



# Numerical modeling of the effects of beach slope on water-table fluctuation in the unconfined aquifer of Donghai Island, China

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**Abstract** Beach slope is an important factor influencing the tide-induced water-table fluctuation in coastal unconfined aquifers. However, research about the effect of beach slope on water-table fluctuation is limited, especially for gentle slopes. To understand the effect of beach slope on beach groundwater dynamics, a numerical model, calibrated with field monitoring data from Donghai Island (China), was built to simulate the observed water-table fluctuation. Sensitivity analysis was performed to assess the sensitivity of water-table fluctuation to the parameters and conceptualization of the model. The analysis indicated that the water-table fluctuation was especially sensitive to the hydraulic conductivity and specific yield, and the horizontal length of the model domain could affect the amplitude of the water-table fluctuation. Moreover, it is found that the variation of the amplitude is more evident when the beach-slope angle changes in the range from 1.5 to 45°, especially in the range from 1.5 to 5°. Understanding the effect of beach slope on tide-induced water-table dynamics could help modelers deal with the slope better in their beach groundwater flow models.

**Keywords** Beach slope · Sensitivity analysis · Water-table fluctuation · Numerical modeling · China

## Introduction

Coastal groundwater dynamics is a very interesting and complicated research topic because of the interactions of freshwater and seawater under tidal forcing. Understanding coastal groundwater dynamics is very important for analyzing many environmental and ecological problems such as remediation of oil spills on beaches (e.g., Guo et al. 2010; Li et al. 2007c; Li and Boufadel 2010; Li and Boufadel 2011; Xia et al. 2010b), ecology and biodiversity of nearshore areas (e.g., Cao et al. 2012; Carol et al. 2012; Kumar et al. 2012; Li et al. 2005; Miller and Ullman 2004; Robinson et al. 2007a, b; Xia and Li 2012), beach accretion and erosion (e.g., Horn 2002; Li L et al. 2002; Turner 1995), chemical transfer with seawater-groundwater circulation (e.g., Boufadel et al. 2011; Li et al. 1999; Li et al. 2008; Li and Jiao 2003a; Mao et al. 2006; Robinson et al. 2009), and saltwater intrusion (e.g., Ataie-Ashtiani et al. 1999; Boufadel et al. 1999; Boufadel 2000; Chen and Hsu 2004; Kuan et al. 2012; Mao et al. 2006; Narayan et al. 2007). The details are described as follows.

Li et al. (2007c) simulated beach-slope groundwater dynamics and obtained an optimal nutrient application strategy for remediation of oil. It was found that the beach slope could affect the nutrient injecting rate. Li and Boufadel (2010); Li and Boufadel (2011); Guo et al. (2010) and Xia et al. (2010b) found that water-table dynamics could affect the persistence of oil in a two-layered structure aquifer of Alaska, following the Exxon Valdez oil spill in 1989.

Miller and Ullman (2004) described the potential ecological role of submarine groundwater discharge (SGD) at Cape Henlopen, Delaware Bay, United States. Li et al. (2005) examined the tidal dynamics and aeration conditions for plant growth in a marsh and found the location with optimal aeration conditions. Robinson et al. (2007a, b) simulated the seawater-groundwater dynamic effect on submarine groundwater discharge (SGD) which plays an important role in coastal or estuary ecosystems (Church 1996; Lee and Kim 2007). Cao et al. (2012) found that tide-induced water-table fluctuation could influence soil conditions which, therefore, can affect the plant growth in Chongming Dongtan wetland, China. Carol et al. (2012) observed that the salinity of groundwater varies depending on the tide fluctuation, along

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with variation in the water table in the marsh area in the Ajó River, Argentina. Kumar et al. (2012) revealed that tidal fluctuation significantly affects the ionic signature of groundwater along with water-table fluctuation for a coastal unconfined aquifer in Japan. Xia and Li (2012) revealed that the aquifer shape could affect the seawater–groundwater circulation, which could affect survival of mangroves.

Turner (1995) reported a modelling study that included the effects of groundwater on swash sediment transport. Li L et al. (2002) simulated the effect of the water table on beach shape change. Horn (2002) reviewed research on beach groundwater dynamics and discussed the mechanisms for sediment transport.

Li et al. (1999) developed a theoretical model for submarine groundwater discharge and the associated chemical transfer to the ocean; this work analyzed the influence of beach slope on the estimated submarine groundwater discharge. Li and Jiao (2003a) analyzed the mechanism of the seawater–groundwater cycle in a multi-layered leaky aquifer system. Mao et al. (2006) revealed that the tidal dynamics could affect contaminant transport from the aquifer to the estuary, whereas Li et al. (2008) simulated the tidal effects on water exchange between groundwater and seawater and revealed that the beach slope could affect the size of salt-water plumes. Robinson et al. (2009) revealed that BTEX (benzene, toluene, ethylbenzene and xylene) may undergo significant attenuation in tidally influenced aquifers, while Boufadel et al. (2011) simulated the solute transport pattern during the tidal cycle.

Ataie-Ashtiani et al. (1999) and Mao et al. (2006) revealed that tidal activity enhances the seawater intrusion in unconfined aquifers, especially for a sloping beach and Ataie-Ashtiani et al. (1999) also revealed that the groundwater dynamics can affect the configuration of the interface, and the unconfined aquifer shape could affect the scale and dynamics of the seawater intrusion. Boufadel et al. (1999) developed a model for water flow and solute transport and studied the effects of the beach hydraulic and hydrodynamic properties on seawater intrusion. Boufadel (2000) carried out experimental and simulation works about the effect of tidal dynamics on seawater intrusion. Chen and Hsu (2004) determined, by simulation, that the shape of an aquifer could affect the intrusion of seawater and the velocity of intrusion, while Narayan et al. (2007) analyzed the effect of tidal fluctuation, aquifer properties and pumping rate on seawater intrusion and Kuan et al. (2012) determined the influence of tidal effects on the behavior of the seawater wedge in unconfined aquifers through both laboratory and numerical experiments.

Concerning the importance of understanding tide-induced groundwater dynamics, as noted already, numerous scholars have conducted a large number of studies (e.g., Cartwright et al. 2006; Cartwright et al. 2004; Dong et al. 2012; Geng et al. 2009; Guo et al. 2007; Jacob 1950; Li H et al., 2002; Li et al. 2006; Li et al. 2007a, b; Li and Chen 1991; Li and Jiao 2001; Li and Jiao 2002; Li and Jiao 2003b; Liu et al. 2008; Monachesi and Guarracino 2011; Tang and Jiao 2001; Turner et al. 1996; Vandenbohede and Lebbe 2007; Xia et al. 2007; Xia et al. 2010a) focusing on the dynamic

rules and mechanisms of tide-induced water-table fluctuation by using (1) experimental, (2) analytical, and (3) numerical methods:

1. With an *experimental system*, Cartwright et al. (2004) investigated the influence of a sloping boundary on water-table–tidal dynamics. Wu and Zhuang (2010) studied the tide-induced water-table fluctuation characteristics.
2. *Analytical methods* can reveal the governing parameters of the groundwater system and provide benchmarks for numerical solutions. Analytical methods are widely used to study tide-induced water-table fluctuation in coastal areas. The vertical beach model is widely used. For example, many scholars used a linearization of the Boussinesq equation to study the influence of tide on the water table of coastal regions (e.g., Chuang and Yeh 2007; Jacob 1950; Jeng et al. 2002; Jiao and Tang 1999; Li et al. 2001; Li and Jiao 2001; Li and Jiao 2002; Xia et al. 2007). Although the vertical beach model is still used, more scholars are gradually considering the non-linear Boussinesq equation and complex hydrogeological conditions in their research—for example, using second-order theory, Parlange et al. (1984) solved the non-linear Boussinesq equation subject for a tidal boundary condition, which can describe steady periodic motion in porous medium. Based on the work of Parlange et al. (1984), Song et al. (2007) obtained a new third-order perturbation solution of the non-linear Boussinesq equation for one-dimensional (1D) tidal groundwater flow in a coastal unconfined aquifer. Xia et al. (2010a) derived a new analytical solution for a tide-induced groundwater flow model with a vertical beach and a thin submarine outlet-capping. To investigate the effects of bottom slope on water-table fluctuation in coastal aquifers, Asadi-Aghbolaghi et al. (2012) developed a new analytical solution to describe water-table fluctuation in a sloping coastal aquifer system with a vertical beach. The results show that a greater bottom-slope onshore angle results in smaller amplitude of water-table fluctuation in an unconfined aquifer. Moreover, the time lag could reach the peak value when the bottom-slope angle is in the range between  $-5$  and  $0^\circ$  in the unconfined aquifer.

