Numerical modeling of the effects of pumping on tide-induced groundwater level fluctuation and on the accuracy of the aquifer's hydraulic parameters estimated via tidal method: a case study in Donghai Island, China

Pengpeng Zhou, Xiaojuan Qiao and Xiaolei Li

ABSTRACT

Coastal groundwater level is affected both by tide and pumping. This paper presents a numerical model to study the effects of pumping on tide-induced groundwater level fluctuation and on accuracy of hydraulic parameters estimated via tidal method. Firstly, for the effects of pumping on the groundwater level fluctuation under the combined influence of pumping and tide, groundwater level has a drawdown but eventually reaches a quasi-steady-state again. Steady pumping can attenuate the amplitude but cannot affect the phase of the quasi-steady fluctuation. However, seaward steady pumping plays a relatively obvious role in enhancing drawdown compared with landward pumping, a partial penetration well leads to greater drawdown than a full penetration well, and transient pumping induces large amplitude which does not reflect large transmissivity. Secondly, for the effects of pumping on the accuracy of the parameter estimated via the tidal method, transient pumping or large steady pumping, especially in a full penetration well, significantly affects accuracy of the estimated parameters. However, when the distance between the pumping well and tide observation well exceeds 200% of the distance between observation well and shoreline, pumping effect on estimated parameters can be neglected. The conclusions could provide guidance for reasonable application of the tidal method.

Key words | coastal aquifer, groundwater level, hydraulic parameter, numerical modeling, pumping, tidal method

Pengpeng Zhou
Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences,
No. 19 Beitucheng West Road, Chaoyang District,
Beijing 100029,
China

Xiaojuan Qiao (corresponding author)
College of Earth Science, University of Chinese Academy of Sciences,
19A Yuquan Road,
Beijing 100049,
China
E-mail: *qiaoxiaojuan_ucas@163.com*

Xiaolei Li
China Institute for Geo-Environmental Monitoring,
20 Dahuisi Road, Haidian District,
Beijing 100081,
China

INTRODUCTION

The ocean tide is an important factor that affects groundwater level dynamics in coastal aquifers. It is important to understand the tide-induced groundwater dynamics for many environmental and ecological problems, such as oil spill remediation (Singh *et al.* 2016), nearshore area ecology and biodiversity, beach accretion and erosion, seawater-groundwater circulation, saltwater intrusion (Lian *et al.* 2015; Sadeghi-Tabas *et al.* 2016), and estimation of aquifer parameters, such as transmissivity (T), storativity (S), and their ratio (Millham & Howes 1995; Zhou *et al.* 2015).

In addition to ocean tidal forcing, groundwater pumping which is very common in coastal areas for water resource demand is also an important factor affecting coastal groundwater level dynamics. The combined influences of tide and pumping can induce more complicated groundwater level dynamics, which in turn presents challenges in solving environmental problems and estimating aquifer parameters. For example, Chen & Jiao (1999) observed that the tide-induced hydraulic head fluctuation affected the pumping test data for estimating the hydraulic parameter. They

doi: 10.2166/hydro.2017.089

corrected the pumping test data by deducting the groundwater fluctuation data. Influenced by periodic tidal forcing, Qu & Chen (2010) found multiple cycles of drawdown in the pumping tests.

To accurately revise the drawdown data of the pumping test, some studies have been conducted. Liu (1996) derived an analytical solution that described the combined effects of periodic tidal forcing and steady pumping on the groundwater level fluctuation of a confined aquifer. This solution showed that, under the combined effects of tide forcing and groundwater pumping, the pressure head of a confined aquifer varied periodically, with a drawdown for a long period. Trefry & Johnston (1998) developed a standard transient method to correct the drawdown data during a coastal pumping test. This research found that the pumping/tide-induced piezometric head dynamics in shallow and deep positions of the aquifer were different because of aquifer heterogeneity. Using the superposition principle, Chapuis *et al.* (2006) derived a closed-form theoretical solution to correct the drawdown and recovery curves of a pumping test under sinusoidal tidal influence. This solution is reliable when the radial distance (i.e., distance of the observation well to the pumping) is less than 10% of the distance between the shoreline and the pumping well. Wang *et al.* (2014) developed a closed-form analytical solution that described the variation of groundwater level in a coastal leaky confined aquifer during a steady pumping test in a full penetration well. This research pointed that long-term pumping was needed to distinguish tidal influence from groundwater level drawdown in the pumping test.

All the above studies adopted the assumption of a full penetration well. For the partially penetrating well effects, Hantush (1961) presented an analytical solution for the wellbore drawdown in a partially penetrating well under constant pumping rate in a homogeneous confined aquifer. Ruud & Kabala (1997) derived a closed form solution for computing the drawdown at the well face in a partially penetrating well in a heterogeneous confined aquifers. Cassiani & Kabala (1998) gave a more efficient semi-analytical solution for the groundwater level drawdown in a partially penetrating well with a mixed-type boundary condition. Derived from this typical drawdown curve influenced by a partial penetration pumping well, the transmissivity (T) value should be close to the value derived from the drawdown curve obtain from a full penetration well, but the storage value would be inaccurate (Qu & Chen 2010; Ni *et al.* 2011, 2013). Considering the influence of a partial penetration pumping well, Yang *et al.* (2006) derived a solution for describing the confined groundwater level drawdown in a partial penetration well under constant pumping rate conditions. This research found that the partial penetration effect is more apparent when the well's screen is shorter. Considering the influence of partial penetration type and large diameter of the pumping well, Ni *et al.* (2011, 2013) presented data reduction methods to remove these influences and determine the hydraulic parameters. Regarding the large-diameter effect, some research reported that the large diameter has an early-time influence on drawdown curve (Qu & Chen 2010; Ni *et al.* 2013). Together with the influence of water storage in wells (monitoring wells and pumping wells), the large-diameter effect can lead to an overestimation of storage coefficient (Narasimhan & Zhu 1993; Qu & Chen 2010).

From the above reviews, it can be seen that all the previous researches mainly focused on the pumping test, and the previous researches about the combined effects of tide and pumping on groundwater level dynamics primarily focused on correcting the drawdown values during the pumping test for estimating the hydraulic parameters. However, in the coastal area, the tidal method is more economical and convenient than the pumping test to determine the hydraulic conductivity (K) value of the coastal aquifer (Millham & Howes 1995). When we estimate the hydraulic parameters of a coastal aquifer using the tidal method, which is based on monitoring groundwater level data, groundwater pumping can affect the accuracy of the monitoring of groundwater level data and the hydraulic parameter estimated by the tidal method.

