Journal of Hydrology 528 (2015) 397–407

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Effects of vadose zone on groundwater table fluctuations in unconfined aquifers

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ARTICLE INFO

Article history:
Received 7 January 2015
Received in revised form 26 May 2015
Accepted 22 June 2015
Available online 26 June 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Ming Ye, Associate Editor

Keywords:
Groundwater fluctuation
Boussinesq equation
Vadose zone
Capillary fringe
Analytical solution

SUMMARY

Above a shallow unconfined aquifer, a considerable amount of water is stored in the vadose zone. Through water exchange with the underlying unconfined aquifer, the vadose zone affects the groundwater table dynamics and overall behavior of the aquifer. In this paper, we examine tide-induced groundwater table fluctuations in unconfined aquifers influenced by vadose zone of finite thickness. Under the condition of small aquifer thickness (D) compared with the groundwater wavelength (L) (i.e., $\mu^2 = (D/L)^2 \ll 1$) and small boundary oscillation amplitude (a) (i.e., $\varepsilon = a/D \ll 1$) (where μ^2 and ε are two parameters), an approximate analytical solution was derived to quantify systematically the vadose zone effects, with a particular consideration of capping by the ground surface, i.e., the upper boundary of the vadose zone. Depending on the extent to which the capillary rise is truncated by the ground surface, the vadose zone enhances the groundwater table fluctuations in an unconfined aquifer. However, the mean groundwater table height and exchange between surface water and groundwater are reduced due to the presence of the vadose zone. These effects are intensified with increased capillary rise, but weakened as the vadose zone thickens. This study provides a criterion for assessing the importance of vadose zone in modulating the response of unconfined aquifers to low-frequency forcing oscillations such as tides.

1. Introduction

Subjected to oceanic oscillations such as tides and waves, groundwater table fluctuates in coastal unconfined aquifers. This dynamic behavior significantly affects water and nutrient exchange between the land and ocean. The fluctuating groundwater table also alters the eco-environmental condition of coastal aquifers, including the moisture content in the overlying vadose zone (Kuang et al., 2013; Xin et al., 2013b).

As an important natural phenomenon, groundwater table fluctuations in coastal unconfined aquifers have been widely examined via field investigations (Austin et al., 2013; Cao et al., 2012; Horn, 2006), numerical simulations (Cartwright et al., 2006; Kong et al., 2010; Zhu et al., 2012), analytical solutions (Jeng et al., 2005; Jiao and Tang, 1999; Nielsen et al., 1997; Teo et al., 2003) and various studies incorporating different methods (Guo et al., 2010; Li et al., 2008, 2000a; Li and Jiao, 2003; Song et al., 2007; Stojsavljevic et al., 2012). Because analytical solutions can provide directly mechanistic insights into groundwater table fluctuations, this approach has been the focus of numerous recent investigations (Horn, 2006). Most existing analytical solutions are based on 1-D (one dimensional) governing equations for describing cross-shore groundwater table fluctuations in coastal unconfined aquifers.

The traditional Boussinesq equation only considers water movement in the saturated zone. Using this equation, various numerical and analytical studies have been conducted to investigate the groundwater table fluctuations affected by various geometric and oceanic forcing factors, e.g., sloping beach (Nielsen, 1990) and spring-neap tides (Li et al., 2000c). However, these studies neglected the effect of vadose zone, which is expected to alter the water movement in the saturated zone and thus groundwater table fluctuations (Cardenas, 2010; Cartwright et al., 2005; Moench, 2008). Situated above the phreatic surface (water table), the vadose zone includes a capillary fringe (fully saturated zone with pressure less than the atmospheric pressure) and unsaturated zone (partly saturated zone with pressure also less than the atmospheric pressure).

The traditional Boussinesq equation, based on the Dupuit–Forchhimer assumption, is relatively simple and readily to be employed to examine groundwater dynamics in various environments. The assumption of negligible vadose zone effects is

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http://dx.doi.org/10.1016/j.jhydrol.2015.06.045
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reasonable only when the length scale of capillary rise is significantly smaller than any other length scales (Gillham, 1984). Barry et al. (1996) pointed out that, with no consideration of the vadose zone effects, the calculation of groundwater change and water storage in a unconfined aquifer could be substantially wrong. The vadose zone can store or release water and thus alter the groundwater table fluctuations. Parlange and Brutsaert (1987) modified the traditional Boussinesq equation to take into account the vertical water exchange between saturated and vadose zones. By assuming a vadose zone of infinite thickness, they introduced an equivalent capillary fringe thickness (B), which represents the total water volume in the vadose zone. Through adjusting the water in this "capillary fringe", Parlange and Brutsaert (1987) introduced an additional term into the Boussinesq equation to account for the mass transfer across the groundwater table. This method was widely used in the subsequent studies. Barry et al. (1996) solved analytically Parlange and Brutsaert's (1987) equation subject to a periodic boundary condition and quantified the effects of vadose zone. Li et al. (1997) adopted a similar correction term in a numerical model and found that the damping rate of high-frequency oscillations propagating inland quickly reached an asymptotic finite value and the groundwater wave propagated much farther inland. Li et al. (1997) introduced a coastal aquifer response number, C_{AR} $(K_s/B\omega)$, to quantify the response time of capillarity in comparison to the time scale of groundwater fluctuations. It was suggested that as the C_{AR} decreases (e.g., low permeability and high-frequency forcing), the vadose zone would play a more important role in altering the groundwater table fluctuations. Li et al. (2000b) further incorporated the approximation of capillary fringe into an intermediate-depth Boussinesq equation (Nielsen et al., 1997) considering the combined effects of capillarity and vertical flow.

