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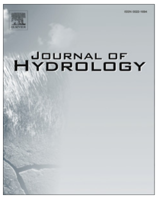

Salinity control in a clay soil beneath an orchard irrigated with treated waste water in the presence of a high water table: A numerical study

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SUMMARY

A citrus orchard planted on a structured, clay soil associated with a high water table, irrigated by drip irrigation system using treated waste water (TWW) and local well water (LWW) was considered here. The scope of the present study was to analyze transport of mixed-ion, interacting salts in a combined vadose zone–groundwater flow system focusing on the following issues: (i) long-term effects of irrigation with TWW on the response of the flow system, identifying the main factors (*e.g.*, soil salinity, soil sodicity) that control these effects, and (ii) salinity control aiming at improving both crop productivity and groundwater quality. To pursue this two-fold goal, 3-D numerical simulations of field-scale flow and transport were performed for an extended period of time, considering realistic features of the soil, water table, crop, weather and irrigation, and the coupling between the flow and the transport through the dependence of the soil hydraulic functions, $K(\psi)$ and $\theta(\psi)$, on soil solution concentration C, and sodium adsorption ratio, SAR. Results of the analyses suggest that in the case studied, the long-term effect of irrigation with TWW on the response of the flow system is attributed to the enhanced salinity of the TWW, and not to the increase in soil sodicity. The latter findings are attributed to: (i) the negative effect of soil salinity on water uptake, and the tradeoff between water uptake and drainage flux, and, concurrently, solute discharge below the root zone; and, (ii) the tradeoff between the effects of C and SAR on $K(\psi)$ and $\theta(\psi)$. Furthermore, it was demonstrated that a data-driven protocol for soil salinity control, based on alternating irrigation water quality between TWW and desalinized water, guided by the soil solution salinity at the centroid of the soil volume active in water uptake, may lead to a substantial increase in crop yield, and to a substantial decrease in the salinity load in the groundwater.

1. Introduction

In semi-arid and arid regions, the shortage of rain and other water resources necessitates the use of marginal water (i.e., treated waste water (TWW) and saline water) for irrigation. TWW may contain relatively large quantities of soluble salts, predominantly, chloride salts with calcium and sodium of ions, which, in turn, interact with the soil matrix and may affect the capability of the soil to convey water and solutes (*e.g.*, Bresler et al., 1982; Shainberg, 1984; Russo, 2005). The use of TWW for irrigation may have negative effects on crop yield (*e.g.*, Rusan et al., 2007; Zavadil, 2009), on soil structure and hydraulic properties due to soil sodification (*e.g.*, Coppola et al., 2004; Lado et al., 2005; Assouline and Narkis, 2011; Levy et al., 2014), and on soil and groundwater salinization and contamination (*e.g.*, Russo et al., 2013, 2014; Ronen et al., 2015).

These negative effects may be particularly severe in orchards planted on clay soils irrigated with TWW in the same spatial configuration (*e.g.*, drip irrigation) during many years (Assouline et al., 2015). Furthermore, the combination of orchards irrigated with TWW planted on clay soils associated with a high water table (*e.g.*, Ben Hur et al., 2001; Azenkot et al., 2005), may magnify the aforementioned negative effects. This stems from of the low conductivity and the appreciable capillary forces associated with clay soils, which, in turn, may decrease the rate of salt leaching below the root zone, and, in the presence of a high water table, may provoke transfer of salt from the saturated zone into the relatively shallow unsaturated zone, and, consequently, may reduce the soil volume active in water uptake.

The management of irrigation with TWW, therefore, should be aimed at maximizing the crop yield, while at the same time, minimizing the contamination and/or salinization of the underlying

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groundwater by the drainage water. These tasks require predictive tools for forecasting field-scale water flow and solute transport through the subsurface. Such tools can be developed by adopting physically-based, mathematical models capable of simulating flow and transport on the field-scale. For reliability, such a description must include a realistic representation of the subsurface including the inherent spatial variability in the soil hydraulic properties (*e.g.*, Nielsen et al., 1973; Russo and Bresler, 1981; Jones and Wagenet, 1984; Russo and Bouton, 1992; Russo et al., 1997; Khaleel and Relyea, 2001; Botros et al., 2009), and the spatial and the temporal variations in the water and solute fluxes imposed on the soil surface, and in the water and solute uptake by the plant roots (*e.g.*, Russo et al., 2006, 2013).

In the case of a soil associated with a relatively high water table, the transport domain of interest is the combined vadose zone–groundwater flow system. Transport starts in the vadose zone, which, in turn, acts as a source of water and solute for the transport processes in the saturated zone. A combined approach to solute-transport modeling is needed which accounts for the processes unique to each of the subsystems, and at the same time properly models the mass transfer between the two sub-regions.