So it is necessary and meaningful to research the effects of pumping on tide-induced groundwater level fluctuation and on the accuracy of the aquifer's hydraulic parameters estimated via the tidal method. For this objective, firstly, based on the groundwater level monitoring data in Donghai Island, a two-dimensional (2D) numerical groundwater flow model was conducted for simulating the coastal groundwater level dynamics induced by sea tide; secondly, based on this calibrated model, a series of numerical simulations considering different pumping scenarios (including transient pumping, different pumping well location, and partially penetrating wells) were conducted to obtain in-depth understanding of the effects of pumping on tide-induced groundwater level dynamics and to discuss the effects of pumping on the accuracy of the hydraulic parameters estimated via the tidal method.

METHODS

Study area and hydrogeological conditions

Donghai Island is located at the southwest of Guangdong, China (Figure 1). The morphology is primarily flat, with the terrain elevations of 2–60 m. The average annual precipitation is 1,354 mm, and the average annual evaporation is about 1,775 mm. The sea tide is characterized by an irregular semidiurnal tide with a mean sea level of 2.04 m, an average low sea level of 0.43 m, high sea level of 4.59 m.

From a geological point of view, the island is a tectonic depression covered with continental and marine sediments of Cenozoic age. The sediments prevalently consist of interbedded loose sand and soft clay. The Cenozoic sediments form the multi-layer aquifers system (Figure 2); these aquifers are generally separated by aquitard composed of 14–18 m thick clay layer. As shown in Figure 2, the upper unconfined aquifer layer extends only up to the coastline; the aquitard and confined aquifer extend up to the mainland underneath Zhanjiang Bay. The upper unconfined aquifer is mostly recharged by the rainfall infiltration and discharged through runoff to the sea. The confined aquifer is recharged through the lateral runoff and discharged through withdrawal and lateral runoff.

A cross-section of the upper unconfined aquifer in the northern part of this island is selected as the research object (the dashed frame in Figure 2). In this section, the unconfined aquifer that is about 30 m thick consists of silty clay and fine sand. The groundwater level is about 2.0–3.2 m. In this profile, two groundwater level observation wells GC1 and GC3 are located 126 m and 256 m from the shoreline, respectively. Using those two wells, tide-induced groundwater level monitoring had been conducted during December 2–5, 2009, with a monitoring frequency of three times per hour.

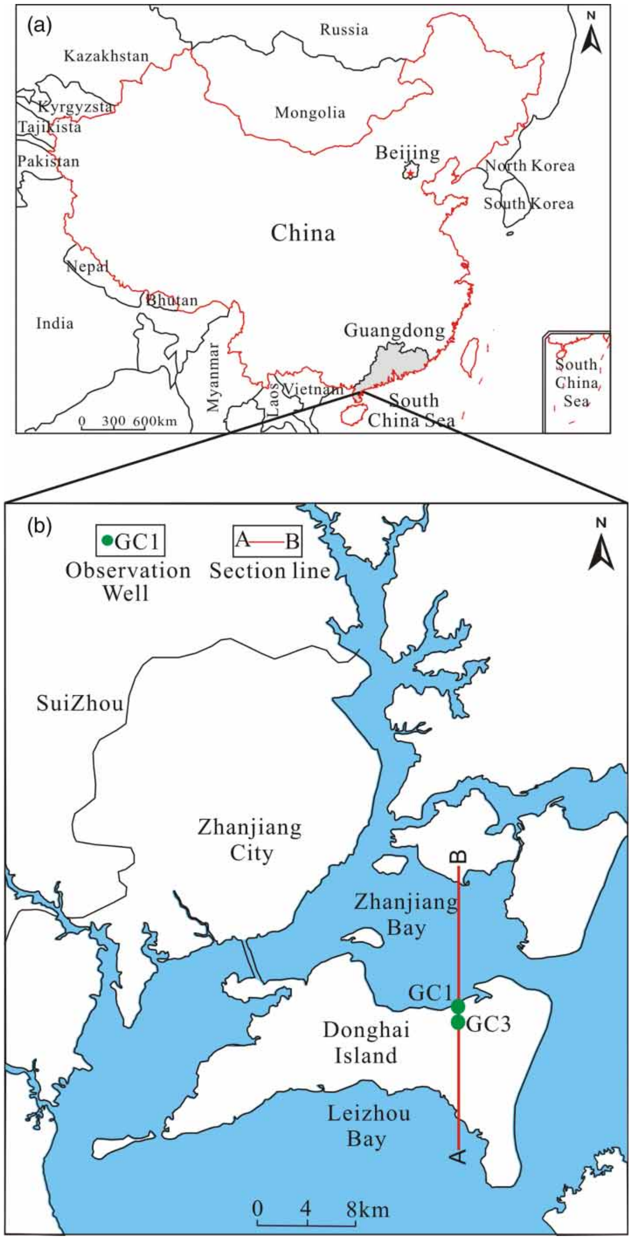

Figure 1 | Location of Donghai Island. (a) Map of China; (b) map of Donghai Island (cited from Zhou et al. (2014). Copyright: Springer-Verlag Berlin Heidelberg, 2013; Pengpeng Zhou).

Numerical modeling of groundwater level dynamics

In this modeling study, according to the locations of observation wells GC1 and GC3, a 2D vertical cross-section perpendicular to the coastline was selected as the model domain (Figure 3). This model domain is homogeneous, with a horizontal bottom and a gently sloping beach.

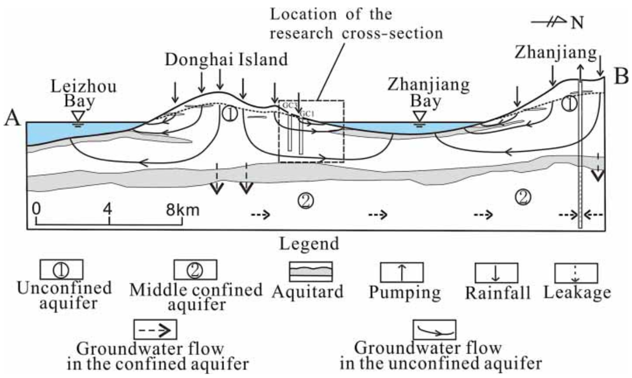

Figure 2 | Schematic cross-section of Donghai Island along the line AB in Figure 1(b) (cited from Zhou *et al*. (2014). Copyright: Springer-Verlag Berlin Heidelberg, 2013; Pengpeng Zhou).

