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Modeling the effects of different irrigation water salinity on soil water movement, uptake and multicomponent solute transport

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SUMMARY

Simulation models can be important tools for analyzing and managing irrigation, soil salinization or crop production problems. In this study a mathematical model that describes the water movement and mass transport of individual ions (Ca^{2+}, Mg^{2+} and Na^{+}) and overall soil salinity by means of the soil solution electrical conductivity, is used. The mass transport equations of Ca^{2+}, Mg^{2+} and Na^{+} have been incorporated as part of the integrated model *WANISIM* and the soil salinity was computed as the sum of individual ions. The model was calibrated and validated against field data, collected during a three year experiment in plots of maize, irrigated with three different irrigation water qualities, at Thessaloniki area in Northern Greece. The model was also used to evaluate salinization and sodification hazards by the use of irrigation water with increasing electrical conductivity of 0.8, 3.2 and 6.4 dS m^{-1}, while maintaining a ratio of Ca^{2+}:Mg^{2+}:Na^{+} equal to 3:3:2. The qualitative and quantitative procedures for results evaluation showed that there was good agreement between the simulated and measured values of the water content, overall salinity and the concentration of individual soluble cations, at two soil layers (0–35 and 35–75 cm). Nutrient uptake was also taken into account. Locally available irrigation water (EC_{iw} = 0.8 dS m^{-1}) did not cause soil salinization or sodification. On the other hand, irrigation water with EC_{iw} equal to 3.2 and 6.4 dS m^{-1} caused severe soil salinization, but not sodification. The rainfall water during the winter seasons was not sufficient to leach salts below the soil profile of 110 cm. The modified version of model *WANISIM* is able to predict the effects of irrigation with saline waters on soil and plant growth and it is suitable for irrigation management in areas with scarce and low quality water resources.

1. Introduction

Salinity is one of the most severe environmental factors limiting the productivity of agricultural crops. About 17% of the world's cropland is under irrigation, but irrigated agriculture contributes well over 30% of the total agricultural production. Thus, secondary salinization of irrigated lands is of major concern for global food production. Estimates indicate that at least 20% of the irrigated lands are salt-affected. On the other hand, there is a limited amount of directly usable fresh water, contrasting with continuing increases in the world population and demand for fresh water. Irrigated agriculture uses about 65% of the consumed water. However, the extent of water dedicated to irrigated agriculture is likely to be challenged, as pressure is mounting to meet increased demands for human consumption and industrial uses (Ghassemi et al., 1995; Pitman and Läuchli, 2002).

In order to fill the gap between demand and supply of freshwater, agriculture in semi-arid areas will increasingly resort to using marginal-quality waters, such as urban wastewater, drainage water generated by irrigated agriculture and moderately saline surface and groundwater (Qadir et al., 2007; Oster et al., 2012). A variety of strategies have been adopted to overcome problems associated with soil salinity, including improving the productivity of saline soils mainly through leaching of excess soluble salts, blending saline with better quality waters, cyclic use of saline and non-saline waters, selecting of tolerant varieties of suitable crops and using appropriate agronomic practices (Qadir and Oster, 2004; Grattan et al., 2012).

Adoption of suitable salinity control measures requires determination of salt and water movement through the soil profile and prediction of crop response to soil water and soil salinity, subject to various climatic, soil and agronomic factors (Rasouli et al., 2013). Mathematical models that consider and integrate various climatic, crop, and edaphic factors have been suggested as useful tools for assessing the best management practices for saline conditions (Gonçalves et al., 2006; Ramos et al., 2011).

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A large number of models for simulating water flow and solute transport in the unsaturated zone are used for a wide range of applications in research, management and risk assessment of subsurface systems. Most vadose zone models are based on the numerical solution of the Richards equation for variably-saturated water flow (transient-state models) and on analytical or numerical solutions of the Fickian-based convection–dispersion equation for solute transport. A sink term is usually included in these equations to account for root water and nutrient uptake and the effects of water and osmotic stress (Feddes and Raats, 2004). Evaluation of these models under field conditions is increasing lately, although there is need for a vast number of input data, including soil hydraulic properties, solute transport parameters, parameters characterizing the partitioning between the solid phase and the soil solution, meteorological and crop related information.

Many models have been developed over the past years that describe soil salinity through the electrical conductivity of the soil solution (EC_{sw}). EC_{sw} is determined either as an independent solute or from individual ions, available only in the liquid phase. Although the first approach severely simplifies several processes, it is incorporated in several models with acceptable results published in the literature. Models SWAP (Kroes et al., 1999), SALTMED (Ragab, 2002) and ENVIRO-GRO (Pang and Letey, 1998) use the equation of solute transport to describe EC_{sw} as an individual solute. On the other hand, models UNSATCHEM (Šimůnek et al., 1996) and HYDRUS-1D (Šimůnek et al., 2008) incorporate modules of major ions chemistry in soil, considering complex processes of adsorption and cation exchange and have proved to be very efficient in modeling major cations in the soil solution. However, these models require a vast number of input data related to physical and chemical parameters and significant computational time for the simultaneous solution of the non linear mass transport equations for every cation, in each time step.