Although the vertical beach model is widely used, beaches are usually sloping, even mildly sloping. Tidal fluctuation on a sloping beach can form a moving aquifer boundary that will affect the dynamics of tide-induced water-table fluctuation. From the 1990s, research on water-table fluctuation dynamics in coastal unconfined aquifers with a sloping beach has been a research hot topic. Numerous analytical works have been conducted. For example, Nielsen (1990) solved an analytical solution to the 1D Boussinesq equation for a sloping beach case using a perturbation technique and showed that a sloping beach can produce an additional water-table overheight as the result of the asymmetry of the tidal infiltration/drainage process for a sloping beach. Li et al. (2000) developed a new perturbation approach for solving the moving boundary problem in tidal propagation in a coastal unconfined aquifer with a sloping beach. Considering the

sloping beach and aquifer bottom, Su et al. (2003) solved the linearized Boussinesq equation using the Fourier series solutions, while Teo et al. (2003) derived a new higher-order solution for tide-induced water-table fluctuation in a coastal aquifer with a sloping beach. The higher-order solution can be applied to all ranges of beach slope. The results show that the water table increases as beach slope decreases; however, there was no analysis of the beach slope effects on the amplitude of tide-induced water-table fluctuation. Jeng et al. (2005) derived a new two-dimensional (2D) analytical solution for tide-induced water-table fluctuation in a sloping beach; they analyzed the beach slope effects on the tide-induced water-table fluctuation and the analysis results showed that a steeper beach slope could reduce the tidal influence on water-table fluctuation. Singh and Jha (2012) adopted a data-driven approach for the analysis of tide-aquifer interaction dynamics in coastal aquifers.

3. Compared with the analytical method, the *numerical method* can generalize complex hydrogeological conditions, so the numerical method is also widely used in research projects on coastal hydrogeology. In the early time, a number of scholars had developed models for tide-induced water-table fluctuation in coastal unconfined aquifers with a vertical beach (e.g., Dominick et al. 1971; Fang et al. 1972; Harrison et al. 1971). Since the 1990s, a large number of numerical studies on tidal effects in beach groundwater dynamics have been intensively done. Turner (1993) developed a seep model to simulate the motion of the seepage face. Li et al. (1997b) developed a numerical model based on the boundary element method, which simulated the 2D groundwater flow with free and moving boundaries; additionally, the model also simulated the seepage face and water-table dynamics. Li et al. (1997a) developed a modified kinematic boundary condition for the water table which incorporates capillarity, and this study was used in a boundary element model to simulate the high-frequency water-table fluctuation due to wave run-up. Sun (1997) built a 2D finite difference model using the Crank-Nicolson method to simulate the water table in a coastal confined aquifer. Turner et al. (1997) used MODFLOW to simulate the super-elevation of groundwater in a tidally influenced laboratory sloping beach. Robinson and Gallagher (1999) developed a saturated groundwater flow model and simulated the water table in a tidally influenced sloping beach. Raubenheimer et al. (1999) simulated the water-table fluctuation in a sloping beach with the spring-neap tidal forcing. Boufadel (2000) used the density-and-viscosity-dependent, finite-element, flow numerical model MARine UNsaturated (MARUN) (Boufadel et al. 1999) to simulate the tide-induced pressure head dynamics in a laboratory sloping beach. Ataie-Ashtiani et al. (2001) built a 2D variably saturated numerical model in a hypothetical coastal aquifer with a sloping beach. This work demonstrated the water-table overheight in a sloping beach condition and analyzed the beach slope effect on water-table and groundwater flux. Cheng et al. (2004) built a three-dimensional (3D)

saturated groundwater flow numerical model in a coastal aquifer system, simulating the tide-induced water-table fluctuation of the confined aquifer. Cartwright et al. (2006) used a coupled ground-surface water flow model to simulate water-table fluctuation in response to periodic forcing across a sloping boundary, whereas Li et al. (2006) launched a semi-numerical method for periodic aquifer models by means of complex transformation; additionally, this method was used to simulate the tide-induced water-table fluctuation of a unconfined aquifer with vertical seaward boundary in Hong Kong. Mao et al. (2006) built a 2D groundwater flow numerical model in a coastal aquifer of Ardeer site (UK) and then analyzed the beach slope effects in tide-induced water-table fluctuation. The results show that a small beach slope enhances the tidal effects on coastal groundwater dynamics. Li et al. (2008) investigated the tide-induced seawater-groundwater circulation in shallow beach aquifers using MARUN and analyzed the tidal effects on water exchange between groundwater and seawater. Liu et al. (2008) simulated the tide-induced water-table fluctuation in a confined aquifer with a sloping submarine outlet capping and revealed that the structure of the outlet capping can significantly affect the water-table fluctuation. Abdollahi-Nasab et al. (2010) simulated the pressure head dynamics for different seawater concentration in a laboratory sloping beach by using MARUN. Using MARUN, Guo et al. (2010), Li and Boufadel (2010), Li and Boufadel (2011) and Xia et al. (2010b) simulated the field-observed water table of a two-layered structure aquifer with a sloping beach in Prince William Sound, Alaska (USA), with the effect of the two-layered beach structure on tidal water-table behavior being discussed and quantified. Bakhtyar et al. (2011) coupled the hydrodynamic model and groundwater flow model SEAWAT-2000; the new combined model was used to simulate the wave-induced water-table fluctuations. Boufadel et al. (2011) simulated the tide-induced pressure head dynamics with tracer in the aquifer by using MARUN. Bobo et al. (2012) simulated the groundwater dynamics of a gravel beach on Eleanor Island (Alaska) by using the saturated-unsaturated transport (SUTRA) numerical model; furthermore, this research revealed that the decrease in the slope of the beach in the seaward direction could affect the groundwater flow dynamics. Chassagne et al. (2012) simulated the groundwater flow dynamics in a sloping beach with the tidal forcing by using SUTRA. Liu et al. (2012) analyzed the beach slope effects on tide-induced groundwater dynamics in a beach slope ranging from 15 to 90°. The results show that the amplitude increases logarithmically with the beach slope. Xia and Li (2012) simulated the tide-induced water-table dynamics of the aquifer in a tidal wetland whereby this work revealed that the aquifer shape could affect the tidal water-table fluctuation. Bakhtyar et al. (2013) simulated the groundwater flow dynamics and solute transport in a coastal unconfined sloping aquifer subject to different oceanic forcing and different densities of the injected solute by using SEAWAT.

Yang et al. (2013) simulated the coastal groundwater flow dynamics by using the HydroGeoSphere model, which is a 3D numerical model describing fully coupled surface–subsurface, variably saturated, variable-density flow and advective-dispersive-diffusive salt transport (Brunner and Simmons 2012). Yuan et al. (2008) developed a new integrated surface and groundwater flow model which can deal with a moving boundary problem to simulate shallow beach groundwater flow.

