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Predicting salinisation in a heavy clay soil subjected to a saline shallow water table.

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Abstract

Salt increase in a heavy clay soil due to capillary rise was simulated by an analytical model and a numerical model. Predicted values were compared with experimental data. The analytical model was inadequate in predicting salinisation in a dynamic crop/soil system. When root growth was accounted for, the numerical model satisfactorily predicted salt increase in the soil profile.

Introduction

Salinisation of soil refers to an increase in readily soluble salts in the root zone. The rate of salinisation is influenced by climate, soil type, crops, irrigation practices, and the depth to and the quality of the shallow water table. The ability to predict such complex phenomenon is of vital importance for managing irrigated heavy clay soils in the Murray basin, where soil salinisation is primarily caused by capillary rise from shallow saline water tables.

Since the rate of salinisation is governed by the movement of water and salt, the mathematical models to predict the rate of salinisation are derived from the governing equations of water and salt movement within the root zone. Both analytical and numerical models have been formulated. The analytical models are efficient and easy to use when data are sparse and uncertain. However, the use of analytical methods is limited to idealised situations such as homogeneous and isotropic conditions. Numerical models on the other hand, can accommodate spatial and temporal variation of soil properties. But, the application of numerical models to complex conditions is generally restricted by the availability of temporal and spatial data.

The objective of this study was to compare an analytical model and a numerical model to predict salinisation of a soil profile subjected to a saline water table. Capillary rise and increase in salt within the soil profile predicted by the models were compared with experimental data.

Theory

Transport of water in the unsaturated zone of a non hysteretic, non swelling soil is given by Richards' equation (eq. 1).

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$$\frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}\right)+\frac{\partial K}{\partial z}=\frac{\partial\theta}{\partial t} \tag{1}$$

where

z : vertical cartesian coordinate (L)
K : unsaturated hydraulic conductivity (L/T)
ψ : matric potential (L)
θ : volumetric water content
t : time (T)

Philip (1988) provides a review of analytical solutions for Richards' equation under various conditions. Under steady state conditions the capillary rise q from a water table in a one dimensional profile without the roots is given by

$$q=-K(\psi)\left(\frac{d\psi}{dz}+1\right) \tag{2}$$

Transport of salt by diffusion and convection in a one dimensional soil profile is given by

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial z^2}-v\frac{\partial C}{\partial z} \tag{3}$$

where

C : concentration of salt (M/L^3)
D : hydro dynamic dispersion coefficient (L^2/T)
v : velocity of water (L/T)

Van Genuchten and Alves (1982) and Bond (1986) provide reviews of analytical solutions for eq. 3 for a variety of initial and boundary conditions.

Numerical models to predict salinisation solve equations 1 and 3 simultaneously. Addiscott and Wagenet (1985) and Nour el-Din *et al.* (1988) provide reviews of numerical models to predict salinisation and leaching of a soil profile.

Materials & Methods

The Experiment

Data for in this study was obtained from an experiment conducted by Percy *et al.* 1988. An undisturbed soil core, 0.75 m diameter and 1.4 m deep, of

Mundiwa clay loam was obtained and installed at the CSIRO-DWR, Griffith lysimeter facility. The Mundiwa clay loam is a duplex soil with approximately 0.2 m clay loam over lying a heavy clay sub soil. A saline effluent of electrical conductivity (EC) 15.0 dS/m was introduced at the bottom. The saline water table was maintained at a depth of 1.2 m by a marriot tank.

Wheat (var. Bindawarra) was sown on the core. Neutron probe readings were obtained regularly during the growing season to determine soil water deficit. Irrigation water of approximately 0.1 dS/m electrical conductivity was applied periodically to meet the soil water deficit. Water volumes supplied by the marriot tank to maintain the water table at 1.2 m (capillary rise) was monitored weekly.

Soil samples were obtained along the profile at 0.15 m depth interval before the introduction of saline water table and 21 weeks after introducing the saline water table. EC of 1:2 soil:water suspension were determined from these samples.

The Analytical model

In the analytical model, the unsaturated soil profile of 1.2 m was divided into a root zone of 0.7 m (DRZ) and a sub soil of 0.5 m (DSUB). Roots were assumed to be uniformly distributed within the root zone.

A crop coefficient K_c of 0.3 was assigned for the first 20 days after sowing (DAS). Subsequently it was increased linearly to 0.8 until 60 DAS, kept constant at 0.8 until 150 DAS and decreased linearly to 0.3 until 180 DAS. Evapotranspiration on a particular day was determined by multiplying observed pan evaporation by the corresponding K_c.

