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Groundwater response to tidal fluctuation and rainfall in a coastal aquifer

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SUMMARY

This paper presents an analytical solution generated by linearizing the one-dimensional non-linear Boussinesq equation to characterize the variation of groundwater level induced by tidal waves and rainfall in a coastal unconfined sloping aquifer. The area of the coastal aquifer is divided into 2 zones – the coastal zone of rainfall and the inland zone of non-rainfall. The derivation of the solution is based on the Dupuit–Forchheimer assumptions of a wide range of problems in unconfined groundwater flow and the analytical solutions of coastal and inland water tables of both zones are obtained. The results indicate that the effects of the bottom slope of the aquifer and the beach slope on the groundwater fluctuation are substantial in the unconfined aquifer. Large rainfall intensity with tidal waves will enhance the fluctuation significantly, but less effect on the fluctuation is found for the cases of steeper sloping bottom under the same rainfall condition.

1. Introduction

The groundwater table in coastal unconfined aquifers is typically affected by rainfall recharge and artificial pumping, and fluctuates based on tides and ocean waves. The data of groundwater fluctuation are generally acquired from observation wells; however, setting up numerous observation wells along beaches is difficult and expensive. Familiarity with the coastal aquifer properties enables mathematical models to predict groundwater fluctuations, and the results can be considered for managing groundwater systems.

Most studies modeling groundwater flow inside aquifers have been based on the Boussinesq equation, which assumes the vertical flow negligible. Since the equation is nonlinear, most researchers solved it by a perturbation method. For example, Dagan (1967) presented a second-order theory to discuss shallow free-surface flow in porous media by employing the perturbation method to solve the nonlinear equation, and obtained an analytical solution to describe the flow in an aquifer. By employing the theory of Dagan (1967), Parlange et al. (1984) presented a second-order solution to the nonlinear equation for groundwater fluctuations in coastal aquifers with vertical beaches, and compared the results with numerical solutions. Later, Nielsen (1990) considered the beach slope effect and obtained a second order solution to the tide-induced groundwater table problem in coastal aquifers. However, the solution does not satisfy the seaward boundary, and the error increases as the beach slope decreases. To overcome the boundary problem that Nielsen (1990) encountered, Li et al. (2000) presented a moving boundary method and generated an analytical solution to beach water table fluctuations. When the beach slope is vertical, both solutions presented by Nielsen (1990) and Li et al. (2000) degenerate into a first-order solution; therefore, their solutions are not complete nonlinear solutions.

According to the field measurements of Nielsen (1990), the real and imaginary parts of the wave number are observed to be different. Also, the deviations of the observations from the predictions by the linearized Boussinesq equation (i.e. diffusion equation) are most likely due to the nonlinear nature. Barry et al. (1996) and Nielsen (2009) commented this difference is due to either capillary effects or effects of aquifers of intermediate depth, which is also delineated in the work of Nielsen et al. (1997). Jeng et al. (2003) also proposed a second-order solution that satisfies the coastal boundary and increases the accuracy of the water table estimation. Lately, Asadi-Aghbolaghi et al. (2012) presented analytical solutions of groundwater response to tidal fluctuation in a sloping leaky aquifer system, comprising an upper unconfined aquifer, an aquitard, and a lower confined aquifer. Nevertheless, only the

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vertical coastal beach was discussed in their study, and rainfall was not taken into account.

In the real world, the boundary between the ocean and an aquifer is generally non-vertical, and the bottom of an aquifer is generally non-horizontal. Therefore, a coastal unconfined aquifer usually has a sloping beach face subjected to the periodic ocean forcing. Li et al. (2008) found that the major portion of the offshore groundwater discharge usually occurs in the shallow part of the submerged beach, and remarked that smaller beach slopes, smaller onshore freshwater recharges. Guo et al. (2010) studied the hydrodynamics in a gravel beach and discussed its impact on the Exxon Valdez oil. Li and Boufadel (2010) proceeded with a tracer study in an Alaskan gravel beach and its implications on the persistence of the Exxon Valdez oil. Later, Li and Boufadel (2011) carried on their study on a long-term persistence of oil from the Exxon Valdez spill in two-layer beaches. In the meantime, Xia et al. (2010) conducted a field study and six numerical simulations of exchange flow between the beach and the sea due to the tide effect. They thought that the major reason for the presence of oil in the lower layer is that it gets entrapped there by the capillary forces of the fine-grained sediments. Later on, Xia and Li (2012) proceeded with a combined field and modeling study of groundwater flow in a tidal marsh.

Near the coastal areas, the variation of groundwater table is not only affected by the tidal waves, but also affected by the rainfall. To manage the groundwater in the coastal aquifers, it is, of course, significant to consider these two factors together. Moreover, a coastal beach is not always vertical, and the impermeable bottom of the aquifer is not always horizontal. Therefore, groundwater fluctuations due to the beach slope effect and both upward and downward bottom of aquifers are examined. In the following sections, the Boussinesq equation and proper boundary conditions are described first, and they are then linearized and non-dimensionalized. Finally, after the analytical solutions are verified by previous experimental data and present numerical solutions, these foregoing effects on groundwater table are investigated.

