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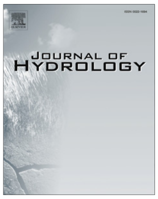

Numerical modeling of water flow and salt transport in bare saline soil subjected to evaporation

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SUMMARY

A numerical study, based on a density-dependent variably saturated groundwater flow model MARUN, was conducted to investigate subsurface flow and salt transport in bare saline aquifers subjected to evaporation, which was simulated using the bulk aerodynamic formulation. As evaporation was assumed to depend on the pore moisture, the evaporation flux evolved gradually causing a gradual increase in the pore salinity. This is in contrast to prior studies where the high salinity was imposed instantaneously on the ground surface. Key factors likely affecting subsurface hydrodynamics were investigated, including saturated hydraulic conductivity, capillary drive, relative humidity in the air, and surrounding groundwater replenishment. The simulations showed two temporal regimes where the first consists of rapid evaporation for a duration of hours followed by slow evaporation, until evaporation ceases. In the absence of surrounding groundwater replenishment, evaporation-induced density gradient generated an upward water flow initially, and then the flow decreased at which time a high density salt ''finger'' formed and propagated downwards. Capillary properties and atmospheric condition had significant impacts on subsurface moisture distribution and salt migration in response to the evaporation. The results also suggested that the presence of subsurface water replenishment to the evaporation zone tended to produce a steady evaporation rate at the ground surface.

1. Introduction

Soil water salinization has been recognized as a serious environmental problem adversely impacting environment and ecosystems. The increase in salinity would deteriorate water quality used for drinking and irrigation. In Australia, more than 60% of the 20 million ha of crop soils are sodic and salinization of land has become a major issue in irrigation water management (Rengasamy, 2002, 2006). Soil salinization can also cause an alteration of the ecosystem as many freshwater plants are not resistant to saltwater, and thus they would die and/or be overtaken by salt-tolerant plants such as spartina, an invasive species in Northern America (Vasquez et al., 2006). As evaporation causes predominantly the water to evaporate leaving the salt behind, even minute amounts of solutes in water could result in highly saline conditions if the evaporation is severe. In this case, the salt source for soil salinization, could be from rainfall, rock weathering, saltwater intrusion, or chemical contamination due to heavy use of mineral fertilizer. In arid and semi-arid regions, saline lakes would typically form due to rare precipitation events and high rates of evaporation. An example is Lake Eyre, a great salt lake in central South Australia, with a total area of 3700 square miles (Bonython, 1965).

In the last two decades, efforts have been dedicated on quantification of evaporation and its associated impacts on subsurface flow pattern and solute fates (Mahfouf and Noilhan, 1991; Wooding et al., 1997a; Wooding et al., 1997b; Boufadel et al., 1999b; Mohamed et al., 2000; Yanful and Mousavi, 2003; Il'Ichev et al., 2008; Qiu and Zhao, 2010; Shimojima et al., 2013), which are critical for reclamation, improvement and management of saline soils.

Evaporation over bare ground soil involves a complex water vapor and heat exchange between the ground surface and the atmosphere (De Vries, 1958; Mahfouf and Noilhan, 1991). It has become evident that the vapor transport due to both diffusion and advection should be considered (Cahill and Parlange, 1998; Parlange et al., 1998). These studies noted that not accounting for vapor transport underestimated the extent of water evaporation by up to 30% (Westcot and Wierenga, 1974; Cahill and Parlange, 1998). Thus, modeling evaporation could involve solving a set of differential equations for water and energy (heat) along with considerations for various means of transport. However, the

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impact of this enhanced evaporation (due to vapor transport) is typically limited to the top 10 cm of most soils (e.g., Parlange et al., 1998; Bittelli et al., 2008). Therefore, one could use a "mass transfer formulation" to simplify the approach by assuming that the water flux is proportional to the difference in moisture between the atmosphere and the pore space, with a proportionality constant that capture in an empirical means the physics of the problem. This is known as the "bulk aerodynamic method" (Mahfouf and Noilhan, 1991; Vandegriend and Owe, 1994; Mahrt, 1996), which provides an explicit relation between the evaporation flux at ground surface and the near-surface atmospheric water content. Using this approach, the specific humidity of the ground surface is required to estimate the evaporation rate, but the approach provides an explicit relation between near-surface humidity and the evaporation flux, which is desired. A simpler approach consists of estimating the maximum flux that the soil could supply or the maximum rate that the atmosphere would demand (Mahrt and Ek, 1984; Wetzel and Chang, 1987; Chattopadhyay and Hulme, 1997; Zarei et al., 2009). As this simple approach does not account for the interaction between surface moisture and atmospheric conditions, the bulk aerodynamic method is adopted herein. Another justification for using the bulk aerodynamic method is that our main goal is to investigate subsurface hydrodynamics due to a gradual (i.e., realistic) evaporation, and not to predict evaporation flux nor to estimate the maximum possible evaporation rate.