Previous analyses of field-scale transport in a combined vadose zone–groundwater flow system (*e.g.*, Destouni and Graham, 1995; Foussereau et al., 2001; Russo et al., 2001; Russo and Fori, 2009), focused on the transport of a single, passive solute that does not interact with the soil matrix. Very little has been done to develop a suitable framework for the analysis of field-scale transport of mixed-ion salts with ions that interact with the soil matrix, relevant to irrigation with TWW (*e.g.*, Russo, 2013; van der Zee et al., 2014). In this case, in addition to advection and dispersion, the transport process is governed also by physicochemical interactions between the soil solution and the soil matrix, *i.e.*, cation exchange, anion exclusion, and changes in the soil pore-size distribution, PSD; the latter could affect the hydraulic conductivity and the water retention of the soil (*e.g.*, Russo and Bresler, 1977a,b; Bresler, 1978). Furthermore, because the magnitude of soil solution-soil matrix interactions depends on water content and on the concentration and composition of the soil solution, in the case of transport of interacting, mixed-ion salts, the flow is coupled to the transport through the dependence of the soil hydraulic properties on solute concentrations (*e.g.*, Russo, 1988; Russo et al., 2004).

Considering irrigation with TWW, at least three sub-systems should be taken into account in the modeling effort: (i) the N–C–O sub-system describing the cycling of nitrogen and carbon compounds in the unsaturated zone; (ii) the major ions sub-system (Cl, SO_4, HCO_3, Ca, Mg, Na, and K) contributing to salinity; and (iii) phosphate, boron, and trace metals. Considering crops planted on Hamra red Mediterranean (Rhodoxeralf) soils, previous studies (*e.g.*, Russo et al., 2013, 2014) focused on groundwater salinization and contamination by chloride and nitrate, respectively, originating from irrigation with TWW, disregarding Na/Ca exchange and the effect of these ions on the soil hydraulic properties. The present investigation focuses on the adverse effects of irrigation with TWW, related to soil salinity and soil sodicity, on the yield of orchard planted on clay soils. Consequently, in the modeling effort adopted here, only the practical soil water system containing Na, Ca and Cl is taken into account.

The present study investigates field-scale transport of mixed-ion salts in a three-dimensional (3-D), heterogeneous, combined vadose zone–groundwater flow system by means of a numerical approach. The case study considered here in an orchard irrigated with drip irrigation system using TWW and local well water (LWW), planted on a clay soil associated with a high water table; the latter combination represents a rather severe case which may magnify the negative effects of irrigation with TWW. The specific, two-fold objective of the present investigation, therefore, is, first, to assess the long-term effects of irrigation with TWW, as compared with irrigation with LWW, on the response of the flow system, and to identify the main factors (*e.g.*, soil salinity, soil sodicity) that control these effects, and, second, to test protocols for salinity control aiming at improving both crop productivity and groundwater quality.

To pursue the aforementioned objectives, field-scale water flow and transport of mixed-ion salts for the case in which the flow is coupled to the transport through the dependence of the soil hydraulic properties on solute concentrations, are simulated by a numerical procedure, which, in turn, is based on the approach of Russo et al. (2004), extended to a combined vadose zone–groundwater flow system (Russo, 2013). Realistic features of the flow domain taken into account in the simulations, include the irrigation water quantity and quality, the spatial pattern of the irrigation system, and, consequently, of the water influx imposed on the soil surface, the spatial variability of the relevant soil properties, the spatial pattern of the trees' roots, and the time-dependent atmospheric forcing conditions and the depth to the water table, imposed on the top and the bottom of the unsaturated zone, respectively.

2. Materials, methods and theoretical considerations

2.1. The physical domain

A citrus orchard irrigated with TWW and LWW, using a drip irrigation system is considered here. The orchard is planted on a structured clay (Vertisol) soil, dominated by montmorillonite, at the Mizra site located in the Izra'el Valley, Israel (Ben Hur et al., 2001), with a typical Mediterranean climate characterized by relatively long dry season requiring irrigation, and a distinct rainy period (with mean precipitation of 570 mm) during the winter. The planting spacing of the orchard is 6 m × 4 m, with trees 4 m apart along the trees' rows. Each trees' row is irrigated with a set of two drip line laterals, located along both sides of the trees' row, 0.5 m apart; each lateral consists of a set of drippers with emitter discharge of 1.6 ℓ/h, 0.5 m apart. It should be emphasized that under natural conditions, the soil in the Mizra site may crack during the dry season. In the frequently-drip irrigated orchard, however, cracks are not visible in the wetted strips along the tees' rows. Furthermore, because in the agricultural practice employed in this region, the soil surface is covered with crop residues, cracks are not visible also between the tree rows.

Considering a Cartesian coordinate system (x_1, x_2, x_3), where x_1 is directed downwards, a subplot of this orchard consisting of a 3-D, spatially heterogeneous, variably saturated flow domain which extends over $L_1 = 5$ m, $L_2 = 15$ m and $L_3 = 10$ m along the x_1, x_2, and x_3 axes, respectively, is addressed here. The subplot includes two adjacent tree rows, located 6 m apart, with four trees, located 4 m apart, along each row, i.e., a total of $N_t = 8$ trees.

The subplot was sampled to the depth of 5 m at nine different boreholes, dug diagonally over the entire experimental subplot of the orchard (five in-rows and four between rows). The soil cores were analyzed for different soil properties (*i.e.*, soil texture, bulk density, saturated hydraulic conductivity, lime content, exchangeable cations, and soil cation exchange capacity, CEC), and flow-controlled variables (*i.e.*, water content, soil solution concentrations of chloride, sodium and calcium). For each of the nine boreholes, 0.5 m-segments of the soil core extending to a depth of 5 m, were analyzed for grain size distribution using the traditional hydrometer-and-sieves method (HSM), and the laser diffraction method (LDM) (Eshel et al., 2004), and for bulk density, ρ_b.