Considering the existence of a thick layer of very low-permeability clay, the vertical leakage through clay layer is neglected in this model. To build the numerical groundwater flow model in this profile, the density-dependent groundwater numerical model SEAWAT (Guo & Langevin 2002) was used. With this model, the tide-induced groundwater level dynamics was simulated. Then, the effects of pumping on tide-induced groundwater level fluctuation were assessed under various groundwater pumping scenarios.

Model domain and model discretization

As shown in Figure 3, this cross-section domain with a sloping beach has a length of 1,200 m, a depth of 30 m on the left inland boundary, and a width of 5 m. For this vertical model domain, the model cells are uniform of $4\ \mathrm{m} \times 0.2\ \mathrm{m} \times 5\ \mathrm{m}$, resulting in 300 columns, 150 layers and 1 row.

Boundary conditions

The boundary conditions assigned in the numerical model are shown in Figure 3. A time-varied head was assigned to the right boundary where groundwater is in contact with the sea. According to the observational groundwater level data, a specified head of 3.2 m was assigned to the saturated portion of the left boundary. For the bottom of the model domain, no-flux boundary was adopted. The phreatic surface was the upper boundary. For transport, a specified concentration equal to saltwater chloride (15,883 mg/L) was assigned at the right boundary. A constant chloride concentration of 45 mg/L was used on the inland boundary to represent the fresh water. The bottom and upper boundaries of the model domain were assigned as no solute transport boundaries. It should be noted that, with a short time (72 h) of the transient simulation, the evaporation and rainfall infiltration were not considered in our model.

Model parameters

According to the hydrogeologic investigation in this area, the horizontal hydraulic conductivity (Kx) of this coastal aquifer is 3.27–5.43 m/d, and the specific yield (S_y) of this coastal aquifer is 0.09–0.22. For the transport in SEAWAT model, it is difficult to obtain actual dispersivity values through field dispersion experiments. In our model, the longitudinal dispersivity (α_L) was set as 10 m that was determined based on the relationship between longitudinal dispersivity (α_L) and scale (L_s) of 2D numerical model for porous media (Li & Chen 1995). The research of Ranganathan & Hanor (1988) proved that a transverse dispersivity (α_T) close to one-fifth of the longitudinal dispersivity (α_L) can be used in a cross-sectional transport modelling for an aquifer system. So in our model, the transverse dispersivity (α_T) was set as 2 m. The density of seawater was set to 1.025 g/cm^3 while the density of freshwater was set to 1 g/cm^3. The model input parameters are listed in Table 1.

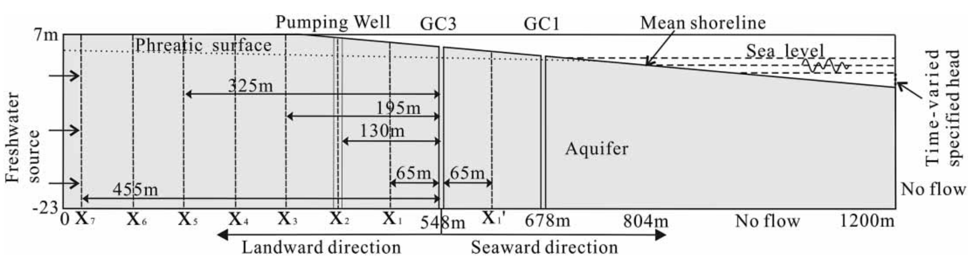

Figure 3 | Schematic of the conceptual model (revised from Zhou *et al*. (2014). Copyright: Springer-Verlag Berlin Heidelberg, 2013; Pengpeng Zhou).

Table 1 | Model input parameters

Parameter	Value
Hydraulic conductivity	3.27–5.43 m/d
Specific yield	0.09–0.22
Porosity	0.3
Longitudinal dispersivity (α_L)	10 m
Transverse dispersivity (α_T)	2 m
Seawater density	1,025 kg/m^3
Freshwater density	1,000 kg/m^3

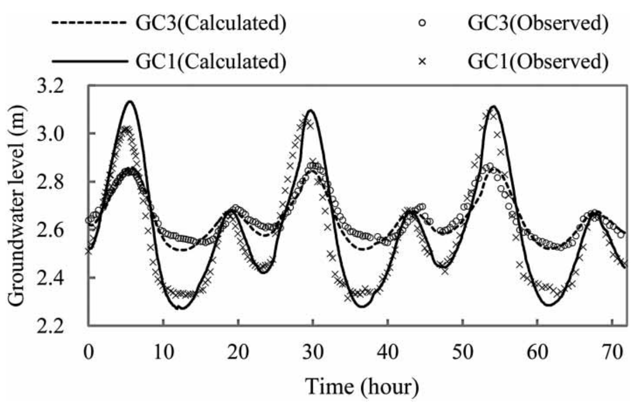

Figure 4 | Calibration map obtained for transient-state conditions.

Initial conditions

Before transient simulation with the tidal fluctuation at the seaward boundary, a steady state simulation without the tidal fluctuation was conducted to calculate the initial hydraulic head situation calibrated by the observed data monitored at the mean sea level period. Then, the computed result of the steady flow and concentration fields served as the initial conditions for the transient simulation.

Model calibration

The main objective of calibration is to obtain reasonable results matching with the field monitoring data by adjusting the parameters that can characterize the aquifers system.

Firstly, using the groundwater level data of GC1 and GC3 measured in mean sea level period, a preliminary calibration for the steady groundwater flow model was initially conducted to estimate the hydraulic conductivity (K) value. The anisotropy ratio Kz/Kx (vertical versus horizontal hydraulic conductivity) was 0.1. For this model, the calibrated Kx value was 5 m/d.

Secondly, this 2D model was calibrated for the transient conditions with the tidal fluctuation at the seaward boundary. This calibration had a period of 72 h during December 2–5, 2009. These calibration results were obtained by comparing simulated groundwater level data of observation wells GC1 and GC3 in 72 hour period. Figure 4 shows the time series graph of simulated versus observed groundwater level fluctuations for those two wells. This graph shows general similar groundwater level dynamics between simulated and observed groundwater levels data, despite discrepancies around the peaks and troughs. Such discrepancies are likely due to the neglect of the seepage face dynamics during the tide oscillation. The calibrated specific yield (S_y) was 0.15. It should be noted that, because of the neglect of the seepage face, this model assumed that the exit point of the groundwater level was coupled with the sea level on the beach face. Thus, this model cannot be used to accurately calculate the net submarine groundwater discharge (Ma *et al.* 2015).

