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Modeling shallow water table dynamics under subsurface irrigation and drainage

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ABSTRACT

We develop conceptual and numerical models of water table dynamics under a subsurface irrigation and drainage system. The numerical model is implemented with distinct drainable and fillable porosity parameters that are estimated by accounting for the unsaturated zone fluxes to and from the shallow water table. The model was applied to two field sites under subsurface irrigation and drainage system in northeast Florida to simulate water table dynamics during potato growing seasons in 2010 and 2011. Simulated water table elevations showed a close agreement with the observed water table dynamics in the fields during both growing seasons. Furrows that act as shallow drains in the field facilitated rapid drawdown of the water table after rainfall events, while the outer, deeper ditches provided little drainage of water from the root-zone. Intermittent irrigation regimes, although could substantially reduce surface runoff from the fields, resulted in relatively deeper water tables during the growing season, suggesting a potential trade-off between water deliveries and root-zone soil moisture availability.

1. Introduction

Shallow water tables are found in many areas of the world where the field hydrology differs significantly from that of well drained soils. The growth and development of plants in shallow water table environments are controlled by the dynamics of the phreatic surface (Bierkens, 1998; Nachabe et al., 2005; Hilberts et al., 2005). In humid areas such as Florida, where the groundwater level is naturally shallow, even a small amount of precipitation may quickly raise the water table to the surface (Gillham, 1984; Hilberts et al., 2007). Crop production in these areas therefore requires an efficient drainage system to quickly lower the water table and avoid waterlogging stress to plants. Water table drawdown is normally enabled by constructing ditches and drains in the field. However, because drains and ditches hasten the drainage process, the soil in the crop root-zone is likely to dry quickly. Therefore, many of these subsurface drainage systems are operated as water table management systems, which can be used for controlled, subsurface drainage and irrigation whenever necessary.

While maintaining the water table near the crop root-zone facilitates unrestricted moisture supply to crop roots throughout the growing season, it requires continuous pumping of water to the field. After the water table rises close to the root-zone, much of this water is lost from the field as runoff because the water supply rate exceeds the rates of infiltration and evapotranspiration, resulting in poor irrigation efficiency. Due to rapid depletion of groundwater, the sustainability of such irrigation systems in shallow water table areas is questionable. Sustainable alternatives that can reduce water deliveries without compromising crop yields are required. However, detailed understanding of the water table response to irrigation and drainage, crop evapotranspiration, and rainfall during the crop growing season is critically important for evaluating the feasibility of potential water management alternatives. Our goal is to develop and apply conceptual and numerical models to study the water table dynamics associated with specific scheduling of irrigation and drainage under water table management systems.

Most studies of subsurface drainage of agricultural lands with shallow water tables are based on the Dupuit–Forcheimmer (D–F) theory that describes groundwater flow in unconfined aquifers (e.g., van Schilfgaarde, 1974; Moody, 1966; Skaggs, 1991; Verhoest and Troch, 2000). The D–F assumption states that in shallow, unconfined aquifers with small water table inclinations, the vertical hydraulic gradient can be neglected and the flow can be assumed to occur entirely in the horizontal direction. Adoption of these assumptions results in Boussinesq-type groundwater flow models, also known as the hydraulic groundwater model (Brutsaert, 2005).

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The Boussinesq-type groundwater flow models typically consist of a storage parameter that enables the expression of aquifer moisture storage in terms of water table elevation. The response of the water table to groundwater, evapotranspiration and recharge fluxes is therefore controlled by this parameter. When the water table is receding, the parameter is called drainable porosity (λ_d) and is estimated as the change in aquifer storage per unit decline in water table depth (Bouwer, 1978; Freeze and Cherry, 1979). In the case of a rising water table, the parameter controlled by the moisture-deficit of the aquifer and is fillable porosity (λ_f, Healy and Cook, 2002; Park, 2012; Acharya et al., 2012).

The storage parameters of unconfined aquifers are largely determined by the capillary properties and moisture status of the soil (Healy and Cook, 2002; Gillham, 1984; Childs, 1960). However, in most previous studies of water table response to subsurface drainage and irrigation, these parameters are treated as constants (e.g., Skaggs, 1991; Singh and Jaiswal, 2006). Implementing a constant drainable porosity parameter can introduce substantial errors in estimated water table rise or drawdown rates, as the effect of unsaturated flow, due to ET and recharge, is not incorporated (Acharya et al., 2012). While some authors have incorporated the effect of unsaturated zone soil moisture status during estimation of drainable porosity, they assume that a single λ_d could sufficiently describe the dynamics of shallow water tables (e.g., Hilberts et al., 2005; Laio et al., 2009; Nachabe, 2002). In a recent study, Acharya et al. (2012) showed that, when unsaturated zone fluxes (e.g. ET or recharge) are present, λ_d and λ_f may have different values for a given water table elevation and presented a modified model that implements distinct λ_d and λ_f parameters to describe water table movement.