The initial total water content of the root zone (WRZ) and the sub soil (WSUB) were determined from volumetric water content θ_i and depth of each zone. The WRZ on a particular day was calculated from the previous day's WRZ by subtracting evapotranspiration and adding irrigation on the day. Resultant θ of the root zone θ_{rz} was determined by dividing the WRZ by DRZ. The change in WSUB was determined using eq. 4 and added to WSUB. Consequently θ_{sub} was determined by dividing WSUB by DSUB.

$$\Delta WSUB = 0.5 * (\theta_{rz}^2 - \theta_{rz}^1) * DSUB \tag{4}$$

where

θ^2_{rz} : volumetric water content of root zone on a day

θ^1_{rz} : volumetric water content of root zone on the previous day

The ψ_{rz} and the K_{sub} were determined using Campbell (1974) functions and soil parameters presented in Table 1. Subsequently capillary rise was determined by eq. 2, using K_{sub}, ψ_{rz} as the potential at the bottom of the root zone and

DSUB as the distance over which the capillary rise took place. Total increase in salt within the profile was estimated by multiplying the cumulative capillary rise by the salt concentration of the water table.

Table 1. Soil properties used in the Analytical model

Property	Value
Initial vol. water content of the root zone	0.34
Initial vol. water content of the sub soil	0.32
Air entry value of the root zone (AEV_{rz})	57 mm
Air entry value of the sub soil (AEV_{sub})	96 mm
Beta of the root zone (β_{rz}) for Campbell equation	17.1
Beta of the sub soil (β_{sub}) for Campbell equation	20.5
Sat. hyd. conductivity of the root zone K_{srz}	630 mm/d
Sat. hyd. conductivity of the sub soil K_{srz}	8 mm/d
Saturated vol. water content of the profile θ_s	0.4

The Numerical Model

The numerical model (Wagenet & Hutson, 1989) utilised a one dimensional finite difference solution for the transient unsaturated flow equation (eq. 1) together with transient diffusive and convective solute transport equation (eq. 3). The numerical model moves the salt as individual ions within the soil profile and then calculates the electrical conductivity using the method of Robbins *et al.* (1980). Furthermore, the model estimates soil evaporation and evapotranspiration from pan evaporation data and crop data. It can also take into account of the effects of a user specified root growth rate and root distribution pattern.

Two simulations were made using the numerical model. The first used a uniform root profile to a depth of 0.7 m. This is similar to the root profile used in the analytical model. The second simulation used a growing root profile for wheat to a maximum depth of 0.7 m (Wagenet & Hutson, 1989).

The soil profile was divided into 13 layers, each of 0.1 m in thickness. The 13th layer represented the water table. Initial conditions and properties of soil layers used in the simulations are presented in Table 2.

Table 2. Initial conditions used in the Numerical model

Layer	AEV (mm)	θ_i	β	K_s	EC dS/m
1	37	.36	10.7	1900.	1.30
2	37	.35	13.0	1500.	1.30
3	55	.34	17.8	950.	1.51
4	60	.34	18.5	50.	1.51
5	70	.34	19.2	3.	1.51
6	70	.33	20.1	3.	2.47
7	75	.32	20.2	7.	2.97
8	85	.31	20.3	9.	3.27
9	90	.31	20.4	9.	3.85
10	96	.32	20.5	9.	4.23
11	96	.33	20.6	7.	5.29
12	96	.36	20.6	6	11.01
13	96	.41	20.6	6.	15.50

Results & Discussions

Measured and predicted cumulative capillary rise for a period of 21 weeks after installation of the core are presented in Fig. 1.

Cumulative capillary rise increased rapidly until the end of 4 weeks after introduction of saline water table. At installation the θ_{sub} was approximately 0.32, which resulted in favourable ψ_{sub} and K_{sub} for a rapid wetting of the sub soil. Rate of capillary rise was markedly reduced when 20 mm of irrigation water was applied at the end of 4 weeks. This was due to the reduction in ψ within the profile. While irrigation water reduced the ψ of the top soil, the ψ_{sub} was reduced due to capillary rise from the saline water table.

Between the fifth week and the eleventh week the cumulative capillary rise continued to increase at a low rate of approximately 1.4 mm/week. During this period the pan evaporation increased from 12.8 mm/week to 22 mm/week. Further the rooting depth was shallow and the soil water deficit was met by two irrigations, each of 35 mm.