Based on the calibrated results of the reasonable head match and hydraulic parameters (including hydraulic conductivity and specific yield), it can be seen that this numerical model is reasonable and can be selected as the base model for simulating groundwater level dynamics under influence of groundwater pumping.

It should be noted that, as a result of the lack of salinity data, this model was not able to calibrate the salinity dynamics. Some previous research about the variable density effect on the groundwater level dynamics shows that the variable density has no significant influence on tide-induced groundwater level dynamics (Ataie-Ashtiani *et al.* 2001; Li & Jiao 2001; Zhou *et al.* 2014), because the hydraulic gradients generated by the tidal cycle is much larger than that generated by variable density effects. Overall, this model can be used to study the pumping effects on groundwater level dynamics of the aquifer part above the salt wedge. In the next modeling study of the pumping effects on groundwater level dynamics, the salinity or density effects were neglected.

RESULTS AND DISCUSSION

Using the calibrated model, various groundwater pumping scenarios were designed to study the pumping effects on tide-induced groundwater level fluctuation and on the accuracy of the hydraulic parameter estimated by tidal method. Those pumping scenarios considered different pumping well location, transient pumping, and partial penetration wells with different screen length, respectively.

Effects of the pumping well location

Previous studies (Trefry & Johnston 1998; Chapuis *et al.* 2006; Ni *et al.* 2013; Wang *et al.* 2014) about the groundwater level dynamics jointly induced by groundwater pumping and tidal forcing mainly focused on correcting the drawdown data during the pumping test, with a fixed pumping well location. In contrast to those previous studies, this study concentrates on the effect of pumping on tide-induced groundwater level fluctuation and on the accuracy of the estimated parameters values of the aquifer via tidal method. In addition, we change the well location in our model to examine this pumping effect.

In this section, eight simulation scenarios with different pumping well locations (i.e., distance to the observation well GC3) were designed (Figure 3). In all those scenarios, 65 m is a base distance. For example, in scenario X_1', the seaward distance between the pumping well and observation well GC3 is 65 m; in scenario X_1, the landward distance between the pumping well and observation well GC3 is 65 m; in scenario X_2, the landward distance between the pumping well and observation well GC3 is 2×65 m (130 m); in scenario X_j, the landward distance between the pumping well and observation well GC3 is $j \times 65$ m. In all scenarios, the pumping well is a partial penetration well with a screen length of 15 m, and the groundwater pumping rate is constant at 20 m^3/d.

The simulated groundwater level fluctuations in the observation wells in all the simulated scenarios are illustrated in Figure 5(a) and 5(b). The results show that shorter

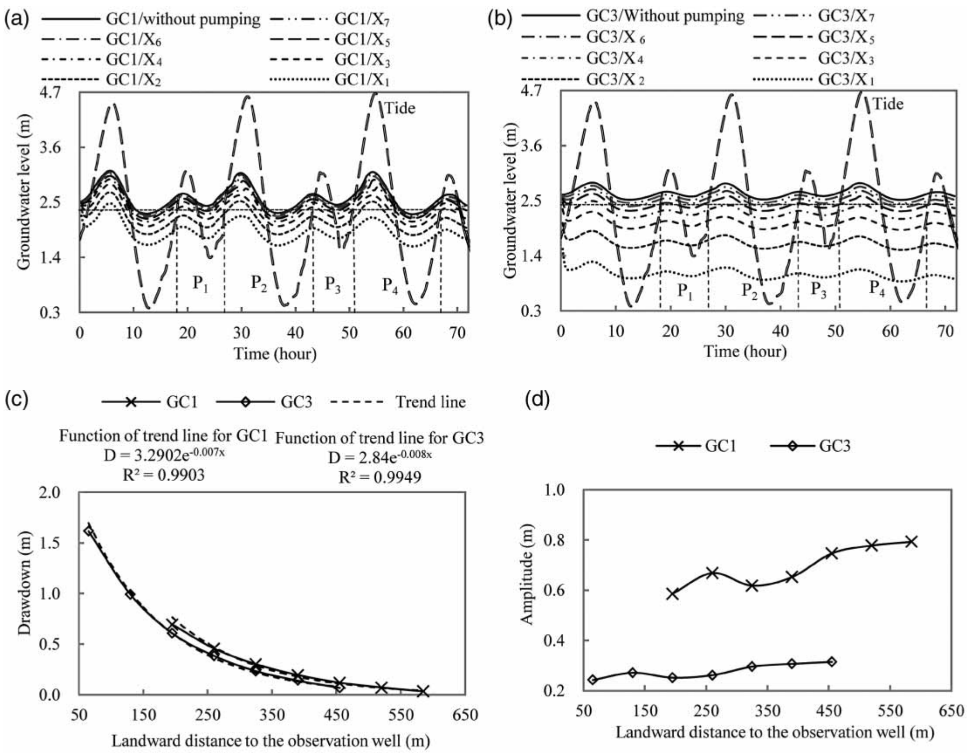

Figure 5 | Groundwater level dynamics in the observation wells with the pumping well located at different landward locations: (a) groundwater level fluctuation in GC1; (b) groundwater level fluctuation in GC3; (c) variation of the mean groundwater level drawdown, i.e., each *trend line* is defined by a function that expresses the relationship between the drawdown (represented by D in the function) and the landward distance (represented by x in the function); (d) variation of the amplitude.

landward distance between the pumping well and observation well induces larger mean groundwater level drawdown because of the influence radius of the pumping well. In any of these scenarios, the groundwater level fluctuation can eventually reach a quasi-steady state, no matter how short the landward distance.

Figure 5(c) shows that an exponential correlation exists between the drawdown (D) and landward distance (x) in this homogeneous coastal aquifer. Figure 5(d) shows that, in all pumping scenarios, the amplitudes of the tide-induced groundwater level fluctuations are smaller than the monitoring amplitudes without pumping's influence ($A_{GC1} = 0.844$ m, $A_{GC3} = 0.335$ m). However, there is no consistent rule for describing the influence of the pumping well location on the amplitude.

