Modelling Root Water Uptake and Soil Moisture Dynamics under Saline Water Conditions

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Abstract

Agriculture sector is a major consumer of available fresh water. Increasing demand for fresh water in the various sectors has necessitated the use of treated waste water for irrigation. This water has marginal amount of salts which are known to affect the soil properties and crop growth. Hence a scientific approach is necessary to model the moisture uptake by plant roots under varying saline conditions. A numerical model is developed for solving the one dimensional Richards equation for moisture movement in variably saturated vadose zone. The root water uptake is incorporated in the model as the sink term as per the Ojha and Rai (1996) model, which is a non-linear root water uptake model. Combined water and salinity stress in the root water uptake is incorporated as per Feddes et al. (1978) and Mass and Hoffman (1977). Effect of varying salinity concentrations on the water uptake by plant roots and soil moisture dynamics in the root zone is studied on a 40 day period of crop growth. This is attained by providing fresh water and saline water irrigation with 15, 30 and 50 dS/m electrical conductivity. Irrigation field experiments of winter wheat crop were carried out to measure the crop parameters used in the analysis like leaf area index and root depth. The analysis to study the effect of salinity on soil water retention (SWR), hydraulic parameters and plant root water uptake was performed for silt loam (fine textured) and sandy loam (coarse textured) soils. The results show that the roots extract water at potential rate with fresh water, with no water uptake in the case of higher salinity as osmotic stress reaches permanent wilting phase. Overall, the root water uptake reduces as the concentration of salinity increases, even if there is no water stress. However, water stress was encountered at an earlier time in the case of sandy loam soil than in the case of silt loam. As the water content falls below the available moisture content, the water uptake is affected by water stress, which affects the growth and yield of crops. The results obtained from the study are useful in the better management of available water resources for irrigation practices in crop production.

Modelling Root Water Uptake and Soil Moisture Dynamics under Saline Water Conditions

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Introduction

Soil-water retention and hydraulic properties are key parameters influencing the moisture flow dynamics in the vadose zone. These hydraulic parameters are often considered invariant of saline-sodic concentrations in the soil water. Often it is considered that these properties only depend on the soil texture, particle size distribution and other physical properties of the soils (Ahuja et al. 1985; Feike J. Leij et al. 1997; Kosugi 1999), but it has been observed that concentration of salts in soil water also affects these properties. It is seen that in coarse textured soils with salinization infiltration rate increases, and unsaturated hydraulic conductivity increases (Chawla et al. 1983), and retention water content reduces with the increase in the salinity concentrations (Singh et al. 2011). The present work studies the effect of salinity on trend of change in soil-water retention characteristics and saturated hydraulic conductivity of two contrast soils, for which pressure plate and permeameter experiments with salt solutions of varying concentrations were conducted. A Numerical model is developed for simulation of moisture flow dynamics to analyse the effect of varying salt concentrations on moisture flow dynamics and root water uptake characteristics in the crop root zone. For this numerical experiments were performed with the obtained water retention and crop parameters for winter wheat crop for a crop period of 10 days. The main objective of this paper is to quantify the effect of salinity on water retention and hydraulic properties of soils and consequent effect on root water extraction properties.

Soil Sampling Sites

Soil samples were collected from the agricultural fields in the vicinity of river Solani and from the irrigation research field facility of Indian Institute of Technology Roorkee, Uttarakhand India, which is located at an altitude of about 274 m. Roorkee has hot humid summers and very cold dry winters, classified as "humid subtropical climate" (Thornthwaite 1948) having an average annual rainfall of 1100 mm, 80 % of which falls in the monsoon season (June – September). 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).