In summary, although numerous studies focused on the beach slope effects on tide-induced groundwater dynamics in coastal unconfined aquifers, their conclusions are uniform. Furthermore, limited research has been conducted on the effect of the slope at a range from 0 to 10°, which is the most common kind of beach in reality; and, previous research has shown that the beach slope is an important factor influencing coastal aquifer water-table fluctuations. So describing the beach slope reasonably in the numerical model is very important for the modelers. Therefore, it is necessary to research the effect of beach slope on the tide-induced water-table dynamics, especially for mild beach slope. For this purpose, field water-table monitoring and numerical modelling work were done. In this paper, based on the field data of Donghai Island, China, a 2D coastal groundwater flow numerical model with sloping beach was built to research the effect of beach slope on the tide-induced water-table dynamics. Based on the calibrated model, sensitivity analysis was conducted to assess the role of parameters and conceptualization of the model on tide-induced water-table fluctuation.

### Hydrogeological condition of Donghai Island

Donghai Island is located south of Zhanjiang City, China (Fig. 1), and exhibits typically flat topography. Geologically, the island is characterized by interbedded loose sand and soft clay of Cenozoic age overlying a Cretaceous basement. The

sediments of Cenozoic age are relatively continuous laterally and form the aquifer system of Donghai Island. As shown in Fig. 2, the unconfined aquifer in this island is separated from the corresponding unconfined aquifer in the mainland by Zhanjiang Bay. However, the aquitard and confined aquifer are continuous and extend up to the mainland underneath Zhanjiang Bay. The unconfined aquifer that flows radially from the watershed to the ocean is mainly recharged primarily through rainfall infiltration and is discharged through runoff to the ocean and leakage to the confined aquifer. Conversely, the confined aquifer is mainly recharged primarily through the leakage from the upper aquifer and lateral runoff and is discharged through pumping and runoff. The groundwater in the confined aquifer flows from south to north, eventually reaching the mainland underneath Zhanjiang Bay. The authors refer to this kind of island as a ‘continental island’. A schematic cross-section of the island is presented in Fig. 2.

Here, the profile of the single-layer unconfined aquifer in the northern part of Donghai Island represents the research cross-section (indicated by the red dashed frame in Fig. 2). This cross-section terminates at the aquitard layer, which is formed by early Pleistocene clay.

### Numerical modelling of the coastal unconfined aquifer in Donghai Island

In this study, the SEAWAT model (Guo and Langevin 2002) was chosen to simulate tide-induced groundwater flow and the groundwater flow dynamics. In coastal hydrogeology, tidal loading is an important factor for tide-induced groundwater flow dynamics in deep confined aquifers. Many analytical studies have been conducted to investigate the effects of tidal loading under different conditions such as offshore roof length, leakage, loading from unconfined aquifers, submarine outlet capping, and submarine springs (Chuang and Yeh 2007; Geng et al. 2009; Jacob 1950; Jiao and Tang 1999; Li and Chen 1991; Li and Jiao 2001; Li et al.

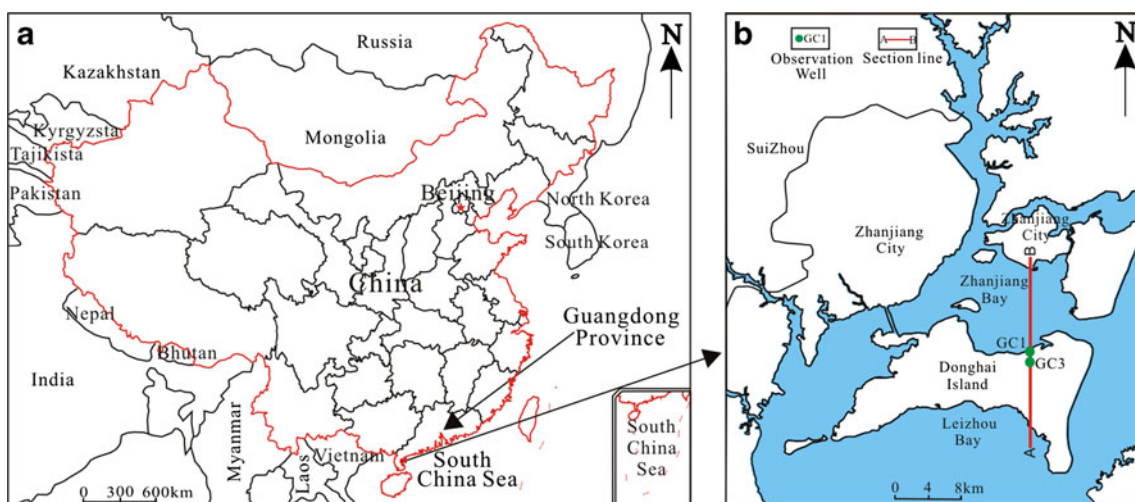


Fig. 1 Location of the study area. **a** map of China (the red line is the boundary of China); **b** map of Donghai Island

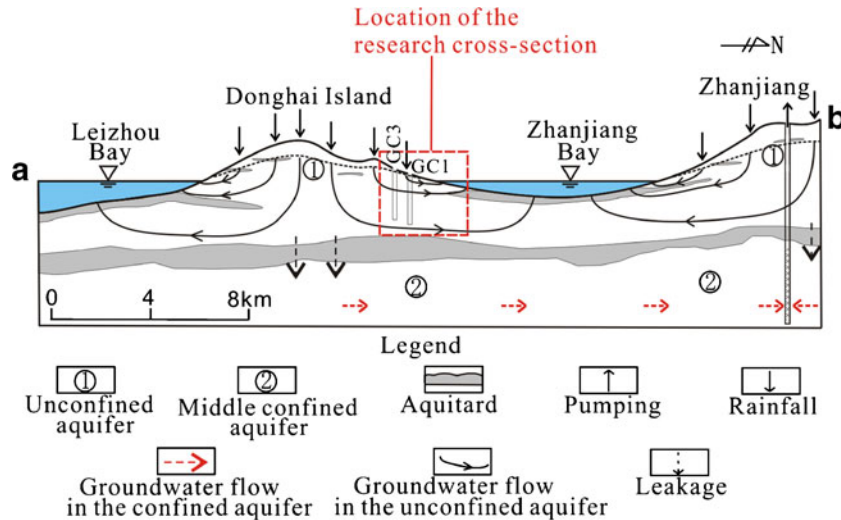


Fig. 2 The schematic cross-section of Donghai Island along the line AB (shown in Fig. 1)

2001; Van der Kamp 1972; Wang et al. 2012; Xia et al. 2012). But it should be noted that the SEAWAT numerical model could not simulate the tidal loading effects on deep confined groundwater tidal dynamics. In the present study, the SEAWAT model is used only to simulate the tide-induced water-table fluctuation in the unconfined aquifer.

Some numerical models have incorporated code that can investigate tidal loading effects. For example, the MARUN code was revised to incorporate the loading term  $T_e S \frac{dh_s}{dt}$  (where  $t$  is time,  $S$  is storage coefficient,  $T_e$  is tidal efficiency, and  $h_s$  is seawater level) into the governing equations for flow in the confined aquifer (Wang et al. 2012). In addition to the revised MARUN, the modified SUTRA numerical model also could simulate the impact of tidal loading on groundwater flow in the confined aquifer (Reeves et al. 2000).

### The SEAWAT model

SEAWAT was first developed through combining the MODFLOW-2000 (groundwater) model with the MT3DMS (solute transport) model to form a single program capable of simulating 3D variable-density groundwater and solute transport equations. In the SEAWAT process, the Variable-Density Flow (VDF) process is based on the constant-density Ground-Water Flow (GWF) process of MODFLOW-2000. The VDF process uses the familiar and well-established MODFLOW methodology to solve the variable-density groundwater flow equation. The MT3DMS part of SEAWAT, referred to as the Integrated MT3DMS Transport (IMT) process, solves the solute transport equation.