Inspite frequent application of irrigation water, the rate of capillary rise increased to 3.6 mm/week between the 11th and 21st week. This was associated with an increase in root activity in deeper layers of the soil profile and increased pan evaporation from 22 mm/week to 49 mm/week. During this period 11 irrigations totalling 427 mm were made.

The analytical model did not predict initial wetting of the sub soil satisfactorily. This was due to the calculated low value of K_{sub}. With gradual calculated wetting of the subsoil, K_{sub} increased such that a rapid capillary rise was estimated from the end of the seventh week. However the sudden introduction of a water table to a dry soil will not generally occur in nature. Thus the inability of the steady state model to predict initial wetting satisfactorily should not override our assessment of the potential usefulness of this model in more general applications.

Following the second irrigation (week 8) daily capillary rise values were generally within an expected range for this soil and water system. However the daily values estimated immediately prior to an irrigation were extremely high. This was due to the drier root zone resulting in lower ψ_{rz} and nearly saturated sub soil resulting in higher K_{sub}. Over estimated capillary rise prior to irrigation could partially be attributed to a uniform root zone assumed in the analytical model.

The numerical model predicted the initial wetting of the soil profile satisfactorily during both simulations. However, when a uniform and static root distribution was assumed the numerical model predicted higher rates of capillary rise than those measured between weeks 4 and 15. This is due to the assumed removal of water at deeper layers which resulted in steeper hydraulic gradients and higher capillary rise. The measured and predicted capillary rise were closer after the 15th week of the same simulation.

When a growing root system was assumed, the prediction of capillary rise by the numerical model was exemplary. Results from the numerical simulations show that the capillary rise could be predicted well when initial conditions and the properties of soil profile and root growth functions were accurately known.

Measured cumulative capillary rise and increase in salt within the soil profile are compared with predicted values in Table 3. The increase in salt within the profile was calculated from the concentration of salts of the water table and cumulative capillary rise. Consequently, the increase in salt predicted by the numerical model assuming a growing root profile was closer to the measured increase in salt than the other two.

Fig. 2 compares the measured EC_{ex} values 21 weeks after introducing saline water table with EC_{ex} values predicted by the numerical model. Simulation assuming the uniform and static root distribution under estimated the EC_{ex} in the upper profile and over estimated it in the lower profile. The simulation with growing root had the same weakness, but to a lesser degree.