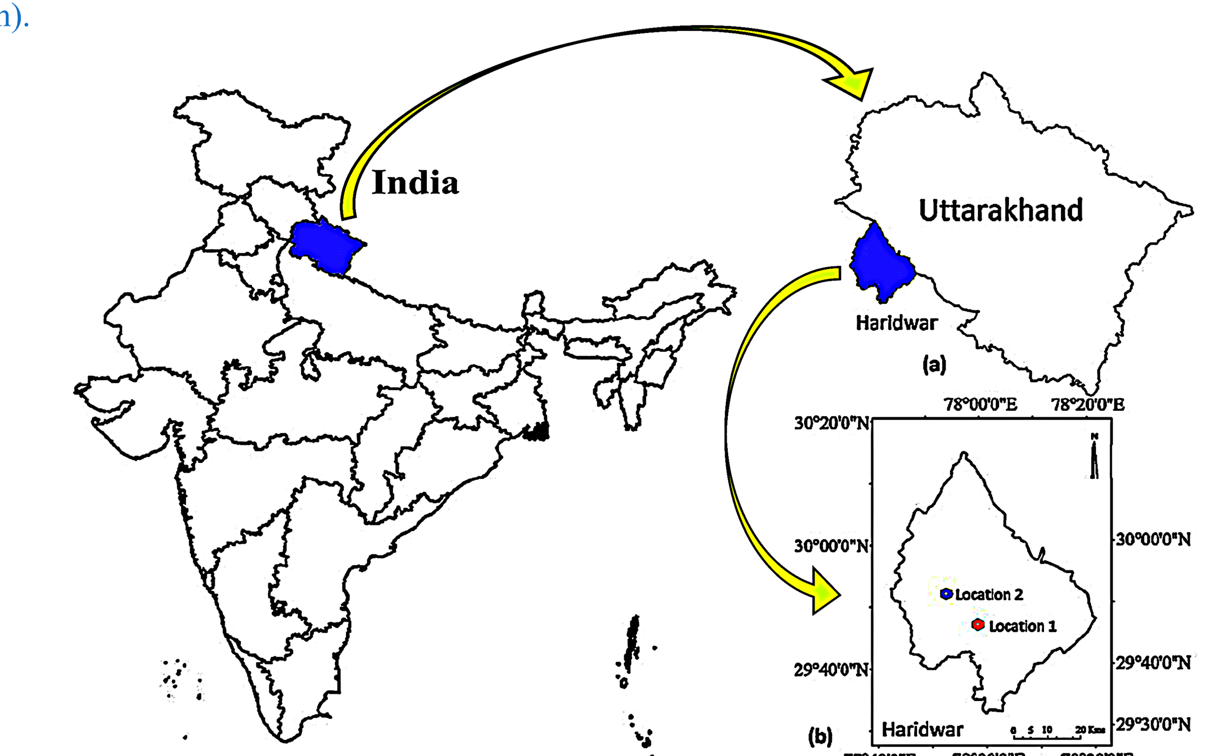

Fig.1: (a) District Haridwar of Uttarakhand with (b) location of sampling sites.

Textural Analysis

- Sample at location 1 is designated as A and at 2 as B.
- IS:2720-4 1985 was followed for textural analysis
- Sieve analysis was done for coarser particles.
- Hydrometer test was performed on samples passing through 150μ sieve for finer particles.
- In-situ bulk density of soils was obtained by core cutter method.

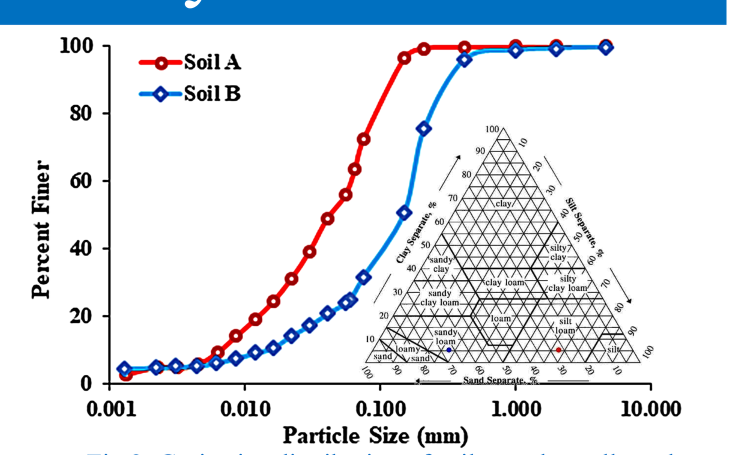

Fig.2: Grain size distribution of soil samples collected.