In the SEAWAT model, the governing equation for density-dependent groundwater flow is as follows:

$$\nabla \cdot \left[ \rho K_f \left( \nabla \cdot h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z \right) \right] = \rho S_f \frac{\partial h_f}{\partial t} + \theta \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \bar{\rho} q_s \quad (1)$$

where  $\rho$ ,  $\rho_f$  and  $\bar{\rho}$  [ $\text{ML}^{-3}$ ] are the fluid density, freshwater density, and source or sink fluid density respectively;  $K_f$  [ $\text{LT}^{-1}$ ] is the equivalent freshwater hydraulic conductivity;  $h_f$  [L] is the equivalent freshwater head;  $S_f$  [ $\text{L}^{-1}$ ] is the equivalent freshwater storage coefficient;  $t$  [T] is the time;  $\theta$  is the effective porosity; and  $q_s$  [ $\text{T}^{-1}$ ] is the flow rate per unit volume of aquifer of the source or sink; and  $C$  [ $\text{ML}^{-3}$ ] is chloride concentration.

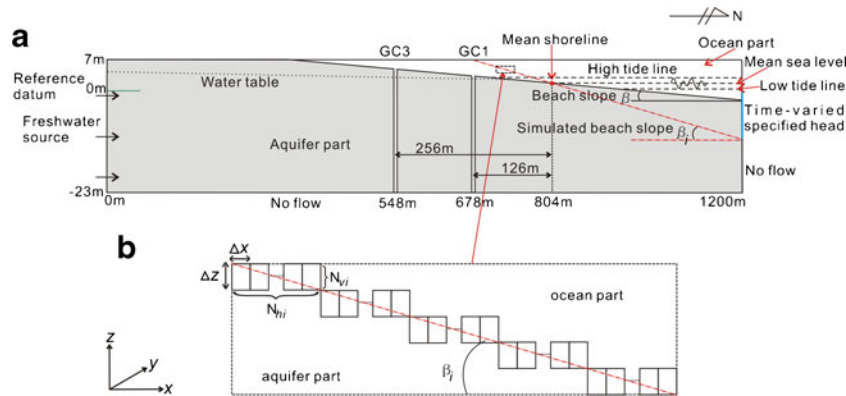
The governing equation for multi-species conservative transport is as follows:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \nabla \cdot (VC) - \frac{q_s}{\theta} C_s + \sum_{k=1}^N R_k \quad (2)$$

where  $D$  [ $\text{L}^2 \text{T}^{-1}$ ] is the hydrodynamic dispersion coefficients;  $V$  [ $\text{LT}^{-1}$ ] is the fluid velocity;  $C_s$  [ $\text{ML}^{-3}$ ] is the solute concentration of water entering from sources or sinks; and  $R_k$  ( $k=1, \dots, N$ ) [ $\text{ML}^{-3} \text{T}^{-1}$ ] is the rate of solute production or decay in reaction  $k$  of  $N$  different reactions (Guo and Langevin 2002).

### Model discretization

The coastal unconfined aquifer of Donghai Island consists of Quaternary deposits of fine sand. The water-table depth (i.e., distance from the ground surface to the water table) of this aquifer is approximately 4–5 m. The groundwater flows from the land to the ocean. In the present study, a cross-section along the groundwater flow direction was used as a research profile to simulate tide-induced water-table dynamics in this aquifer. As shown in Fig. 3a, the cross-section is 1,200 m long (in the x direction), 30 m deep (in the z direction), and 5 m wide (in the y direction), with a real beach slope ( $\beta$ ) of  $0.6^\circ$ . The model area was discretized to 45,000 quadrilateral cells (300 columns, 150 layers, and 1 row). The  $\Delta x$ ,  $\Delta z$  and  $\Delta y$  for each cell were 4, 0.2 and 5 m respectively. The details of the model domain and boundary conditions are presented in Fig. 3a.



**Fig. 3** The map of conceptual model. **a** Model domain and boundary conditions; **b** description of the beach slope in the model

The transient simulation period was 72 h, and the time step was 0.33 h.

### Boundary conditions

Figure 3a depicts the model domain and boundary conditions for the present study. To mimic tidal forcing on the sloping beach, the model domain was divided into two parts: the aquifer part and the ocean part. Furthermore, high hydraulic conductivity ( $5 \times 10^5$  m/d) was assigned to cells in the ocean part to represent seawater. This approach has been applied previously in groundwater simulation (Anderson et al. 2002; Hunt and Krohelski 1996; Lee 1996; Mao et al. 2006; Robinson et al. 2007b). The sloping beach was represented by a sloping line between the two parts, and each simulated beach slope was described in the model by  $\frac{N_{vi} \times \Delta z}{N_{hi} \times \Delta x} = \tan \beta_i$ , as shown in Fig. 3b. Here,  $N_{vi}$  represents the number of high-conductivity cells in the vertical direction along the aquifer-ocean interface in each simulation,  $\Delta z$  is the height of each cell,  $N_{hi}$  is the number of high-conductivity cells in the horizontal direction along the aquifer-ocean interface,  $\Delta x$  is the length of each cell, and  $\beta_i$  is the simulated beach slope. The location of the mean shoreline was fixed in all simulations.

In the model, a time-varied head boundary was specified based on tidal data obtained from field monitoring; this boundary is equivalent to the freshwater head boundary in SEAWAT, and was assigned to the right column cells below the low sea level in the ocean part. The reason for selecting the cells below the low sea level is that the lowest head value should not be smaller than the bottom elevation of all the specified head cells in SEAWAT and the no flow boundary was set for the seaward vertical boundary under the ocean. Robinson et al. (2007b) demonstrated that implementation of a no-flow boundary condition (rather than time-varying tidal heads) along the vertical seaward boundary under the ocean does not have a significant effect on flow in the near shore aquifer. A constant head boundary, set to 3.2 m based on observational data, was assigned to the inner landward vertical boundary as the freshwater source.

A no-flow boundary was adopted for the base of the model domain, because a layer of very low-permeability clay is present at the base of the unconfined aquifer. The upper boundary is a phreatic surface. Because of the small research area and limited simulation time in transient simulating process (72 h), the influences of rainfall and evaporation are negligible to this research.

The solute transport boundary conditions are as follows: constant concentration boundary with high chloride (15,883 mg/L) seawater and zero chloride (0 mg/L) fresh groundwater were specified in the ocean part and landward boundary, respectively. The bottom boundary and upper boundary (water table) are zero solute flux boundaries.

It should be noted that only saturated flow was considered in this model, and the SEAWAT model cannot model the variably saturated groundwater flow; however, the water table of the unconfined aquifer may fluctuate in response to tidal oscillations. To simulate this fluctuation of water-table, the US Geological Survey (USGS) extended the block-centered-flow package (BCF2) to allow cells in unconfined layers to become re-saturated during transient simulation; this is known as the rewetting function. This function can be selected to allow the dry cells near the water-table to be wetted when the head in adjacent grid cells exceeds the combined elevation of the base of the dry cell and the defined wetting threshold value.

### Model parameters

The hydraulic conductivity ( $K$ ) of the unconfined aquifer is approximately 5 m/d along the northern coast of Donghai Island. The hydraulic conductivities ( $K$ ) of the aquifer and ocean parts in this model were 5 and 500,000 m/d, respectively. In the ocean part, where hydraulic conductivity was set to high, Darcy's law is not theoretically valid owing to the large local flow rate in the region. However, the flow rate in the ocean part was not used in this study. The study was only concerned with the transmission of the tidal signal from the sea to the cells along the aquifer-ocean interface. Moreover, the previous simulation research shows that the surface-water level can be accurately calculated in a

groundwater flow model when  $\frac{K_{\text{surface water}}}{K_{\text{aquifer}}}$  is equal to 100,000 (Anderson et al. 2002). The specific yield ( $S_y$ ) was set to 0.032 and 1 in the aquifer and ocean parts, respectively.

It has proven difficult to obtain values for actual dispersivity through field or laboratory dispersion experiments owing to the scale effect of hydrodynamic dispersion. Here, dispersivity was selected based on the results of a previous study that investigated the relationship between longitudinal dispersivity ( $\alpha_L$ ) and scale ( $L_s$ ) (Li and Chen 1995). The longitudinal dispersivity was set to 10 m in the present study. According to Ranganathan and Hanor (1988), a transverse dispersivity close to one-fifth of the longitudinal dispersivity may be appropriate when modeling cross-sectional solute transport in systems with isotropic permeability; based on this logic, a transverse dispersivity ( $\alpha_T$ ) of 2 m was adopted in the present study. The model input parameters are presented in Table 1.