The performance and accuracy of a medium structure model, between the two opposing approaches discussed earlier, has not yet been evaluated. Model *WANISIM* (Antonopoulos, 2001) which describes the one-dimensional water and nitrogen movement in the soil, was modified with the incorporation of modules that describe ion transport in the soil, for salinity management. The model presents medium complexity regarding the estimation of EC_{sw} as the sum of the cations in the soil solution, which is a more accurate approach, than using salinity as an independent solute. This approach is more closely related to processes occurring in the soil. Some of these processes are taken into account, and are cation exchange and distribution between the liquid and the solid phase; however, interactions between cations and complex ion chemistry are not taken into account.

The objectives of this paper were as follows: (i) the calibration, validation and evaluation of the modified *WANISIM* model to describe soil water content, concentrations of individual ions and the overall salinity given by the EC_{sw}, under field conditions, (ii) to carry out field experiments to quantify salinization and sodification risks of long term use of saline irrigation water in maize treatments, for three consecutive years and (iii) to examine the impact of salt built up and salinity on plant root water uptake.

2. Materials and methods

2.1. Model description

WANISIM model has been calibrated and evaluated under field conditions for the simulation of water, nitrogen dynamics and soil temperature (Antonopoulos and Wyseure, 1998; Antonopoulos, 1997, 2000, 2006; Rahil and Antonopoulos, 2007). The model has been modified for irrigation management under saline conditions. In the model, the concentration of each cation is calculated by the corresponding mass transport equation. Cation exchange and distribution between the liquid and the solid phase are described by the isotherm of Freundlich, in its linear form and equilibrium chemical reactions between major cations are not taken into account. In the model, EC_{sw} is calculated as the sum of the cations in the soil solution. An overview of the modifications and processes employed by model *WANISIM* is presented below.

2.1.1. Water flow

The one-dimensional vertical flow of water in the soil matrix of the unsaturated–saturated zone is described by the Richard's equation:

$$C_h \frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left\{K\left[\frac{\partial h}{\partial z} - 1\right]\right\} - S_w \tag{1}$$

where C_h is the differential soil water capacity (cm^{-1}), h is the soil water pressure head (cm), z is the vertical coordinate positive in the downward direction (cm), t is the time (h), K is the hydraulic conductivity ($cm\ h^{-1}$), S_w is the sink term for water extraction rate by plant roots ($cm^3\ cm^{-3}\ h^{-1}$). The soil water retention curve, $\theta(h)$, is described by the van Genuchten (1980) model and unsaturated hydraulic conductivity, $K(h)$, is evaluated by the van Genuchten–Mualem model (van Genuchten, 1980). Preferential water flow and hysteresis of soil hydraulic properties are not considered in the model.

The sink term, S_w, is evaluated using the macroscopic approach introduced by Feddes et al. (1978). In this approach, the potential transpiration rate, T_p ($cm\ h^{-1}$), is distributed over the root zone proportionally to the root density distribution function, $\beta(z)$, and is locally reduced depending on soil moisture and salinity status through multiplication with the dimensionless stress response function, $a(h, h_o, z, t)$ (Feddes and Raats, 2004; Ramos et al., 2011):

$$S_w(h, h_o, z, t) = a(h, h_o, z, t)S_p(z, t) = a(h, h_o, z, t)\beta(z)T_p(t) \tag{2}$$

where $S_p(z, t)$ and $S_w(h, h_o, z, t)$ are the potential and actual water uptake ($cm^3\ cm^{-3}\ h^{-1}$) respectively, and $a(h, h_o, z, t)$ is a dimensionless function of the soil water (h) and osmotic (h_o) pressure heads ($0 \leqslant a \leqslant 1$). The osmotic pressure head is assumed to be a linear function of EC_{sw} (US Salinity Laboratory Staff, 1954), according to:

$$h_o(\text{cm}) = -360 EC_{sw}(\text{dS m}^{-1}) \tag{3}$$

The $\beta(z)$ function is described for maize, by the equation proposed by Kang et al. (2001):

$$\beta(z, t) = 1.082 c_1 exp(-c_1 z) \tag{4}$$

where $c_1 = 2.5/z_r$, z is the soil depth and z_r is the maximum rooting depth (cm). The actual transpiration rate, T_a ($cm\ h^{-1}$), over the root depth is expressed as:

$$T_a = T_p \int_0^{z_r} a(h, h_o, z, t)\beta(z)dz \tag{5}$$

In the modified model, the combined matric and osmotic effects on water uptake are described by the multiplicative approach as follows:

$$a(h, h_o, z, t) = a(h, z, t)a(h_o, z, t) \tag{6}$$

The root water uptake reduction factor due to water stress, $a(h, z, t)$, is described according to Belmans et al. (1983) approach as:

$$\alpha(h) = 0 \quad \text{for} \quad h < h_a \text{ or } h \geqslant h_{PWP} \tag{7}$$

$$\alpha(h) = (h - h_a)/(h_{FC} - h_a) \quad \text{for} \quad h_a \leqslant h < h_{FC} \tag{8}$$

$$\alpha(h) = 1 \quad \text{for} \quad h_{FC} \leqslant h < h_{CR} \tag{9}$$