Table 1. Texture and physical properties of soil samples.

Sample	Sand %	Silt %	Clay %	Texture	Bulk Density (g cm^{-3})
A	28	67	5	Silt Loam	1.63
B	68	27	5	Sandy Loam	1.68

Experimental Design

- Pressure plate experiments for the determination of retention water content with varying matric potential were carried out.
- Four sodicity treatments (0.5, 15, 30 and 50 dS/m) and nine pressure treatments (10, 33, 50, 75, 100, 300, 500, 1000 and 1500 kPa corresponding to equivalent negative matric potentials) for the soil samples were arranged in a complete factorial of 36 treatments in the replicates of three .
- Ordinary tap water with an electrical conductivity of 0.5 dS/m is 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 treatments with an EC of 0.5, 15, 30 and 50 dS/m were applied for conducting the experiments .

Fig.3: Pressure plate apparatus with soil samples in the states of (a) saturated, (b) equilibrium pressure and (c) oven dry

Soil-water Retention Parameters

- Most widely used constitutive relationships for water retention of van Genuchten (1980) (Eq. 1) is used for the estimation of soil-water retention parameters from the retention water content data from the experiments for each sodic treatments for both the soil samples.

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

where α_v, n_v and m_v are the van Genuchten shape parameters depending on the shape of curves, with $m_v = 1 - (1/n_v)$. $\theta(\psi)$ is the retained moisture content corresponding to the matric suction ψ. θ_s and θ_r are saturation moisture content and residual moisture content.

- The values of van Genuchten water retention parameters for different sodicity treatments were obtained by fitting the measured soil water retention data using the RETC code (van Genuchten et al. 1991).

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	0.00177	2.219	0.385	0.110	0.983
	15	0.00182	2.450	0.384	0.114	0.987
	30	0.00185	2.649	0.384	0.115	0.985
	50	0.00192	2.833	0.383	0.113	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 — Kumar S et al. (2019)

Saturated Hydraulic Conductivity

- Saturated hydraulic conductivity of soil samples at varying sodicity levels was determined by conducting permeameter experiments.
- Standard procedures as per Indian Standards, Methods of Test for Soils (IS:2720 part 17, 1986), (IS:2720 part 7, 1980), and (IS:2720 part 8, 1983) were followed for conducting the experiments.
- A total of four sets of experiments for each sodic treatment were conducted for both the soil samples.
- 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).
- Results obtained were normalised with respect to viscosity coefficient at 27°C (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	12.10	4.47	3.61	2.48
Soil B	183.21	198.80	213.31	228.56

Kumar S et al. (2019)

Crop Parameters

- Crop growth for a window of 40 days of interval is adopted in the present study for studying the effect of water stress and salinity stress on the water extraction properties of plant roots.
- The parameters: leaf area index and root depth are used as input parameters in the root water uptake model.
- 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.
- crop transpiration is used to determine the water uptake as sink term at different soil depths as modelled by nonlinear root water uptake model.
- The value of nonlinear root water uptake parameter used in the model was 1.72 as per the findings of Sonkar et al. (2018) for winter wheat crop.

Model Formulation

Governing Equation for Moisture Movement

Richards equation is the general governing differential equation which is used for modelling the moisture flow in variably saturated zone (Richards 1931):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\psi)\frac{\partial\psi}{\partial z}\right) + \frac{\partial K(\psi)}{\partial z} - S(z,t) \quad (2)$$

where, ψ is pressure head; θ is soil-moisture content; K is hydraulic conductivity; S is term for root water uptake by plants; t is time and z is vertical coordinate.