### Initial condition

In this study, a steady-state simulation was used to generate the hydraulic head situation prior to field water-table monitoring in this coastal area. Additionally, the hydraulic head output from the steady simulation was used as the initial condition for the transient simulations. In this steady model, the beach slope ( $\beta$ ) was  $0.6^\circ$ , which was the real slope of the research coastal beach. In this steady-state model, a constant head condition that was the same as the sea level at the surveying time was assigned to the seaward boundary in the ocean part. The other boundary conditions were the same as described in the preceding section 'Boundary conditions'. The parameters in the steady-state model were chosen according to the the preceding section 'Model parameters'. The initial chloride concentrations of groundwater and seawater in the cross-section were 0 and 15,883 mg/L, respectively.

### Model calibration

The study area has two water-table observation wells, GC1 and GC3, which are located 126 and 256 m from the mean shoreline, respectively. Field water-table monitoring was conducted for the two observation wells on December 2–5, 2009 for a period of 72 h, with a monitoring frequency of 3 times per hour. The research area has an irregular semidiurnal

**Table 1** Model input parameters

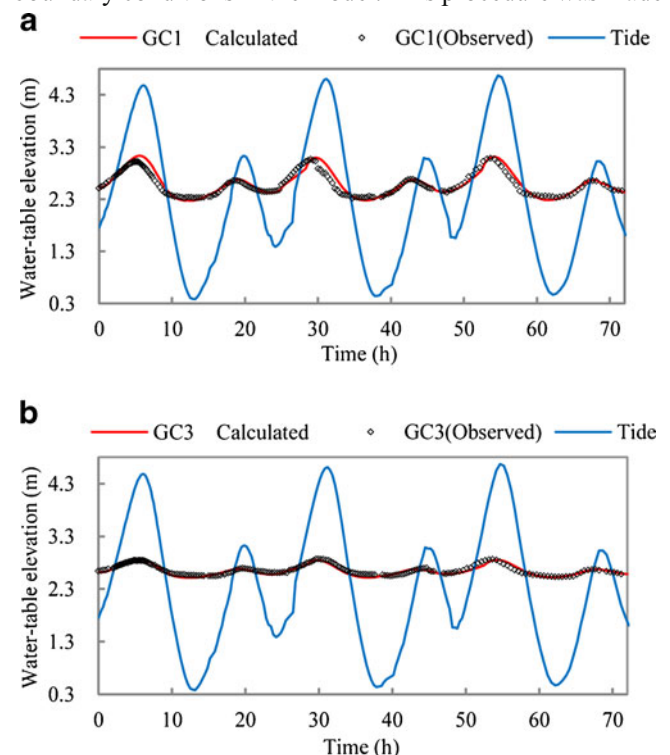
Parameter	Value
Seawater chloride concentration	15,883 mg/L
Groundwater chloride concentration	0 mg/L
Freshwater density	1,000 kg/m <sup>3</sup>
Seawater density	1,025 kg/m <sup>3</sup>
Hydraulic conductivity in aquifer	5 m/d
Hydraulic conductivity in ocean	500,000 m/d
Longitudinal dispersivity	10 m
Transverse dispersivity	2 m
Specific yield in aquifer	0.032
Specific yield in ocean	1
Viscosity of water	0.001 kg/(m·s)

tide, with high and low tides occurring twice daily. The sea levels at the two neighbouring high tides are unequal, and the sea levels at the two neighbouring low tides are also unequal. The mean sea level is 2.04 m, with an average lowest tide of 0.43 m, highest tide of 4.59 m, and the maximum tidal amplitude of 4.16 m. The reference datum is the altitude datum (0 m) of China.

The simulation results were compared with field observation data, as shown in Fig. 4. The results show that the simulation data and observed data are in reasonably good agreement. However, discrepancies exist for the peaks and troughs. The troughs are more pronounced (low) in the simulations than in the monitored data, especially at the well far from the shore. The reasons for the discrepancies could include neglect of the seepage face dynamics during the tidal cycle, differences between the real and simulated boundaries of the aquifer, and the fact that the aquifer system is inhomogeneous such as depth-decaying hydraulic conductivity (Jiang et al. 2009; Bobo et al. 2012) or layered hydraulic conductivity values (Li and Boufadel 2010). The comparison generally indicates that the numerical model is reasonable and can properly simulate tide-induced water-table fluctuation in a sloping beach.

### Sensitivity analysis

A sensitivity analysis was conducted to investigate the sensitivity of the model to changes in parameters and boundary conditions in the model. This procedure was made

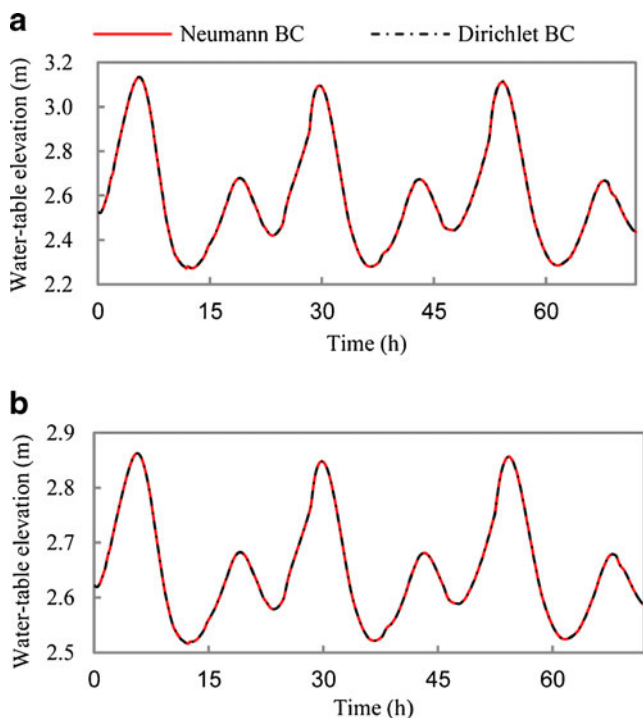


**Fig. 4** Comparison of observation and simulated water-table fluctuation (the reference datum is the altitude datum of China): **a** well GC1; **b** well GC3; GC1 and GC3 are located 126 and 256 m from the mean shoreline, respectively

by changing only one parameter or boundary condition at a time while keeping all others fixed. The response of the model was assessed after each run by observing the simulated water-table fluctuation in the observation wells, then the sensitivity of the numerical model was evaluated by comparing water-table dynamics from the sensitivity simulation with that from the afore-mentioned calibrated model. In this manner, the sensitivity analysis helped determine which parameter or boundary condition has the greatest effect on the model.

### Effects of the landward boundary condition

The Neumann and the Dirichlet boundary conditions are usually used in numerical models such as that employed in the present study, although the choice of landward boundary condition in coastal models is often difficult. Thus, the effect of the landward boundary condition on tide-induced water-table variation was investigated to address this. For this purpose, two simulation scenarios were designed by assigning either Dirichlet or Neumann boundary conditions to the landward boundary. According to the Darcy law, the groundwater flux per unit width ( $0.166 \text{ m}^2/\text{d}$ ) is calculated for the Neumann boundary condition. The results showed that the landward boundary condition did not have a significant influence on the water-table fluctuations in the observation wells (Fig. 5). It should be noted that the initial conditions of the hydraulic head of the two models were the same. Therefore, it is concluded that the groundwater level variations due to tidal forcing in this model were not sensitive to the landward boundary condition.