Coupling evaporation to a comprehensive model of water of subsurface hydraulics (water flow) and hydrodynamics (solute transport) would enable accurate evaluation of both evaporation and subsurface transport processes. Wooding et al. (1997a) and Wooding et al. (1997b) proposed a two-dimensional numerical model and Hele-Shaw cell experiments to investigate groundwater convection and associated salt fingers' evolution below evaporating salt lakes. Their results indicated that for large saline lakes, the stability of the saline boundary layer can be parameterized by traditional Rayleigh criteria, in which the aquifer permeability and the evaporation rate from the lake bed are principal controlling factors; meanwhile, the evolution of salt finger started at the leading edge of the saline layer and developed as a train of growing plumes. In their work, a uniform evaporation rate was assumed at the surface of the lake; meanwhile, the aquifers were assumed to be saturated, and thus capillarity properties were not accounted for. The evolution of salt fingers in evaporating salt lakes has also been characterized by other studies (Gieske, 1996; Simmons et al., 1999; Zimmermann et al., 2006; Wooding, 2007).

Boufadel et al. (1999b) revisited the Elder problem (the experiment of Elder (1967)) while considering capillarity. A two-dimensional finite element model MARUN was used to simulate density-dependent flow and solute transport in variably saturated porous media (Boufadel et al., 1999a; Boufadel, 2000). They found that the subsurface salinity distribution is greatly affected by the distance between the water table and the ground surface and by the height of the static capillary fringe (the capillary fringe is the zone of considerable moisture above the water table). Il'Ichev et al. (2008) developed a one-dimensional model to evaluate the instability of the salinity profile during evaporation of saline groundwater. In their model, a sharp evaporation–precipitation front was posited to separate regions of the ground saturated with air–vapor mixture from those with saline water. The equilibrium thermodynamic relations between air and vapor were used at the evaporation boundary. The simulation results of Il'Ichev et al. (2008) showed that "salt fingering" (Schincariol et al., 1994; Wooding et al., 1997a) is unlikely to occur in low-permeability soils, but is likely in high-permeability (sandy) sediments under conditions of relatively low evaporative upward flow. Although the interaction between air and ground surface was considered at the evaporation boundary (in other words, the evaporation flux was determined by atmospheric and soil properties), the model developed in Il'Ichev et al. (2008) is one dimensional, which could not thoroughly represent subsurface flow pattern and solute distribution in response to evaporation.

The objective of this paper is to investigate the hydrodynamics in variably-saturated porous media (i.e., accounting for capillarity) using a comprehensive approach that couples evolving evaporation to subsurface hydrodynamics. We believe that such is a natural progression on existing works, and the findings could provide insights on the evolution of evaporation fluxes to the atmosphere, which could be useful for forecasting for agricultural management (Cao et al., 2014; Shomar et al., 2014) and global climate change studies (Chattopadhyay and Hulme, 1997; Karl et al., 2009). The two-dimensional finite element model MARUN was used to simulate density-dependent flow and solute transport in variably saturated porous media (Boufadel et al., 1999a; Boufadel, 2000). The bulk aerodynamic formulation (Nappo and Carmen, 1975; Kondo et al., 1990) was implemented as a module in the MARUN model to simulate the temporal evolution of the evaporation rate at ground surface. The layout of the paper is as follows: The conceptual modeling approach is provided to address the governing equations of MARUN and the bulk aerodynamic approach. This includes determining the domain properties and boundaries. The numerical implementation is then presented. The base–case simulation results are presented, including transient evaporation rate, subsurface water flow pattern, moisture distribution profile and salt migration. Key controlling factors likely affecting this system are examined, and they include the saturated hydraulic conductivity, capillary drive, relative humidity in the air, and subsurface water replenishment to the evaporation zone (e.g., assuming a constant water table in the vicinity of the evaporation zone). The simulation results are analyzed to generate insight into the complex behavior of subsurface flow and associated solute fate under the influence of evolving evaporation flux from the ground surface.

2. Numerical approach

2.1. The MARUN model

Numerical simulations were conducted using the MARUN (MARine UNsaturated) model, which can simulate density-dependent flow and solute transport in variably saturated porous media, taking into account the effects of salt concentration on water density (Boufadel et al., 1999a; Boufadel, 2000). The MARUN model has been verified and validated extensively in previous studies (Guo et al., 2010; Li and Boufadel, 2010; Xia et al., 2010; Geng et al., 2014b; Geng and Boufadel, 2015).

2.2. Bulk aerodynamic model

The evaporation flux, E_g, was calculated based on the bulk aerodynamic approach, which can be expressed as follows (Mahfouf and Noilhan, 1991):

$$E_g = \frac{\rho_a}{R_{\text{air}}}(q_g - q_a), \tag{1}$$

where ρ_a is the air density [M L^{-3}], q_a is the air specific humidity [–], R_{air} is the aerodynamic resistance [T L^{-1}], expressed as Liu et al. (2006):

$$R_{\text{air}} = 94.909 U_z^{-0.9036}, \tag{2}$$

where U_z is wind speed [L T^{-1}] at the atmospheric reference level ($\sim$2 m above the soil surface). The surface specific humidity q_g can be expressed as (Lee and Pielke, 1992):

$$q_g = \alpha_1 q_{\text{sat}}(T_s), \tag{3}$$