2. Mathematical formulation

Fig. 1 depicts groundwater level fluctuations under the effects of tidal waves and rainfall in a coastal unconfined aquifer with consideration of the beach slope β and the bottom slope θ. It should be noted that the range of rainfall is equal to the decay length ℓ. If the rainfall occurs more inland than the decay length, the groundwater table outside the region of the decay length is only affected by the rainfall effect, and the variation of groundwater table is smaller than that inside the region of the decay length. If the rainfall occurs more seaward than the decay length, the groundwater table outside the region of the rainfall is only affected by the tidal waves effect, and the variation of groundwater table will also get smaller. The latter condition is not worth being discussed. The former condition covers the assumption, the range of rainfall being equal to the decay length. Therefore, we assume that rainfall occurs between the coastline and the location of the decay length, and merely consider the serious variation of groundwater table under the mutual effects of tidal waves and rainfall.

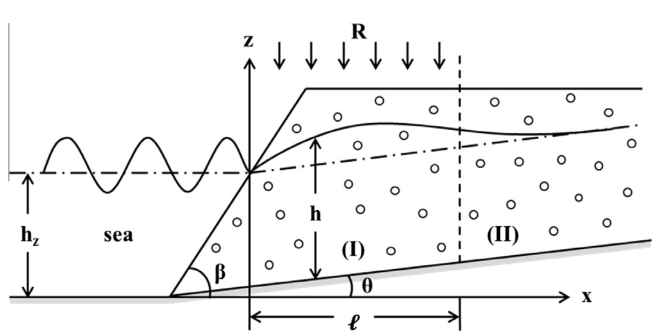

Fig. 1. Schematic diagram. h is the water table height; R is the rainfall intensity; θ is the inclined angle of the impervious bed; β is the angle of the beach slope; h_z is the average height of mean sea water level; ℓ is the decay length. (I) Denotes region 1, rainfall area; (II) denotes region 2, null rainfall area.

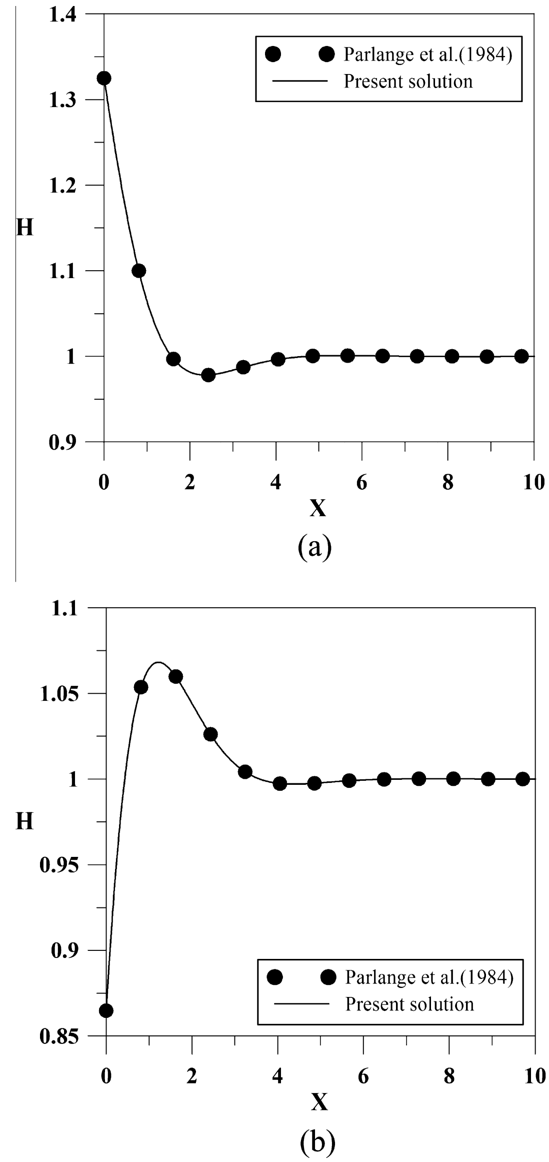

Fig. 2. Comparison with the solution of Parlange et al. (1984) (a) $T = 0$ and (b) $T = 2$ with $\varepsilon = 1$.

2.1. Governing equation and boundary conditions

In an unconfined aquifer, the Boussinesq equation is typically employed to describe groundwater flow; therefore, referring to the study of Chapman (1980), the governing equation can be represented as

$$\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + \tan\theta\left(\frac{\partial h}{\partial x}\right) = \frac{S}{K\cos^2\theta}\left(\frac{\partial h}{\partial t}\right) - \frac{R}{K\cos^2\theta} \tag{1}$$