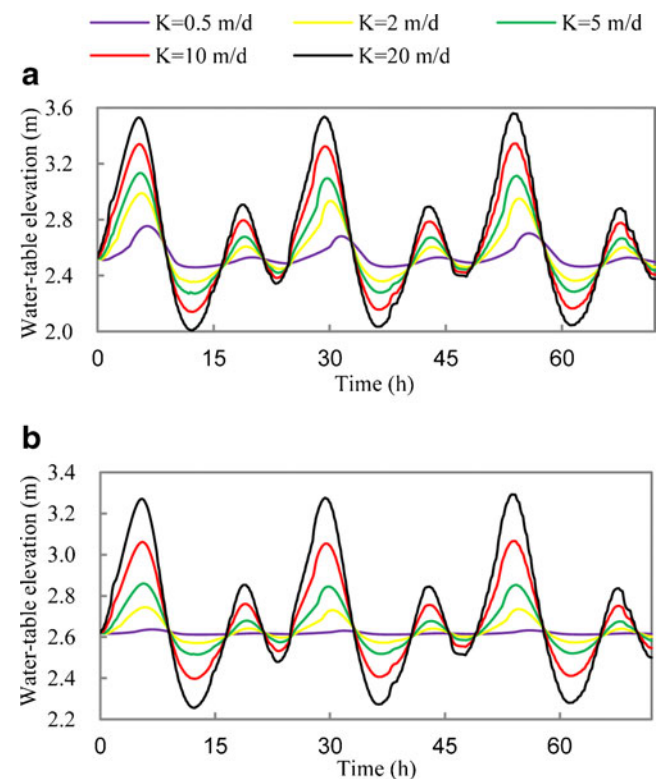
**Fig. 5** Variation of water-table fluctuation with landward boundary conditions (*BC*) (the reference datum is altitude datum of China): **a** well GC1; **b** well GC3

In the authors' opinion, there may be two reasons for this result. First, the groundwater flux from the landward boundary is too small. Second, the distance from the landward boundary to the observation well is great. Due to these two reasons, the variation of the landward boundary conditions has little effect on the water-table fluctuation in the two observation wells, which implies that great groundwater flux from the landward boundary could be an important factor in the choice of landward boundary conditions in the beach-groundwater-flow model.

### Effects of hydraulic conductivity

To assess the impact of hydraulic conductivity on tide-induced water-table fluctuation, the hydraulic conductivity ( $K$ ) value was set to 0.5, 2, 5, 10 and 20 m/d for each simulation, while all other parameters were the same as those of the calibrated model. As shown in Fig. 6, the amplitude of water-table fluctuation increases with increasing hydraulic conductivity values. Moreover, increasing hydraulic conductivity was found to decrease the time lag of the water-table fluctuation, which implies that tidal-driven water-table fluctuations are especially sensitive to values of hydraulic conductivity ( $K$ ) in the beach model.

This sensitivity of water-table fluctuations to hydraulic conductivity can be explained as follows. Greater hydraulic conductivity representing the performance of aquifer permeability results in a more rapid tidal wave energy transfer to the inland aquifer. Consequently, this greater



**Fig. 6** Variation of water-table fluctuation with hydraulic conductivity ( $K$ ) (the reference datum is altitude datum of China): **a** well GC1; **b** well GC3



hydraulic conductivity results in greater amplitude of the tide-induced water-table fluctuation and shorter time lag of the tide-induced water-table fluctuation.

**Effects of specific yield**

The sensitivity of the conceptual model to changes in the specific yield ( $S_y$ ) was examined. The values of all parameters were the same as those of the calibrated model, except specific yield ( $S_y$ ), which was set to 0.05, 0.1, 0.15, and 0.2 for sensitivity analysis. Figure 7 shows the sensitivity of the groundwater level in two observation wells to various specific yield values. It is shown that specific yield has significant influence on the tide-induced water-table fluctuation. The amplitude of water-table fluctuation decreases with increasing of the specific yield values; however, the time lag of the water-table fluctuation increases with increases in the specific yield values. It can be concluded that the tide-induced water-table fluctuation is very sensitive to specific yield in the coastal model. These results are in agreement with those of previous studies (Kim et al. 2007; Slooten et al. 2010).

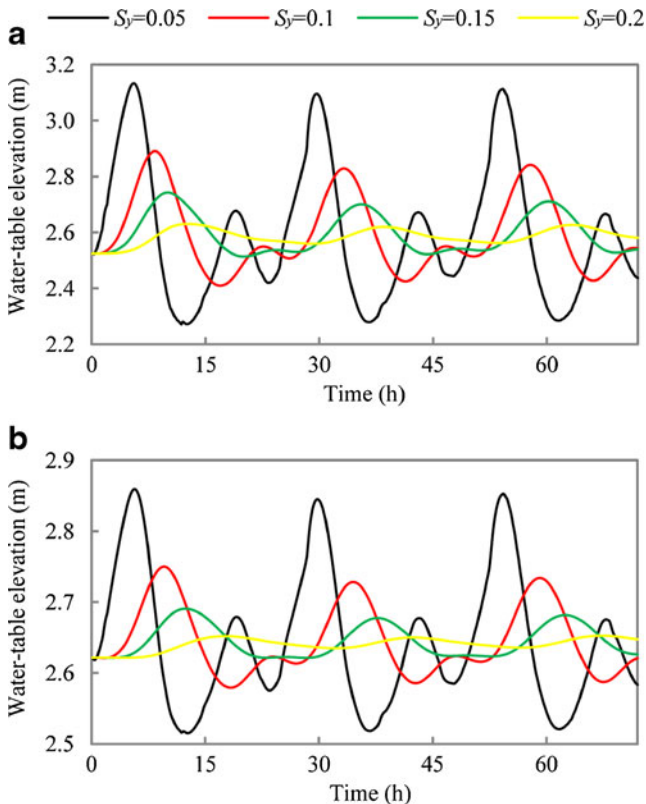
The sensitivity of these water-table fluctuations to specific yield can be explained as follows. The variation of groundwater storage in an unconfined aquifer is generally expressed by the product of the specific yield ( $S_y$ ) of the unconfined aquifer and the amplitude of the water-table fluctuation ( $\Delta h$ ). Therefore, for a specified variation in groundwater storage, a lower specific yield typically results in greater amplitude in the water-table fluctuations. In coastal areas, the tide-induced

variation of groundwater storage during the water-exchange process between seawater and groundwater for an unconfined aquifer can be specified at each time. Therefore, a small specific yield should induce a large amplitude and short time lag for water-table fluctuations.

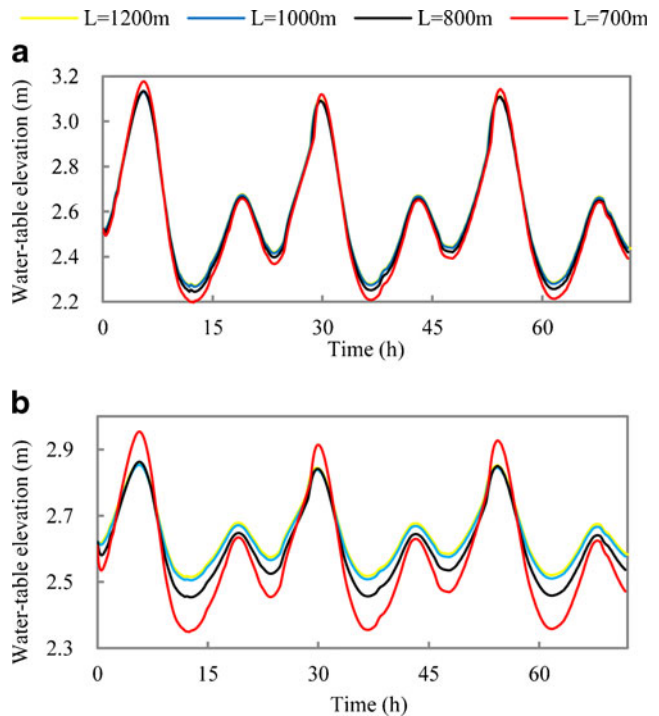
The specific yield of most coastal unconfined aquifers is minimal because such aquifers are typically composed of sand, fine sand, and silty clay. For example, the specific yield of the unconfined aquifer of Donghai Island, which is composed of fine sand and silty clay, is 0.032; that of the unconfined aquifer in Apalachicola Bay (USA), which is composed of fine sand, is 0.002 (Sun 1997). Therefore, tide-induced water-table fluctuation in coastal unconfined aquifers can be significant. Furthermore, in the area investigated for the present study, the notable tide-induced water-table fluctuation in the unconfined aquifer could directly affect the groundwater dynamics of the confined aquifer; therefore, the tide-induced water-table fluctuation in the unconfined aquifer above the confined aquifer should not be ignored in hydrogeological research into the tidal effects of groundwater dynamics of the confined aquifer (Chuang and Yeh 2007; Wang et al. 2012).

