitted in the manifold. Experiments were carried out at matric potential values 10, 33, 50, 75, 100, 300, 500, 1000 and 1500 kPa until equilibrium was attained, equilibrium is reached when water flow through out flow tube ceases. Samples were left in the apparatus for varying time depending on the pressure applied. The equilibrated soil samples were then used for the determination of volumetric soil moisture content at the respective matric potentials.

Soil Water Retention Parameters

SWRCs for the soil samples A and B were obtained by plotting the obtained retention water content from the experiments. Water retention parameters were obtained for SWRCs corresponding to each sodic treatments. Change in retention water content is due to the effect of interaction between soil minerals and salt concentration in applied sodic solutions. These changes in SWRCs are estimated in terms of changes in soil water retention parameters. SWRCs are represented in the form of constitutive relationships defining volumetric soil water content and matric suction. Brooks and Corey (1964), Campbell (1974) and van Genuchten (1980) are the commonly used constitutive relationships which cover wide soil data base. Parameters of these constitutive soil water retention equations are specific to the soil types, each soil pertaining to a particular textural classification will have unique set of water retention parameters, corresponding to its soil water retention characteristics. Of these constitutive relationships van Genuchten water retention equation is the most widely used one because of its continuous and smooth nature, the relationship is defined as:

$$\theta(\psi) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+\|\alpha_v \psi\|^{n_v})^{m_v}}, & \psi \le 0 \\ \theta_s, & \psi > 0 \end{cases} \quad (1)$$

where α_v, n_v and m_v are the van Genuchten shape parameters depending on the shape of $\theta(\psi)$ curves, where $m_v = 1\text{-}(1/n_v)$. $\theta(\psi)$ is the retained moisture content corresponding to the matric suction ψ, θ_s and θ_r are saturation moisture content and residual moisture content.
RETC code was used for the estimation of water retention parameters fitting to van Genuchten equation. RETC is a computer code for quantifying unsaturated soil hydraulic properties for monotonic drying or wetting in homogeneous soils. Table 2 presents the water retention parameters obtained from the analysis.

Table 2. Water retention parameters obtained from the inversion of SWRCs for sodic water treatments.

Soils	EC (dS/m)	α (cm^{-1})	n (-)	θ_s (-)	θ_r (-)	R^2
A Silt Loam	0.5	0.00150	2.231	0.409	0.175	0.987
	15	0.00162	2.255	0.408	0.177	0.985
	30	0.00179	2.407	0.407	0.179	0.983
	50	0.00195	2.524	0.409	0.178	0.986
B Sandy Loam	0.5	0.01862	1.466	0.379	0.051	0.998
	15	0.01766	1.528	0.380	0.051	0.989
	30	0.01681	1.579	0.380	0.050	0.998
	50	0.01574	1.691	0.379	0.056	0.985

R^2 is coefficient of determination

A fit of SWRCs for the obtained parameters in Table 2 and the retention water content obtained from the pressure plate experiments is sown in Fig. 2.