For the solution of equation (2), constitutive relationships proposed by van Genuchten (1980) for (θ-ψ) relationship (equation (1)) and for (K-ψ) relationship as defined below are used:

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

where K_s is saturated hydraulic conductivity

S_e is effective saturation defined as: $S_e = \frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r}$ (4)

Root Water Extraction Model

Ojha and Rai (1996) root wate uptake model is used, which is a general root water uptake model defined as:

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

where S_{max} is the potential extraction rate; α and β are model parameters; z is depth below the soil surface; z_{rj} is root depth at j_{th} day.

Since the root water extraction must be equal to the transpiration rate, defined as:

$$T_j = \frac{\alpha z_{rj}}{(1+\beta)} \quad (6)$$

T_j being transpiration on the j_{th} day.

Using above equations we can derive the following equation:

$$S_{\max} = \frac{T_j(1+\beta)}{z_{rj}}\left[1-\left(\frac{z}{z_{rj}}\right)\right]^{\beta} \quad \text{for } 0 \le z \le z_{rj} \quad (7)$$

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:

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

$f(\psi)$ water stress response function, under the limiting conditions it is defined as:

$$f(\psi) = \begin{cases} 0, & for\ \psi \le \psi_a \\ \left(\frac{\psi-\psi_a}{\psi_{fc}-\psi_a}\right), & for\ \psi_{fc} < \psi < \psi_a \\ 1, & for\ \psi_{amc} \le \psi \le \psi_{fc} \\ \left(\frac{\psi-\psi_w}{\psi_{amc}-\psi_w}\right), & for\ \psi_w < \psi < \psi_{amc} \\ 0, & for\ \psi \le \psi_w \end{cases} \quad (9)$$

where ψ_w is pressure head corresponding to wilting point, ψ_{amc} is pressure head corresponding to available moisture content, ψ_{fc} is pressure head corresponding field capacity, ψ_a is pressure head corresponding to anaerobiosis point.

Under the combined salt-water stress the root water extraction function takes the following form:

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

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

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

where π is osmotic potential, π_{max} is critical osmotic potential up to which plant roots experience no salt stress. π_w

Initial and Boundary Conditions

Equation (2) is numerically solved for the simulation of soil moisture and root water extraction dynamics, for which certain initial and boundary conditions (top and bottom) are required.

Results and Discussion

Effect of Sodicity on Soil-water Retention

- As a result of soil mineral-salt ions interactions, change in SWRCs is observed.
- As the sodicity concentration was increased water retained by the soil samples reduced.
- The effect is more prominent in the mid matric potential region.

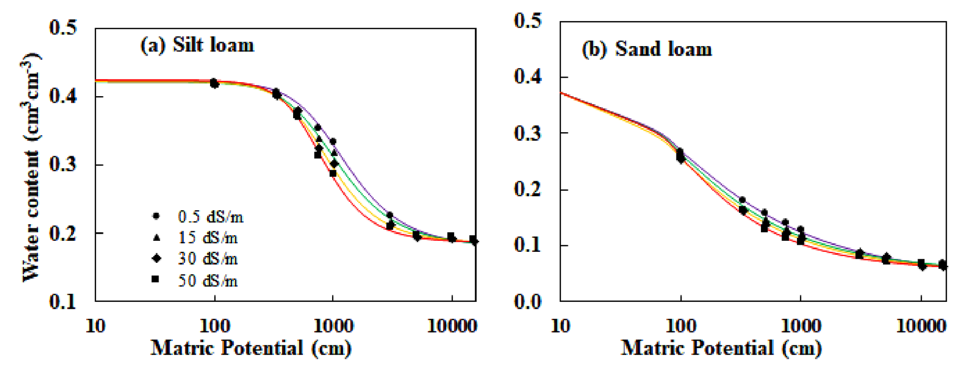

Fig.4: Retention water content with varying sodic treatments (a) Soil A and (b) soil B

- Table 2 and 3 show that with increase in sodicity concentrations, water retention parameters α_v and n_v increased in the soil A. In soil B change in parameter α_v did not show any consistent trend, while n_v increased with increase in sodicity concentration.