The work, based on Parlange and Brutsaert's (1987) method, showed that the effects of the vadose zone enhance the inland propagation of groundwater wave induced by high-frequency fluctuations. However, the results do not show much influence of vadose zone in regulating low-frequency wave propagation in coarse sands. This is inconsistent with the results from Nielsen and Perrochet's (2000) experiments, which found significant effects of vadose zone on groundwater table fluctuations in unconfined aquifers subjected to low-frequency tidal oscillations (i.e., for relatively large C_{AR} values). Further research demonstrated that the capillarity affects water table dynamics over a much wider range of frequency, including the tidal frequency (Werner and Lockington, 2003). Nielsen and Perrochet (2000) introduced the concept of complex porosity to consider the measured damping and phase lag of total moisture oscillations in terms of derivatives of the groundwater table height.

Recently, Cartwright (2014) examined soil moisture-pressure dynamics in a vertical sand column above a water table undergoing simple harmonic oscillations. It was found that for long oscillation periods (large C_{AR} value), the pore-water pressure in the unsaturated zone has sufficient time to respond to the water table motion and satisfies approximately a hydrostatic pressure distribution. This, to some extent, challenges the capillarity correction made by Parlange and Brutsaert (1987), particularly for low-frequency groundwater fluctuations in shallow unconfined aquifers.

Cartwright et al. (2004) pointed out that in a shallow aquifer, the capillary rise (fringe) is likely to be truncated by the ground surface, resulting in change of the overall water storage in the vadose zone. Under the hydrostatic pressure assumption (large C_{AR} value and vertical flow neglected), Xin et al. (2013a) integrated 2-D Richards' equation along the vertical direction and obtained a simple 1-D equation. By fixing the upper bound of the integral, the truncation effect of ground surface on the vadose zone was considered. This 1-D model was subsequently improved by Kong et al. (2013) who used an additional correction term to include the effects of vertical flow in both the saturated zone and the vadose zone of finite thickness. Kong et al. (2013) further derived an analytical solution, which shows that the storage capacity of the vadose zone permits groundwater wave to propagate more readily than predicted by the traditional Boussinesq equation. Furthermore, the new solution reveals that for low-frequency groundwater table fluctuations, a capping effect of the vadose zone associated with the finite thickness alters significantly the behavior of the groundwater table fluctuations.

While the model developed by Kong et al. (2013) represents reasonably well the effects of the vadose zone on groundwater table fluctuations, the non-hydrostatic pressure correction term developed in Kong et al. (2013) do not satisfy the mass conservation principle as the non-hydrostatic pressure in the vadose zone does not respond to the drying and wetting process. Moreover, this study and others (Li et al., 2000b; Nielsen et al., 1997) did not examine the overall groundwater-surface water exchange across the aquifer boundary (e.g., beach surface). It remains unclear how the vadose zone affects the overall groundwater-surface water exchange, which is of importance to coastal eco-environments (Marani et al., 2010; Moffett et al., 2012, 2010).

In order to gain further insights into the effects of vadose zone on groundwater flow in unconfined aquifers, we developed new governing equations for the vadose and saturated zone in this paper under the condition of small aquifer thickness (D) compared with the groundwater wavelength (L) (i.e., $\mu^2 = (D/L)^2 \ll 1$) and small boundary oscillation amplitude (a) (i.e., $\varepsilon = a/D \ll 1$) (where μ^2 and ε are two parameters). For the saturated zone, we solved the Laplace equation that accounts for both the horizontal and vertical flow. The two sets of governing equations for the vadose and saturated zone respectively were combined to simulate the groundwater fluctuations in unconfined aquifers. The new model, with an approximate analytical solution derived, satisfied the mass conservation principle. This paper is organized as follows: in Section 2, we describe the conceptual and numerical models as well as the analytical approximation. In Section 3, the effects of vadose zone are analyzed in detail. In Section 4, a sensitivity analysis is conducted to examine the effects of soil property and aquifer geometry on the mean groundwater table height and overall water exchange between surface water and groundwater. Conclusions are drawn in Section 5.

2. Conceptual and numerical Models

2.1. Conceptual model

The aquifer is assumed to be homogeneous and isotropic, as represented by a rectangular domain perpendicular to the shoreline (ABCD, Fig. 1). BC is the aquifer platform and AD is the impermeable base. Boundary CD is assumed to be an inland boundary infinitely far from the shoreline and thus not affected by oceanic oscillations. To readily derive an analytical solution, the seaward boundary AB is assumed to be vertical, which gives a fixed (simplified) boundary for the model. With a vertical beach, the effect of seepage face is negligible so the groundwater table is coupled with the surface water level at boundary AB. It is worth noting that sloping beaches are common in natural coasts. Here, we neglected the effect of sloping beach and associated moving boundary, as done in most previous studies (Jeng et al., 2002; Li and Jiao, 2003; Xia et al., 2011), to focus on the effect of vadose zone in the first instance. Also note that although the density effect due to the presence of seawater can influence significantly nearshore groundwater flow, it is of secondary importance for water table fluctuations associated with inland propagation of tidal oscillations in coastal aquifers and has been