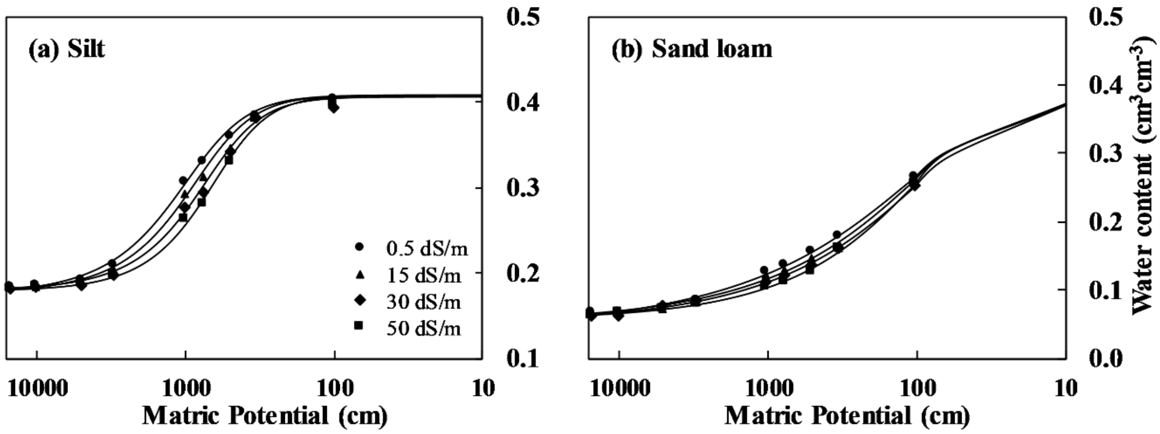

Figure 2. SWRCs with varying sodic treatments for soil sample (a) A silt loam and (b) B sand loam (Kumar et al. 2019).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity K_s of soil samples A and B with four sodic treatments having ECs 0.5, 15, 30 and 50 dS/m was determined by conducting permeability tests. Test specimens were prepared as per the standard procedures of Indian Standards, Methods of Test of soils (IS:2720-7 1980) and (IS:2720-8 1983). Prior to the experimental run, soil specimen were saturated with plain water to ensure complete saturation. Saturated soil samples were then used for performing permeability tests with the sodic solutions of varying concentrations. With the passage of at least two pore volumes of sodic solution through the soil specimen, it was left for overnight salt-water and soil minerals interaction. Falling head permeameter test was performed on soil samples A (silt loam) and constant head permeameter tests was performed on soil samples B (sandy loam). Three set of experiments for each combination of soil and sodicity treatments were performed. Results were standardised by normalising the data at 27 ℃ temperature using the viscosity coefficient relationship for varying temperatures (Table 3).

Table 3. Obtained values of saturated hydraulic conductivity for soil samples considered with sodic treatments.

Soil Samples	**Saturated hydraulic conductivity K_s (cm/day)**			
	0.5 dS/m	15 dS/m	30 dS/m	50 dS/m
Soil A	9.48	3.58	2.67	1.94
Soil B	183.21	198.80	213.31	228.56

Crop Parameters

Crop parameter used in the present analysis are adopted from the study conducted by Sonkar et al. (2018). Crop growth for a window of 40 days of interval is considered in the present study for studying the effect of water stress and salinity stress on the water extraction properties of plant roots. The parameters used as input parameters in the analysis are: leaf area index, root depth. Leaf area index is used in the determination of crop transpiration by multiplying an appropriate crop coefficient to the potential evaporation for the give climate variables. This crop transpiration is used to determine the water uptake as sink term at different soil depths as modelled by nonlinear root water uptake model. For which the β parameter, a model nonlinear root water uptake parameter was used as 1.72 from the study of Sonkar et al. (2018).

3. Moisture Flow Simulation

Governing Equation for Moisture Movement

Richards equation is the governing differential equation used for modelling the moisture flow in variably saturated zone. The mixed form of the Richards equation for moisture flow in variably saturated region is given as (Richards 1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z}\right) + \frac{\partial K(\psi)}{\partial z} \tag{2}$$

where ψ is soil pressure head; θ is volumetric moisture content; K is unsaturated hydraulic conductivity; t is time; z is vertical coordinate taken as upward positive.

Constitutive Relationships

Equation (2) is a highly non-linear partial differential equation, as the independent variables θ and K are non-linear functions of variable ψ. The analytical solution of which is possible for some specific cases only. Hence, constitutive relationships defining $(K - \theta - \psi)$ relationships are required to solve the equation (1) numerically. Constitutive relationships proposed by van Genuchten (1980) for $(\theta - \psi)$ relationship (equation (1)) and for $(K - \psi)$ relationship as defined below are used:

$$K(\psi) = \begin{cases} K_s S_e^{\frac{1}{2}}\left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2, & \psi \le 0 \\ K_s, & \psi > 0 \end{cases} \tag{3}$$

where K_s is saturated hydraulic conductivity and S_e is effective saturation defined as:

$$S_e = \frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r} \tag{4}$$

Root Water Extraction Model

Root water uptake model as given by Ojha and Rai (1996) is used in the analysis. $S_{\max}$ is the maximum extraction which is defined as:

$$S_{\max} = \alpha\left[1-\left(\frac{z}{z_{\mathrm{rj}}}\right)\right]^{\beta} \tag{5}$$

where α and β are model parameters; z = depth below the soil surface, z_{rj} = root depth at j^{th} day. This potential extraction, $S_{\max}$ must be equal to the total transpiration which is given by:

$$T_{\mathrm{j}} = \frac{\alpha z_{rj}}{(1+\beta)} \tag{6}$$

Using the above equations one can find the following relation for $S_{\max}$:

$$S_{\max} = \frac{T_{\mathrm{j}}(1+\beta)}{z_{\mathrm{rj}}}\left[1-\left(\frac{z}{z_{\mathrm{rj}}}\right)\right]^{\beta} \qquad \text{for } 0 \le z \le z_{\mathrm{rj}} \tag{7}$$

Root Water Extraction under Combined Matric and Osmotic Stress

Under the limiting moisture conditions, when soil moisture reaches the lower water content the actual transpiration rate falls below potential transpiration rate. The extraction term is modified as per the following relation:

$$S(\psi) = f(\psi)S_{\max} \tag{8}$$

$f(\psi)$ is water stress response function, which under the limiting conditions assumes the following forms:

$$f(\psi) = \begin{cases} 0, & for\ \psi \le \psi_a \\ \frac{\psi_{\mathrm{a}}-\psi}{\psi_{\mathrm{a}}-\psi_{\mathrm{fc}}}, & for\ \psi_{fc} < \psi < \psi_a \\ 1, & for\ \psi_{amc} \le \psi \le \psi_{fc} \\ \frac{\psi_{\mathrm{w}}-\psi}{\psi_{\mathrm{w}}-\psi_{\mathrm{amc}}}, & for\ \psi_w < \psi < \psi_{amc} \\ 0, & for\ \psi \le \psi_w \end{cases} \tag{9}$$

where ψ_{w} = pressure head corresponding to wilting point, ψ_{amc} = pressure head corresponding to available moisture content, ψ_{fc} = pressure head corresponding field capacity, ψ_{a} = pressure head corresponding to anaerobiosis point.

When salts are introduced in the soil-water the root water extraction function takes the following form:

$$S(\psi,\pi) = f(\psi)f(\pi)S_{\max} \tag{10}$$

where $f(\pi)$ is osmotic stress response function, defined as:

$$f(\pi) = \begin{cases} 1, & for\ \pi_{max} \le \pi \le 0 \\ \frac{\pi_w-\pi}{\pi_w-\pi_{max}}, & for\ \pi_w < \pi < \pi_{max} \\ 0, & for\ \pi \le \pi_w \end{cases} \tag{11}$$

where, π is osmotic pressure head, defined as: $\pi = -400EC$ (cm) (Rhoades et al. 1992), where EC is in dS/m. π_{max} is critical osmotic potential for which plant roots experience no salt stress. $\pi_w$is wilting point osmotic potential, when the salt concentration reaches above this this limit, and plant roots are unable to extract water.

Initial and Boundary Conditions

Numerical solution of a partial differential equation necessitates certain boundary conditions. Defined as:

Initial Boundary Condition

$$\psi_{ini}(z) = \psi(z) \qquad 0 \le z \le L, t = 0 \qquad (12)$$

where, $\psi(z)$ is the initial pressure head defined at depth z for initial moisture content $\theta_{initial}$ at the time of start of numerical run, for L length of soil the column.

Upper Boundary Condition

The upper boundary condition is defined based on the processes taking place at the soil surface:

$$\psi(z) = \psi_{i/r} \qquad z = L \text{ at irrigation or rainfall event} \qquad (13)$$

$$-K(\psi)\left(\frac{\partial \psi}{\partial z} + 1\right) = E_s \qquad z = L \text{ with no irrigation or rainfall} \qquad (14)$$

where, $\psi_{i/r}$ is pressure head corresponding to the irrigation or rainfall event.