Typically, the observed amplitude and time lag of the tide-induced groundwater level fluctuation can be used to estimate hydraulic parameters (such as the ratio of transmissivity to storativity, T/S) of a coastal aquifer. Considering the influence of the landward pumping activities on the observed tide-induced groundwater level data, analysis is conducted to investigate the effects of the pumping well location on the accuracy of the hydraulic parameters estimated via the tidal method. We estimate the aquifer parameter T/S by using the simulated groundwater level data in each scenario and the calculation equation, $T/S = \pi/t_p[x_{GC3} - x_{GC1}/\ln(A_{GC1}/A_{GC3})]^2$ (Zhou *et al.* 2015). In this equation, $T[L^2T^{-1}]$ is the transmissivity of the aquifer, S is the storativity of the aquifer, $t_p[T]$ is the period of the tide, A_{GC1} and A_{GC3} are the amplitudes of the groundwater level fluctuations in wells GC1 and GC3, respectively, and x_{GC1} (126 m) and x_{GC3} (256 m) are the landward distances from the coastline to wells GC1 and GC3, respectively.

A_{GC1} and A_{GC3} can be calculated according to the groundwater level fluctuations that have reached the quasi-steady state in each simulated scenario. In addition, according to the fluctuation pattern of the irregular semidiurnal tide, the tide is divided into four symmetric tidal periods (P_1, P_2, P_3, and P_4) to determine the tidal period t_p ($t_{p_1} = 8.66$ h, $t_{p_2} = 16.34$ h, $t_{p_3} = 7.66$ h, and $t_{p_4} = 16.00$ h) (Figure 5(a) and 5(b)). The results of the aquifer parameters estimated via the tidal method are listed in Table 2. Table 2 shows that the estimated parameters (average value of T/S) in all the scenarios with pumping influence have a certain relative error. It can be concluded that, when the distance between the landward pumping well and the tide observation well exceeds 200% of the distance between the tide observation well and the mean shoreline, the relative error of the estimated parameters is less than 1%, in which case the tidal method can be used to estimate hydraulic parameters.

Moreover, to investigate the difference between the effects of seaward and landward pumping activities on the tide-induced groundwater level fluctuation, two scenarios are designed: locating the pumping well at X_1' and X_1 (Figure 3). The seaward distance from X_1' to observation well GC3 is equal to the landward distance from X_1 to GC3. The simulated result is shown in Figure 6. From Figure 6, it can be seen that seaward pumping activities can cause slightly larger drawdown (0.04–0.10 m) than landward pumping activities; however, the groundwater level fluctuating patterns (phase and amplitude) in scenarios of X_1 and X_1' are overall similar. In a word, the seaward pumping plays a relatively obvious role than the landward pumping in enhancing the groundwater level drawdown.

In summary, the pumping well location is an important factor that contributes to the effects of pumping on tide-induced groundwater level fluctuation; a shorter landward distance can induce a greater mean groundwater level drawdown; during the groundwater pumping process, the groundwater level fluctuation can eventually reach a quasi-steady state again; groundwater pumping can attenuate the amplitude of the groundwater level fluctuation to some extent, but there is no consistent rule to describe this attenuation; seaward pumping have relative more obvious influences on enhancing the groundwater level drawdown than landward pumping. In addition, the pumping well location can affect the accuracy of the hydraulic parameters estimated via tidal method; however, when the distance between the pumping well and the tide observation well exceeds 200% of the distance between the observation well and the shoreline, this pumping effect on the accuracy of the hydraulic parameters can be neglected which means that the tidal method can still be used to estimate the hydraulic parameter.

Effects of pumping dynamics

This section describes the influences of transient pumping on the tide-induced groundwater level fluctuation. The

Table 2 | Estimation of the aquifer parameters using tidal method for all the scenarios with different pumping well locations

Without pumping

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.303	0.118	165,364.4
P_2	0.802	0.320	92,330.5
P_3	0.216	0.087	201,056.1
P_4	0.844	0.335	93,227.3
Average value of T/S			**137,994.6**

Pumping well at X_1

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.273	0.102	153,538.2
P_2	0.586	0.242	100,152.5
P_3	0.200	0.085	224,663.6
P_4	0.579	0.238	100,844.6
Average value of T/S			**144,799.7**
Relative error			**4.93%**

Pumping well at X_2

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.290	0.110	156,496.0
P_2	0.668	0.271	95,763.4
P_3	0.203	0.085	219,384.9
P_4	0.672	0.273	98,098.8
Average value of T/S			**142,435.8**
Relative error			**3.22%**

Pumping well at X_3

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.297	0.113	157,663.2
P_2	0.618	0.252	96,648.4
P_3	0.217	0.089	209,478.8
P_4	0.622	0.252	97,594.9
Average value of T/S			**140,346.3**
Relative error			**1.70%**

Pumping well at X_4

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.298	0.114	159,278.7
P_2	0.653	0.262	93,457.2
P_3	0.216	0.089	211,496.0
P_4	0.692	0.274	92,737.7
Average value of T/S			**139,242.4**
Relative error			**0.90%**

Pumping well at X_5

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.298	0.115	160,632.7
P_2	0.747	0.296	90,879.3
P_3	0.216	0.088	206,915.4
P_4	0.769	0.304	92,247.9
Average value of T/S			**137,668.8**
Relative error			**0.24%**

Pumping well at X_6

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.299	0.115	161,078.6
P_2	0.778	0.307	90,141.1
P_3	0.216	0.088	206,206.6
P_4	0.817	0.324	93,051.2
Average value of T/S			**137,619.4**
Relative error			**0.27%**

Pumping well at X_7

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.299	0.116	163,627.9
P_2	0.793	0.315	91,410.9
P_3	0.216	0.087	203,541.5
P_4	0.834	0.329	92,097.3
Average value of T/S			**137,669.4**
Relative error			**0.24%**

pumping well is located at X_2 in all simulation scenarios. The pumping well is a partial penetration well with a screen length of 15 m. The total extraction of groundwater is 20 m^3/d. The simulated results are shown in Figure 7. From Figure 7, it can be seen that transient pumping can significantly enhance the amplitude of the groundwater level fluctuation, whereas the periodicity and the mean groundwater level of such fluctuations keep the same as those induced by steady pumping. So in conclusion, transient pumping have more significant influence on the

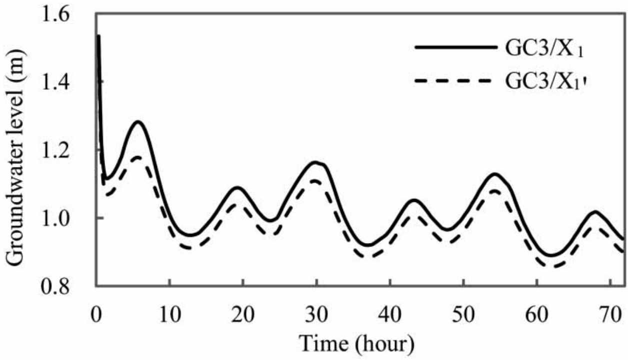

Figure 6 | Groundwater level fluctuations influenced by pumping in the landward and seaward locations.