Soil Moisture Flow and Root Water Uptake

Simulation of moisture flow and root water extraction was carried for 40 days with irrigation on the first day of the simulation period. Figure 3 (a) and (b) show the moisture profiles in the soils at 10 and 40 cm depth.

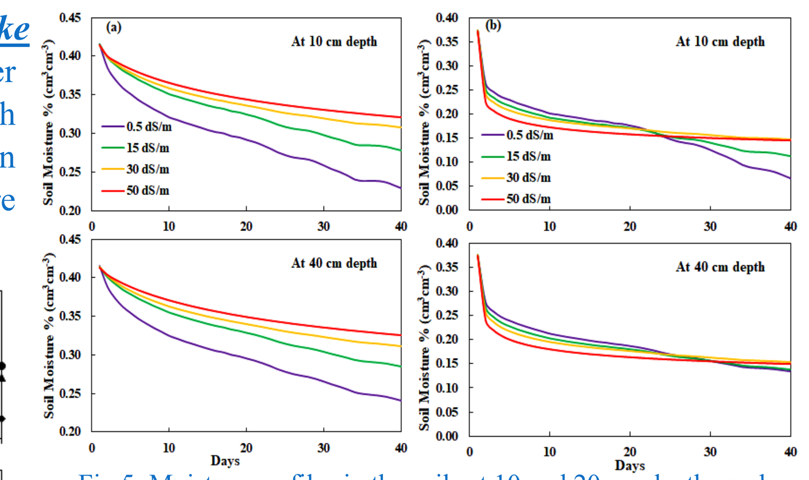

Fig.5: Moisture profiles in the soils at 10 and 20 cm depths under varying matric and osmotic stress conditions.

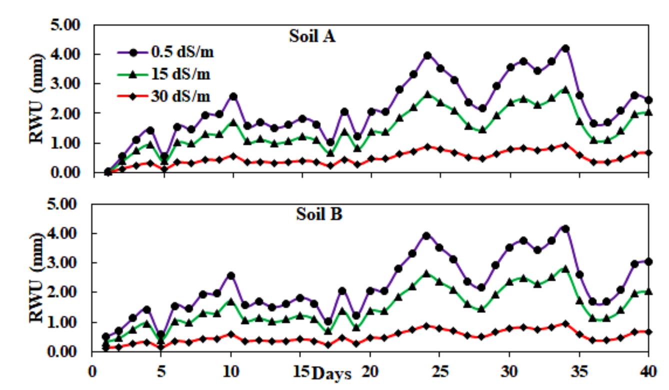

Fig.6: Daily crop root water extraction under varying joint matric and osmotic stress conditions.

Fig.6 show the daily water extraction rates by the plant roots under the four sodic conditions. Crops experience no stress with 0.5 dS/m while no extraction with 50 dS/m salinity, and a reduced extraction rate in the latter two concentrations.

Conclusions

- Experiments show that at same matric suction, soil-water retention reduces as the soil water sodicity concentration increases.
- Saturated hydraulic conductivity of fine textured soil A reduced, while of coarse textured soil increased with increase in sodicity concentration.
- Fine textured soils are affected most while soil having higher fraction of coarser particles are affected most.
- As a result of reduced hydraulic conductivity in soil A, moisture flow slows down in the soil profile and a soil moisture built up in the soil column is observed, while in soil B increase in the hydraulic conductivity results in increased moisture flow rate, resulting in rapid drying up of soil column.
- As the 0.5 dS/m lies in the critical range of osmotic suction, hence the water uptake here is just a function of water stress, while in the case of 50 dS/m osmotic stress reaches the wilting point resulting in no uptake.
- For 15 and 30 dS/m sodic concentrations water uptake is function of both the matric and osmotic stresses and hence a reduced water uptake is observed.

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