Bottom Boundary Condition

In the current analysis the water table below the vadose zone is considered very deep and hence bottom boundary condition is considered to be free gravity drainage, defined as:

$$-K(\psi)\left(\frac{\partial \psi}{\partial z} + 1\right) = -K(\psi) \quad z = 0, t \ge 0 \qquad (15)$$

4. Results and Discussion

From figure 2, it can be observed that as the concentration of sodic treatment increased from 0.5 to 15, 30 and 50 dS/m the retention water content in both the soil samples reduced successively irrespective of their textural composition. The effect was more pronounced in the soil A having higher fraction of fine particles than in case of soil B with lower fraction of fine particles. Moreover, the effect of sodicity on reduction in water retention was more pronounced in 50 to 300 kPa region. This is due to the nature of adsorbed water which is attached as a thin layer to negatively charged clay minerals (Singh and Wallender 2008). Water in soil pores is in two phases, free water that is free to flow and adsorbed water. The thickness of this adsorbed water layer is inversely proportional to electrolyte concentration of soil water. As the concentration of salts increases this thickness of adsorbed water reduces, and water content available for free flow increases.

Table 3 shows the results of permeability tests conducted on the soil samples with varying sodic concentrations. Saturated hydraulic conductivity for fine textured soil A reduced as the concentration of sodic treatment was increased. While, in the case of coarse textured soil B, it increased with increase in sodicity concentration. The reason for the influence of sodicity on hydraulic conductivity can be found in the nature of soil minerals and pore size distribution. In fine textured soil A (silt loam) with increased sodicity, sodium saturated clay particles disperses and dissociates from the soil matrix and plug the smaller conducting pores responsible for reduction in hydraulic conductivity. On the other hand in coarse textured soil B (sandy loam), the sodium saturated clay particles dissociates from the soil matrix and leaches out of the soil matrix resulting in the increased value of saturated hydraulic conductivity.

Effect of Sodicity on Soil Water Retention in Soil Profile

Numerical experiments were conducted on two soils with the textural properties of soils examined in the experiments for the simulation of root water uptake and soil moisture movement in the soil profiles. Irrigation was applied on the first day and the simulation is carried out for forty days. Figure 3 shows the moisture content in the soil column at depths 10, 40 and 100 cm for forty days for the soil A and soil B. It can be seen from the figure that moisture flow rate slows down in the soil A, resulting in built up of soil moisture, while in soil B moisture flow rate increases resulting in depletion of soil moisture as the concentration of sodicity increases in the soil water. In soil B in the case of soil water having ECs 0.5 and 15 dS/m roots continued to extract water until the water content reaches residual moisture content. While in the case of soil water having ECs 30 and 50 dS/m roots cease to extract water after 20 days even with 50 % available moisture content. The pattern is more prominent in the top layers of soil since roots extracts more water from the surface as compared to the bottom parts.