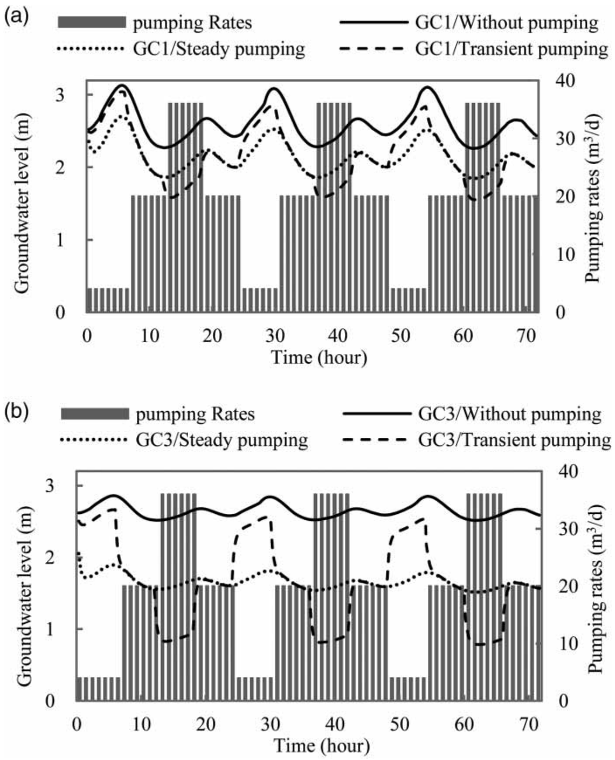

Figure 7 | Groundwater level fluctuations under transient pumping conditions: (a) GC1; (b) GC3.

tide-induced groundwater level dynamics than steady pumping. Meanwhile, it should be noted that, with the combined action of tidal forcing and transient pumping, the enhanced large amplitude does not mean a large transmissivity of the coastal aquifer.

As we know, a higher steady pumping rate can induce a greater groundwater level drawdown. However, the effect of pumping rate on the accuracy of the aquifer's hydraulic parameters estimated via tidal method still needs to be investigated. To this end, using the simulated groundwater level data jointly induced by steady pumping and tidal forcing, the hydraulic parameter (T/S) was estimated via the tidal method (Table 3). From the calculated relative error in Table 3, it can be seen that a larger pumping rate could induce a greater calculation error. So it can be concluded that the influence of pumping rate on the accuracy of the estimated parameters via the tidal method cannot be ignored.

Effects of the partial penetration well

For the purpose of discussing the effect of a partial penetration well on the tide-induced groundwater level dynamics, a series of simulation scenarios with different types of partial penetration wells were designed. The type of partial penetration well is expressed as a ratio of the screen length of the partial penetration well to that of the full penetration well (25 m). A ratio of 1 means a full penetration well. In all the scenarios, the pumping well with a constant groundwater pumping rate (20 m^3/d) is located at X_2 (Figure 3). The simulated results are shown in Figure 8.

Figure 8 clearly shows that the mean groundwater level drawdown in a tide observation well influenced by a landward partial penetration well is greater than that influenced by a full penetration well. The shorter the screen length of the partial penetration well, the larger the mean groundwater level drawdown.

Figure 8(a) and 8(b) show that, for all the simulated scenarios, the phases of the tide-induced groundwater level fluctuations in the quasi-steady state do not show significant variation. However, as shown in Figure 8(c), the amplitudes are smaller than those in the scenario without pumping. No consistent rule exists to describe the effects of the partial penetration well on the amplitude.

Furthermore, the aquifer parameters were estimated according to the tidal method and simulated groundwater level data in each scenario (Table 4). The calculated relative error data in Table 4 clearly demonstrate that the effect of full penetration well on the accuracy of the estimated results via the tidal method is more obvious than that of a partial penetration well.

Table 3 | Aquifer parameters estimated with the tidal method for all the scenarios with different pumping rates

Q = 0 m³/d

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.303	0.118	165,364.4
P_2	0.802	0.320	92,330.5
P_3	0.216	0.087	201,056.1
P_4	0.844	0.335	93,227.3
Average value of T/S			**137,994.6**

Q = 10 m³/d

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.298	0.114	159,278.7
P_2	0.618	0.251	96,004.5
P_3	0.222	0.09	203,962.6
P_4	0.622	0.251	96,655.5
Average value of T/S			**138,975.4**
Relative error			**0.71%**

Q = 20 m³/d

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.290	0.110	155,712.0
P_2	0.669	0.271	95,822.3
P_3	0.203	0.085	218,713.9
P_4	0.672	0.273	98,311.7
Average value of T/S			**142,140.0**
Relative error			**3.00%**

Q = 30 m³/d

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.269	0.1	150,190.3
P_2	0.639	0.263	98,899.4
P_3	0.198	0.084	226,141.9
P_4	0.643	0.264	100,446.9
Average value of T/S			**143,919.6**
Relative error			**4.29%**