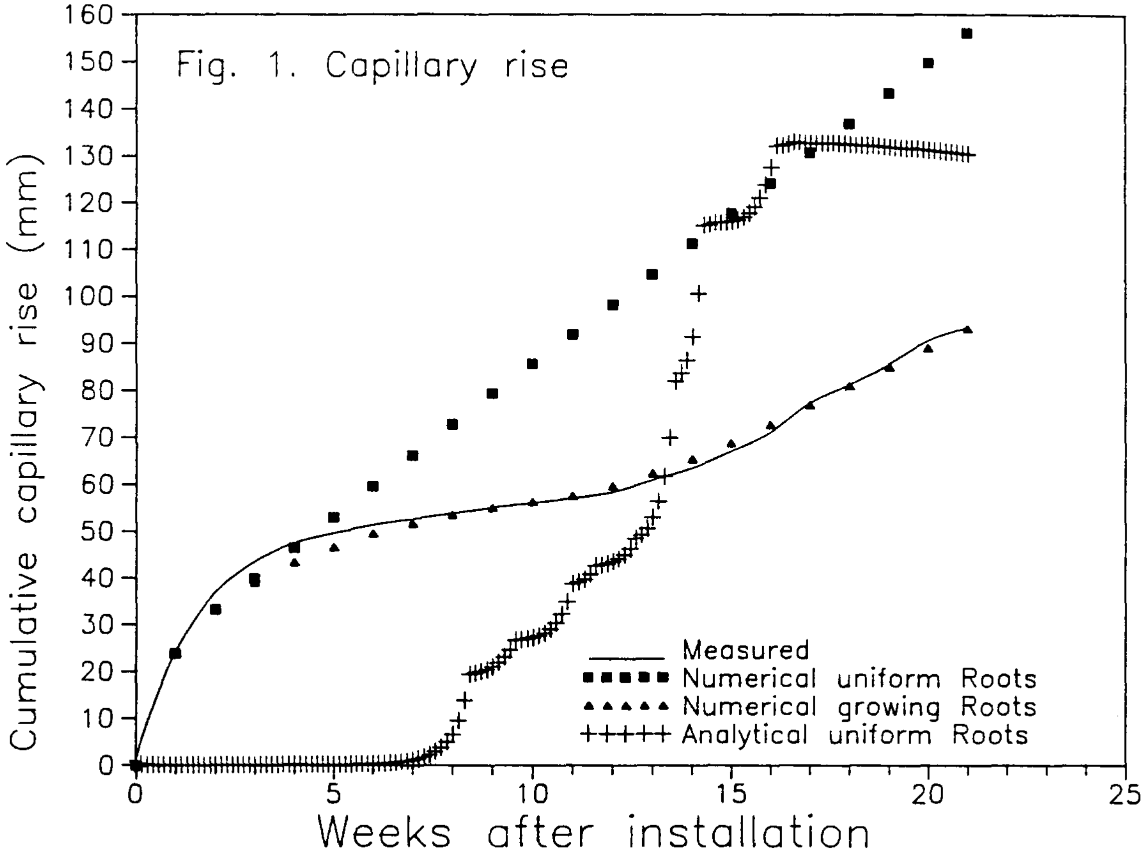

Fig. 1. Capillary rise

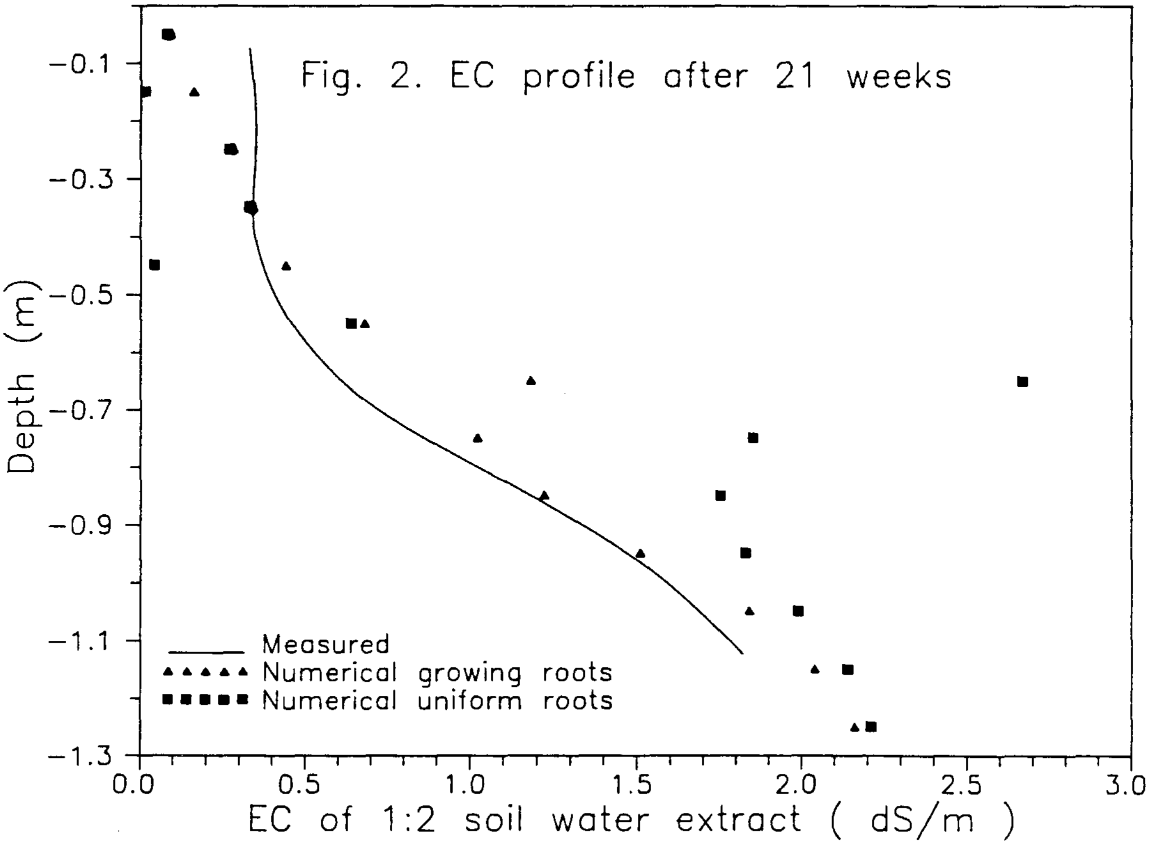

Fig. 2. EC profile after 21 weeks

Table 3. Comparison of capillary rise and salinisation

	Capillary Rise mm	Δ in salt kg/m^2
Observed	93.4	2.58
Numerical Model-Growing Roots	93.1	2.57
Numerical Model-Constant Roots	156.1	4.31
Analytical Model	131.0	3.62

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