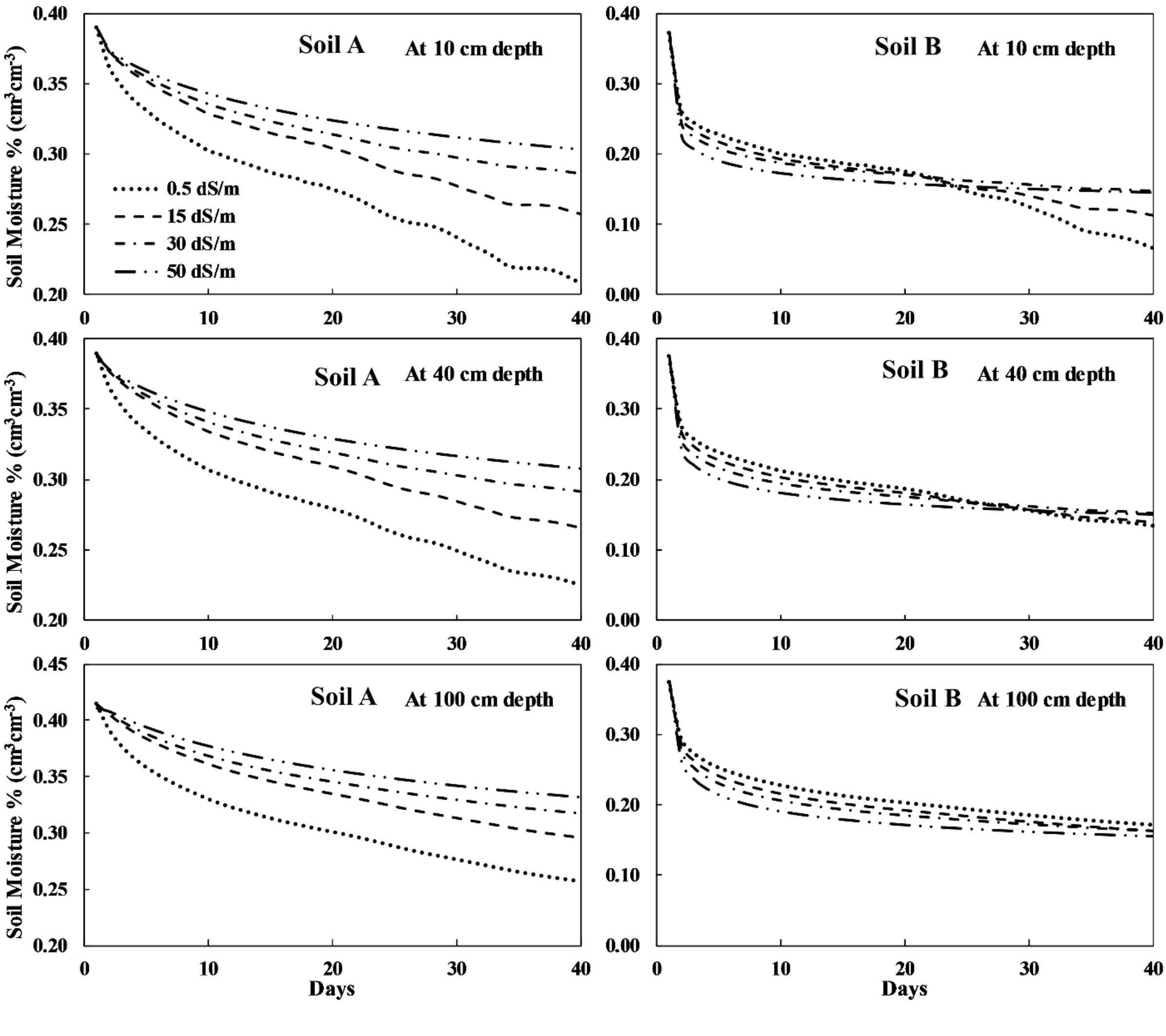

Fig 3. Soil moisture profiles in soils A and B at 10, 40 and 100 cm depths.

Effect of Sodicity on Root Water Uptake

Figure 4 shows the daily uptake of water by the roots of wheat crop in the soil A (silt) and Soil B (sandy loam) for the 40 days of crop growth with the given meteorological conditions and soil crop parameters. As the osmotic stress corresponding to the 50 dS/m sodicity exceeds the permanent wilting point threshold (π_w) i.e. critical osmotic stress limit beyond which the plant roots ceases to extract any water. Hence, root water uptake for 50 dS/m is not shown in the figure 4 (a) and (b). While for 0.5 dS/m sodicity corresponding osmotic stress is lower than the critical osmotic potential limit (π_{max}) for which the osmotic response factor is unity. The water extraction rate thus becomes a function of water stress only. Thus, the root water uptake with fresh water having 0.5 dS/m sodicity is the potential uptake under given meteorological conditions. 15 and 30 dS/m sodicity corresponds to higher osmotic potentials resulting in reduced stress response functions. For which the water uptake by plants roots is a joint function of osmotic and water stress. As seen in the figure 4 (a) and (b) water uptake by reduced with 15 dS/m with respect to that with 0.5 dS/m sodicity, and it was further reduced in the case of 30 dS/m. It can also be observed in the figure 4 (a) and (b) that the pattern of water extraction is same in the interval 5 to 35 days of growth period considered. While, slight in difference water uptake pattern at the initial stage and final stage is observed, which is due to the relative difference in soil water availability for soil types and soil water and salinity stress conditions.