**Effects of the horizontal length of the domain**

In order to assess how the horizontal length of the model domain affects tide-induced water-table fluctuation, three new simulations were designed with horizontal lengths of 1,000, 800, and 700 m. Cells with  $x$  values smaller than 200, 400, and 500 m, respectively, were made inactive to allow for description of different horizontal lengths of 1,000, 800, and 700 m in the models. The resulting hydraulic head fluctuations for these three simulations and the results of the calibrated model (1,200 m) are presented in Fig. 8. The horizontal length



**Fig. 7** Variation of water-table fluctuation with specific yield ( $S_y$ ) (the reference datum is altitude datum of China): **a** well GC1; **b** well GC3



**Fig. 8** Variation of water-table fluctuation with horizontal length ( $L$ ) (the reference datum is altitude datum of China): **a** well GC1; **b** well GC3

was found to influence the amplitude of the water-table fluctuations, which decreased with increasing horizontal length. However, the time lag of the water-table fluctuation did not vary with changes in horizontal length, and the effects of horizontal length were more pronounced for the trough values than for the peak values of water-table fluctuations. Moreover, the effects of horizontal length were greater for observation well GC3 than for observation well GC1, perhaps because GC3 is located nearer the landward boundary, and it was found that the amplitude did not change notably when the horizontal length was larger than 1,000 m; thus, the horizontal length chosen in the calibrated model (1,200 m) is reasonable.

### Effects of the variable density

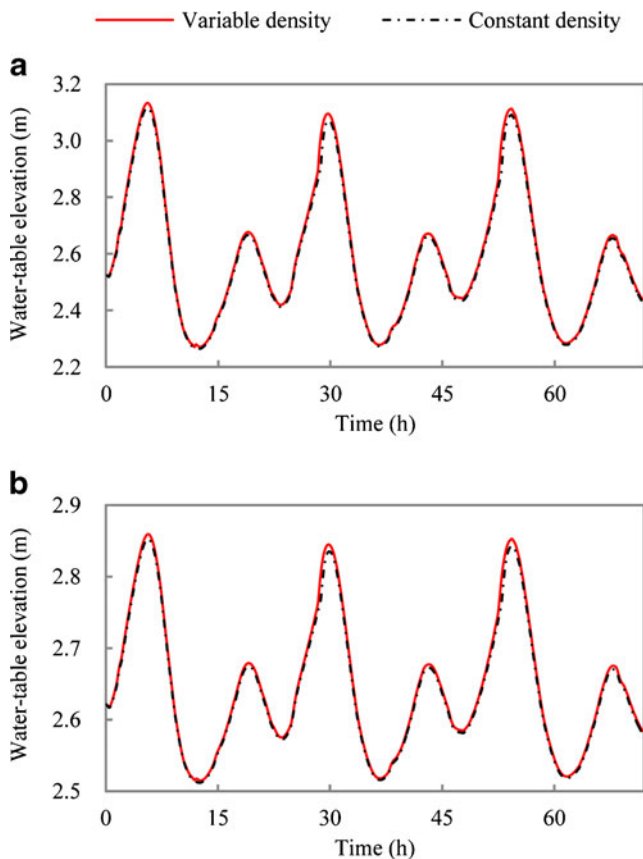
The effects of variable density on tide-induced water-table fluctuations are described here, based on comparison of water-table fluctuations in the variable-density and constant-density simulations. No observable differences in water-table fluctuations were found between the two simulations (Fig. 9). This implies that the variable density has no significant influence on tide-induced water-table fluctuation; therefore, density can be neglected in the numerical beach model if only tidal effects on aquifer hydraulic head are to be considered. Similarly, Ataie-Ashtiani et al. (2001) demonstrated that variable density does not have a major influence on groundwater flow pattern, because the

gradients generated by rising and falling tides will be substantially larger than gradients and consequential velocity components owing to variable density effects.

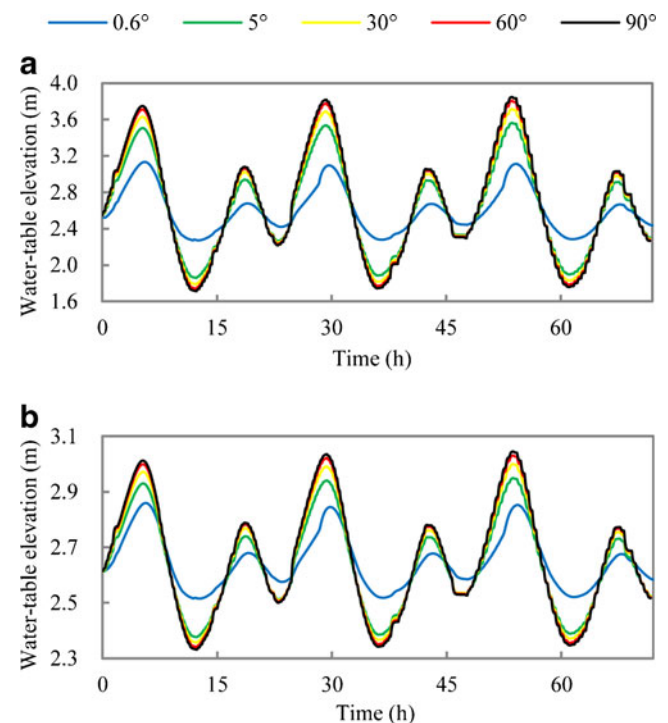
### Effects of beach slope

In the present study, 13 simulation scenarios were designed based on the calibrated numerical model to investigate the effect of beach slope angle on tide-induced water-table fluctuations. In these scenarios, the slope angle of the beach was set to  $90^\circ$  (i.e., a vertical beach),  $75^\circ$ ,  $60^\circ$ ,  $45^\circ$ ,  $30^\circ$ ,  $10^\circ$ ,  $5^\circ$ ,  $3^\circ$ ,  $1.5^\circ$ ,  $1.2^\circ$ ,  $1^\circ$ ,  $0.7^\circ$ , and  $0.6^\circ$  (the beach slope of Donghai Island). That is, both steep beaches ( $15\text{--}90^\circ$ ) and mildly sloping beaches ( $0.6\text{--}10^\circ$ ) were considered, although the latter are most common under real conditions. The location of the mean sea level was fixed in all simulation scenarios. The simulated water-table fluctuations in the two observation wells under different beach slopes are illustrated in Fig. 10.