In this study, we adopt the numerical model presented by Acharya et al. (2012) to simulate the water table dynamics under a subsurface irrigation and drainage system common throughout Florida. The model is implemented with distinct, flux-dependent λ_d and λ_f parameters, in contrast to the conventional Boussinesq model with only one λ_d parameter, treated either as a constant or estimated from the hydrostatic soil moisture profile. The dual parameter model is theoretically more robust and has been shown to better represent the water table dynamics in the field, as it appropriately accounts for the effects of various water budget components on water table movement (Acharya et al., 2012).

Using the numerical model, we also evaluate the effectiveness of water table management system in maintaining the desired water table elevations during cropping periods. We describe conceptual models of water table movement under subsurface irrigation and drainage. These water table management systems typically consist of fields with outer ditches and a number of small, surface water furrows to facilitate both irrigation and drainage (Fig. 1). Appropriate boundary conditions are then applied to solve the governing equations that describe water table movement through the soil profile during irrigation and drainage. Simulated water table elevations are then compared with data collected from two potato fields managed under subsurface irrigation and drainage in northeast Florida. We assess the sensitivity of water table movement to changes in soil parameters, such as K_s and field characteristics. We also evaluate potential alternatives to the water management system using the water table dynamics model.

2. Materials and methods

2.1. Study sites

The field site is located in northeast Florida (29.694′ N, 81.446′ W) near the Atlantic coastline (Fig. 1). The flat, low (<10 masl) landscape with shallow groundwater level (<2 m) in the area requires appropriate water table management measures during crop growing seasons. This is achieved by constructing ditches (1–2.5 m deep) and furrows in the field, using the method conventionally known as “seepage irrigation”. Each seepage irrigated field is divided into approximately 18–20 m wide crop beds (with each bed containing 18–20 crop rows) separated by smaller furrows approximately 0.30–0.50 m wide and 0.2–0.5 m deep (Fig. 1).

During irrigation, water is conveyed to the furrows by means of individual supply pipes. Water infiltrates from the furrows vertically toward the water table while the excess water flows surficially out to the deeper ditches. The ditches are equipped with check gates to raise the water level simultaneously. The rise in ditch water level, coupled with continuous water supply to the furrows, raises the water table close to the crop root-zone. Moisture supply to crop roots occurs via capillary action and subsurface lateral flow (Pitts and Smajstrla, 1989; Smajstrla et al., 2000; Munoz-Arboleda et al., 2008; Acharya and Mylavarapu, 2011). The ultimate water table elevation in the crop beds is determined by the water level in the ditches, which is adjusted accordingly throughout the growing season. Water supply in the furrows is turned-off and water level in the ditches is lowered during rainfall events to facilitate quick water table drawdown. Because the natural groundwater table in the area is close to the land surface, there is little percolation loss and the subsurface flow is predominantly in the lateral direction.

2.2. The model

2.2.1. Conceptual models: irrigation and drainage

At the start of irrigation events, water is supplied to the furrows while the water level is raised in the ditches from an initial height, h_0 (Fig. 2). After the infiltration wetting fronts below the furrows reach the saturated zone, water begins to flow laterally, thus increasing the water table elevation. The initial water table profile in Fig. 2 is assumed to be horizontal. While the water table in most subsurface drained fields normally tends to occur as a curved profile (Skaggs, 1973; van Schilfgaarde, 1974), the horizontal initial profile is a reasonable assumption for our field sites due to the large distance between the ditches (normally >250 m).

Prior to anticipated rainfall events, water supply to the furrows is halted and the water level in the ditches is lowered, which triggers subsurface drainage and consequent water table drawdown. Subsurface drainage in the field occurs in two distinct phases, depending on water table elevation, as depicted in Fig. 3. If the water table is above the depth of furrows, both the outer ditches and the furrows contribute to drainage. This results in rapid drawdown during the initial hours after cessation of rainfall. This is termed as the phase-1 drainage (Fig. 3). Once the water table recedes below the depth of the furrows, subsurface drainage is contributed entirely by the outer ditches, thus resembling a typical ditch drainage system. This is termed as phase-2 drainage (Fig. 3). Phase-2 drainage is normally much slower than phase-1 drainage due to the large distance between the two ditches, as compared with the distance between the furrows.

2.2.2. Governing equations

Movement of the shallow water table during subsurface drainage and irrigation is described by the one dimensional Boussinesq equation. Acharya et al. (2012) modified the original Boussinesq equation by implementing the distinct λ_d and λ_f parameters that are estimated by accounting for the vadose zone fluxes to and from the water table. The governing equations for water table movement are expressed as:

$$\frac{dh}{dt} = \frac{1}{\lambda_d}\left[K_s\left(\frac{d}{dx}\left(h\frac{dh}{dx}\right)\right)\right] - R_e\left(\frac{1}{\lambda_d} - \frac{1}{\lambda_f}\right) - \frac{ET}{\lambda_d} \quad (1)$$