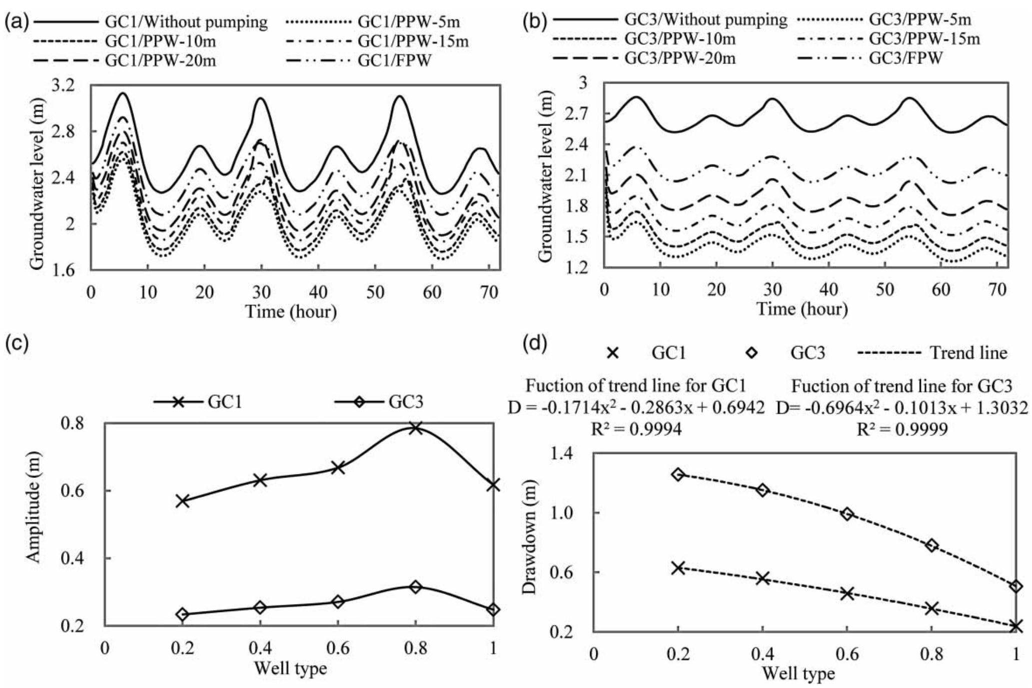

Figure 8 | Groundwater level dynamics in the observation wells with landward pumping in different types of partial penetration wells: (a) groundwater level fluctuation in GC1; (b) groundwater level fluctuation in GC3; (c) variation of the amplitude in the quasi-steady state; (d) variation of the mean groundwater level drawdown.

Table 4 | Aquifer parameters estimated with the tidal method for all the scenarios with different pumping well types

Without pumping

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.303	0.118	165,364.4
P_2	0.802	0.320	92,330.5
P_3	0.216	0.087	201,056.1
P_4	0.844	0.335	93,227.3
Average value of T/S			**137,994.6**

Full penetration well with screen length of 25 m

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.267	0.102	158,289.3
P_2	0.569	0.234	98,529.8
P_3	0.207	0.086	216,448.4
P_4	0.591	0.243	100,841.9
Average value of T/S			**143,527.3**
Relative error			**4.01%**

Partial penetration well with screen length of 20 m

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.267	0.102	158,103.0
P_2	0.631	0.254	93,899.1
P_3	0.196	0.082	220,944.9
P_4	0.626	0.250	94,765.3
Average value of T/S			**141,928.1**
Relative error			**2.85%**

Partial penetration well with screen length of 15 m

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.290	0.110	155,712.0
P_2	0.669	0.271	95,822.3
P_3	0.203	0.085	218,713.9
P_4	0.672	0.273	98,311.7
Average value of T/S			**142,140.0**
Relative error			**3.00%**

Partial penetration well with screen length of 10 m

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.283	0.107	155,928.4
P_2	0.785	0.315	93,376.7
P_3	0.197	0.083	219,580.6
P_4	0.821	0.326	93,589.4
Average value of T/S			**140,618.8**
Relative error			**1.90%**

Partial penetration well with screen length of 5 m

	A_{GC1} (m)	A_{GC3} (m)	T/S (m²/d)
P_1	0.298	0.113	157,057.5
P_2	0.617	0.248	93,518.4
P_3	0.215	0.085	194,312.3
P_4	0.622	0.249	95,379.5
Average value of T/S			**135,066.9**
Relative error			**2.12%**

CONCLUSIONS

This paper presents a series of numerical simulations to study the effects of groundwater pumping on tide-induced groundwater level dynamics and on the accuracy of the aquifer's hydraulic parameters estimated via the tidal method. In those simulations, many specific influencing factors, such as the pumping well location, transient pumping dynamics and partial penetration well, were considered. The general conclusions are presented here.

Under the combined action of the groundwater pumping and sea tide, the groundwater level dynamics is characterized by an obvious drawdown but still with a periodic tidal fluctuation. A shorter distance between the landward pumping well and the tide observation well or a shorter screen length can induce a greater drawdown. By comparison, seaward groundwater pumping plays a relatively obvious role in enhancing drawdown than landward pumping. However, the groundwater level fluctuation can eventually reach a quasi-steady state, no matter how short the landward distance, how short the well's screen length. This phenomenon mainly occurs because of dominant influence of tidal forcing when the drawdown reaches a stable state.

Groundwater pumping can decrease the amplitude of the tide-induced groundwater level fluctuation at quasi-steady state. However, there is no consistent rule for describing the effects of pumping on the amplitude. In addition, the groundwater pumping has no obvious influence on the phase of the groundwater level fluctuation at quasi-steady state.

Transient pumping can significantly increase the amplitude of the groundwater level fluctuation, but the periodicity of such fluctuation keeps the same as that under steady pumping condition. It should be noted that this increased amplitude induced by combined action of tidal forcing and transient pumping does not reflect a large transmissivity of the coastal aquifer.

Groundwater pumping takes a non-negligible role in affecting the accuracy of the hydraulic parameters estimated via the tidal method. Firstly, influenced by a nearby pumping well, the groundwater level data of the tide observation well cannot be used to estimate the hydraulic parameter via the tidal method. However, when the distance between the pumping well and the tide observation well exceeds 200% of the distance between the observation well and the mean shoreline, the monitored data can be used to estimate hydraulic parameter via the tidal method. Secondly, the pumping dynamics are also a significant factor in influencing the accuracy of the hydraulic parameters estimated via the tidal method. There will be a large error in the estimation of hydraulic parameters by using quasi-steady groundwater level fluctuation data induced by the combined effects of tide and transient pumping or large constant pumping. Thirdly, the full penetration effect has a considerably bad influence on the accuracy of the tidal method's calculation results.

Those conclusions not only provide some in-depth understanding about the coastal groundwater level dynamics, but also provide useful guidance for reasonable application of the tidal method in determining hydraulic parameters of a coastal aquifer.

ACKNOWLEDGEMENTS

We are grateful to the reviewers for their thoughtful comments. This work was supported by the National Natural Science Foundation of China (Grant No. 41502255).