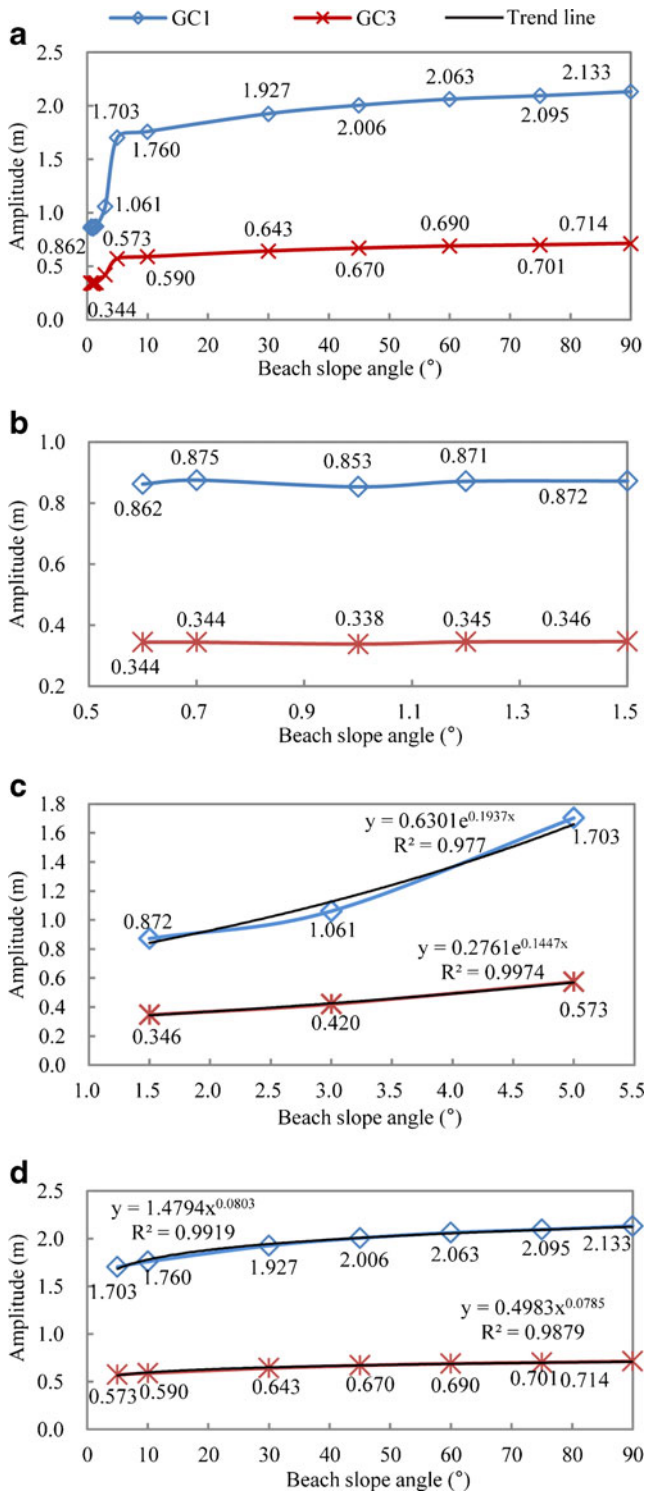
The water-table fluctuation plots (Fig. 11) illustrate clearly that the amplitude of the tide-induced water-table fluctuation increased with increasing beach slope angle, such that steeper beach slopes resulted in greater amplitudes of fluctuation. For example, the amplitude of water-table fluctuations in well GC1 increased by 1.271 m for an increase in beach slope angle from  $0.6^\circ$  to  $90^\circ$  for the unconfined aquifer; the amplitude of water-table fluctuations in well GC3 increased by 0.37 m under similar conditions (Fig. 11a). These results suggest that beach slope has a significant influence on tide-induced water-table fluctuations. In reality, beaches typically exhibit mild slopes, and the approximation of a mildly sloping beach by a vertical beach



**Fig. 9** Variation of water-table fluctuation with constant and variable density (the reference datum is altitude datum of China): **a** well GC1; **b** well GC3



**Fig. 10** Variation of water-table fluctuation with beach slope angle (the reference datum is altitude datum of China): **a** well GC1; **b** well GC3



**Fig. 11** Amplitude of the water-table fluctuation with beach slope angle: **a** beach slope angle 0.6 to 90°; **b** beach slope angle 0.6 to 1.5°; **c** beach slope angle 1.5 to 5°; **d** beach slope angle 5 to 90° (each trend line was defined by a function that expresses the relationship between the amplitude (represented by *y* in the function) and the beach slope angle (represented by *x* in the function))

resulted in the calculated data overestimating the observational data considerably. Therefore, the widely used vertical beach model is unsuitable for unconfined aquifers. Furthermore, despite the significant variation of amplitude

with changes in beach slope angle, no notable changes in the time lag of water-table fluctuations were observed.

The amplitude of the tide-induced water-table fluctuations was found to remain quasi constant when the beach slope angle was varied within the range 0.6–1.5° (Fig. 11b), but varied notably when the beach slope angle was varied within the range 1.5–5° (Fig. 11c), which implies that the amplitude is sensitive to changes in beach slope within the latter range. Therefore, when conducting numerical simulation of coastal beaches with slopes within this range, the beach slope in the model should be set based on the real beach slope in the study area.

The amplitude of the tide-induced water-table fluctuations increased dramatically with increasing beach slope angle in the range 5–90° (Fig. 11d), whereas the variation in the amplitude of the water-table fluctuation was less than 0.1 m for the slope angle range of 45–90°. Therefore, the vertical beach model can be used in simulation of such steep beaches with slope angle range of 45–90°. However, the researchers also should set the beach slope in the model carefully when the beach slope angle was in the range 5–45°.

In summary, the variation of the amplitude of water-table fluctuations was found to be more pronounced for beach-slope angle changes within the range 1.5–5°. Therefore, to obtain more accurate results in the simulation of groundwater dynamics in beach aquifers in future, researchers should describe the modeled beach slope carefully when the beach slope angle is within 1.5–45°, particularly when it is within 1.5–5°.

### Conclusion

Beach slope is known to be a vital factor influencing tide-induced water-table fluctuations in coastal unconfined aquifers, although the effect of beach slope on tide-induced water-table dynamics has remained unclear, particularly for mild beach slopes. To address this, taking the coastal unconfined aquifer in Donghai Island as an example, a 2D coastal groundwater flow numerical model with a sloping beach was built using SEAWAT-2000. Field water-table monitoring data were used to calibrate the model.

Subsequently, using this calibrated numerical model as the base model, sensitivity analysis was conducted to investigate the sensitivity of the tide-induced water-table to the parameters and conceptualization of the model. The following general conclusions were reached.

1. The landward boundary condition does not have significant influence on the tide-induced water-table fluctuation. In the authors' opinion, there are two main reasons for this result. First, the groundwater flux from the landward boundary is small. Second, the distance from the landward boundary to the observation well is great. Due these two reasons, the variation of the landward boundary conditions has little effect on the water-table fluctuation in the two observation wells.
2. Hydraulic conductivity significantly affects the amplitude and time lag of the tide-induced water-table fluctuation,

- which means that the water-table fluctuations are particularly sensitive to hydraulic conductivity in the beach model.
3. Decreases in specific yield can increase the amplitude and reduce the time lag of the water-table fluctuation. This implies that a coastal unconfined aquifer with low specific yield can perform notable water-table fluctuation; therefore, in tidal loading research, researchers should not neglect the water-table fluctuation where there is an unconfined aquifer above a confined aquifer.
  4. The horizontal length of the model domain could affect the amplitude but not the time lag of the tide-induced water-table fluctuation. This effect is more notable for the location that is closer to the landward boundary. Furthermore, the amplitude did not change notably when the horizontal length was larger than 1,000 m, which indicates that the horizontal length chosen in the calibrated model (1,200 m) is reasonable.
  5. The variable density has no significant influence on tide-induced water-table fluctuation. This result is consistent with previous studies (e.g., Ataie-Ashtiani et al. 2001)
  6. In this present study, the authors not only consider the steep beach (15 to 90°) but also the mildly sloping beach (0.6–10°) which is the most common kind of beach in reality. No variations in the time lag of tide-induced water-table fluctuations were found with changes in beach slope angle. However, the amplitude of these fluctuations was found to increase with increasing beach slope angle, which implies that the widely used vertical beach model overestimates such fluctuations with respect to observational data. Moreover, particular care should be taken to describe the beach slope in the beach-groundwater-flow model for beach slope angles in the range 1.5–45°.

In this present model, the authors did not consider the seepage face dynamics. Moreover, it was assumed that the exit point of the water table on the beach face is coupled with the tidal sea level at all times. In reality, as the result of seepage face dynamics, the water-table hydrograph should be mild during the period of ebb tide. To understand more accurately the tidal effects on hydrodynamics in coastal areas with the existence of seepage face, further research will be conducted.

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