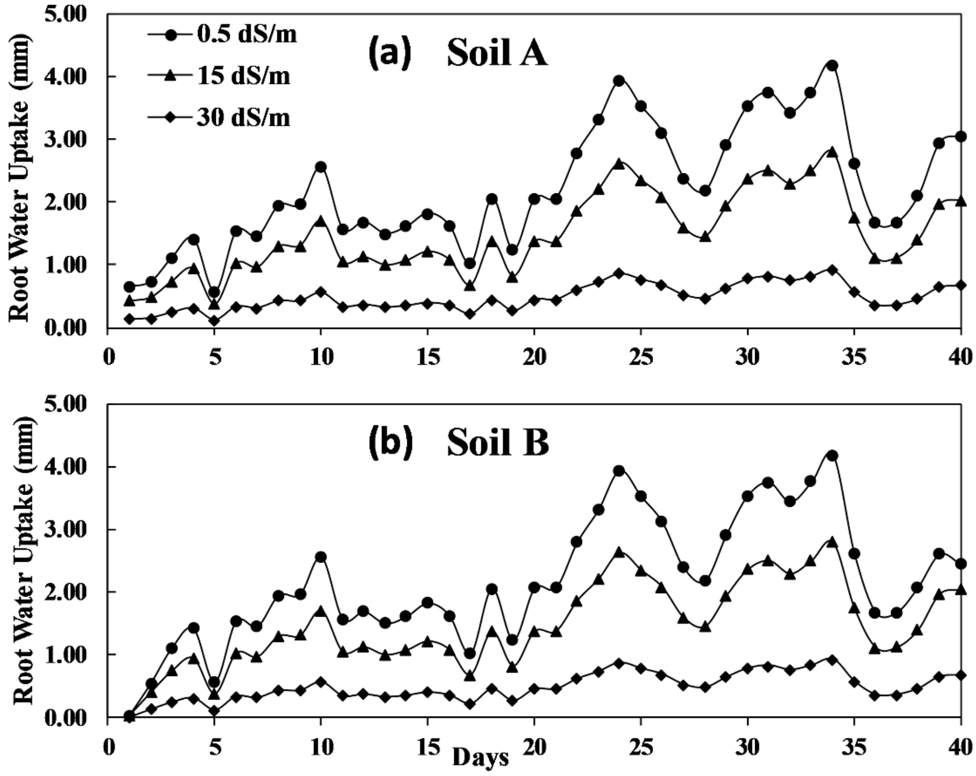

Fig 4. Daily root water uptake of wheat crop in (a) soil A, (b) soil B.

5. Conclusions

Laboratory experiments were conducted for the determination of soil water retention and flow properties with varying sodic concentrations of soil water. These obtained soil properties were used to simulate gravity drainage in the soil columns with the textural properties of soil samples used in the laboratory experiments. A numerical flow model was developed for modelling soil moisture flow in the variably saturated zone. The soil water retention profiles obtained from the pressure plate experiments show that soil water content reduces at higher sodicity values than at lower sodicity values. Fine textured soil having a higher composition of fine particles (clay and silt) is affected more while coarse textured soil with lesser composition of fine particles is affected least. Permeability tests revealed that with increase in sodicity concentration, gravity drainage reduced in the fine textured soil as a result of plugging of smaller conducting pores by dispersed clay minerals. In the case of coarse texture soil gravity drainage increased with increase in sodicity concentration, which could be due to flushing of dispersed finer clay particles. Combined effect of these observed changes are studied on soil moisture dynamics and root water uptake dynamics by simulating numerical experiments. Soil moisture profiles obtained from the simulations show that in fine textured soils flow rate reduces as the concentration of sodicity increases, and increases in the case of coarse textured soils as the concentration of sodicity is increases.

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