REFERENCES

Ataie-Ashtiani, B., Volker, R. E. & Lockington, D. A. 2001 Tidal effects on groundwater dynamics in unconfined aquifers. *Hydrological Processes* **15**, 655–669. doi:10.1002/hyp.183.

Cassiani, G. & Kabala, Z. J. 1998 Hydraulics of a partially penetrating well: solution to a mixed-type boundary value problem via dual integral equations. *Journal of Hydrology* **211**, 100–111. doi: 10.1016/S0022-1694(98)00223-6.

Chapuis, R. P., Bélanger, C. & Chenaf, D. 2006 Pumping test in a confined aquifer under tidal influence. *Groundwater* **44**, 300–305. doi:10.1111/j.1745-6584.2005.00139.x.

Chen, C. & Jiao, J. J. 1999 Numerical simulation of pumping tests in multilayer wells with non-Darcian flow in the wellbore. *Groundwater* **37**, 465–474. doi:10.1111/j.1745-6584.1999.tb01126.x.

Guo, W. & Langevin, C. D. 2002 *User's Guide to SEAWAT: A Computer Program for Simulation of Three-Dimensional Variable-Density Groundwater Flow. Techniques of Water Resources Investigations*, Book 6. US Geological Survey, Florida, USA.

Hantush, M. S. 1961 Aquifer tests on partially penetrating wells. *Journal of the Hydraulics Division, American Society of Civil Engineers Transactions* **87**, 171–195.

Li, G. M. & Chen, C. X. 1995 Fractal geometry and estimation of scale-dependent dispersivity in geologic media. *Earth Science – Journal of China University of Geosciences* **20**, 405–409. (In Chinese).

Li, H. & Jiao, J. J. 2001 Tide-induced groundwater fluctuation in a coastal leaky confined aquifer system extending under the sea. *Water Resources Research* **37**, 1165–1171. doi: 10.1029/2000WR900296.

Lian, J., He, W., Ma, C. & Xu, K. 2015 Guarantee rate of freshwater in a river mouth intruded by saltwater with respect to the joint impact of runoff and tide. *Journal of Hydroinformatics* **17**, 917–929. doi: 10.2166/hydro.2015.038.

Liu, K. 1996 Tide-induced ground-water flow in deep confined aquifer. *Journal of Hydraulic Engineering* **122**, 104–110. doi:10.1061/(ASCE)0733-9429(1996)122:2(104).

Ma, Q., Li, H., Wang, X., Wang, C., Wan, L., Wang, X. & Jiang, X. 2015 Estimation of seawater–groundwater exchange rate: case study in a tidal flat with a large-scale seepage face (Laizhou Bay, China). *Hydrogeology Journal* **23**, 265–275. doi: 10.1007/s10040-014-1196-z.

Millham, N. P. & Howes, B. L. 1995 A comparison of methods to determine K in a shallow coastal aquifer. *Groundwater* **33**, 49–57. doi: 10.1111/j.1745-6584.1995.tb00262.x.

Narasimhan, T. N. & Zhu, M. 1993 Transient flow of water to a well in an unconfined aquifer: applicability of some conceptual models. *Water Resources Research* **29**, 179–191. doi: 10.1029/92WR01959.

Ni, J. C., Cheng, W. C. & Ge, L. 2011 A case history of field pumping tests in a deep gravel formation in the Taipei Basin, Taiwan. *Engineering Geology* **117**, 17–28. doi: 10.1016/j.enggeo.2010.10.001.

Ni, J. C., Cheng, W. C. & Ge, L. 2013 A simple data reduction method for pumping tests with tidal, partial penetration, and storage effects. *Soils and Foundations* **53**, 894–902. doi:10.1016/j.sandf.2013.10.008.

Qu, C. Y. & Chen, S. H. 2010 Performance and analysis of pumping tests in a gravel formation. *Bulletin of Engineering Geology and the Environment* **69**, 1–2. doi: 10.1007/s10064-009-0218-x.

Ranganathan, V. & Hanor, J. S. 1988 Density-driven groundwater flow near salt domes. *Chemical Geology* **74**, 173–188. doi: 10.1016/0009-2541(88)90152-0.

Ruud, N. C. & Kabala, Z. J. 1997 Response of a partially penetrating well in a heterogeneous aquifer: integrated well-face flux vs. uniform well-face flux boundary conditions. *Journal of Hydrology* **194**, 76–94. doi: 10.1016/S0022-1694(96)03217-9.

Sadeghi-Tabas, S., Samadi, S. Z., Akbarpour, A. & Pourreza-Bilondi, M. 2016 Sustainable groundwater modeling using single- and multi-objective optimization algorithms. *Journal of Hydroinformatics* doi: 10.2166/hydro.2016.006.

Singh, M. K., Singh, V. P. & Das, P. 2016 Mathematical modeling for solute transport in aquifer. *Journal of Hydroinformatics* **18**, 481–499. doi:10.2166/hydro.2015.034.

Trefry, M. G. & Johnston, C. D. 1998 Pumping test analysis for a tidally forced aquifer. *Groundwater* **36**, 427–433. doi:10.1111/j.1745-6584.1998.tb02813.x.

Wang, C., Li, H., Wan, L., Wang, X. & Jiang, X. 2014 Closed-form analytical solutions incorporating pumping and tidal effects in various coastal aquifer systems. *Advances in Water Resources* **69**, 1–12. doi:10.1016/j.advwatres.2014.03.003.

Yang, S. Y., Yeh, H. D. & Chiu, P. Y. 2006 A closed form solution for constant flux pumping in a well under partial penetration condition. *Water Resources Research* **42**, W05502. doi:10.1029/2004WR003889.

Zhou, P., Li, G., Lu, Y. & Li, M. 2014 Numerical modeling of the effects of beach slope on water-table fluctuation in the unconfined aquifer of Donghai Island, China. *Hydrogeology Journal* **22**, 383–396. doi:10.1007/s10040-013-1045-5.

Zhou, X., Song, C., Li, T., Chen, R., Zhang, H., Zhao, J. & Cao, Q. 2015 Estimation of aquifer parameters using tide-induced groundwater level measurements in a coastal confined aquifer. *Environmental Earth Sciences* **73**, 2197–2204. doi:10.1007/s12665-014-3570-5.

First received 10 August 2016; accepted in revised form 2 January 2017. Available online 15 March 2017