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Simulation of groundwater-seawater interaction in the coastal surficial aquifer in Bohai Bay, Tianjin, China

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ABSTRACT

This paper quantitatively investigates groundwater-seawater interactions and explores the annual variations and spatial distributions in submarine groundwater discharge (SGD) and seawater intrusion (SWI) in the Bohai Sea coastal zone in Tianjin, China. A three-dimensional finite element model, FEMWATER in the GMS environment, is developed to simulate density-dependent flow and transport in coastal groundwater aquifers. A sensitivity analysis is used to explore how the model output varies with the hydrogeological parameters and boundary conditions. The results suggest that both SGD and SWI occur across the sea-aquifer interface. Along the modeled 45 km stretch of coastline, the annual SGD and SWI rates are 4.23×10^7 m^3/yr and 0.86×10^7 m^3/yr, respectively. The results also indicate that SGD is highest in the winter and lowest in the summer, and SWI exhibits the opposite trend. This change in flow direction across the sea-aquifer interface corresponds to seasonal changes in sea level. SGD mainly occurs in the southern and northern parts of the study area, and SWI primarily occurs in the central part. The results of the sensitivity analysis suggest that the SGD and SWI model outputs are most sensitive to sea level and the hydraulic conductivity in the top layer.

1. Introduction

Water and chemical fluxes across the groundwater-seawater interface provide important links between the terrestrial and marine environments. These interfaces can be hydrologically dynamic and are characterized by groundwater seepage into and out of the surface water body and groundwater-surface water mixing. Submarine groundwater discharge (SGD) constitutes an important source of nutrients, contaminants and trace elements that affects the coastal ocean. Seawater intrusion (SWI) into coastal aquifers may affect groundwater quality and availability in coastal areas and influence sustainable coastal groundwater management. Groundwater-seawater interactions have now become major concerns of oceanographers, hydrologists and hydrogeologists around the world. The researchers share common goals of quantifying and understanding groundwater and seawater interactions.

There are three approaches to quantifying groundwater-seawater exchange: (1) seepage meters, (2) numerical modeling, and (3) geochemical tracers. Numerical models have become an invaluable tool for understanding subsurface flow in coastal aquifers (Li et al., 1999; Smith and Zawadzki, 2003; Thompson et al., 2007). Variable density groundwater flow and solute transport models have been traditionally used to simulate SWI, but these models can also be used to provide quantitative estimates of SGD. The use of numerical models is appealing because a simulation can provide spatially and temporally detailed estimates of SGD and SWI rates. A well-calibrated numerical model is a justifiable tool for estimating SGD and SWI within a study area by interpolating and extrapolating field measurements in space and time (Langevin et al., 2005). Another advantage of hydrogeological simulations is their ability to calculate the terrestrial groundwater flux and even future discharge changes through the integration of scenarios.

The Tianjin plain area is characterized by rapid urbanization and industrialization, particularly in the coastal zone. The environment of the Bohai Sea has been altered greatly in recent years. In particular, the nutrient structure has changed dramatically. The inorganic nitrogen content has increased, and the inorganic phosphorus content has decreased. Moreover, because the nutrient ratio has changed, the phytoplankton community structure has also changed. Local water eutrophication has increased and harmful algal blooms occur frequently. Nutrients supplied to coastal waters

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via SGD have been documented to influence productivity, potentially lead to harmful algal blooms (Hu et al., 2006; Paerl, 1997) and increase bacterial concentrations (Boehm et al., 2004, 2006); however, the potential effects of SGD on this near-shore region have not yet been investigated.

Studies of SGD in coastal aquifers often focus on shallow (<20 m) and narrow (<5 km) zones surrounding the coastline (Kim et al., 2008; Taniguchi et al., 2002). However, flow systems related to SGD may extend to at least 20 km off the shoreline, in some cases reaching the continental slope (Wilson, 2005). Additionally, a small number of studies have attempted to quantify SGD at the regional scale, with estimates typically based on geochemical tracers (McCoy and Corbett, 2009; Wang et al., 2015) or hydrogeological modeling (Langevin, 2003; Langevin et al., 2005; Wilson, 2005; Ferrarin et al., 2008; Li et al., 2008; Qu et al., 2014).

Groundwater-seawater exchange in coastal zones, including SWI and SGD, is an important part of the water cycle. Studying the rates of SWI and SGD is critical and can influence governance and management associated with environmental protection. Few studies have quantified the effects of parameters in simulations. This paper aims to understand groundwater–seawater interactions and investigate the temporal and spatial variations of SGD and SWI in Bohai Bay, Tianjin. We use the three-dimensional, transient, density-dependent, finite element-based flow and transport simulation model FEMWATER (Lin et al., 1997). Combined with actual information from the study site, lengths of 15 km offshore and ~25 km onshore are chosen as the dimensions of the model domain. Furthermore, the parameters affecting the output of the model are quantitatively evaluated by applying the one-at-a-time (OAT) approach.

2. General description of the study area

The study area is located on the western coast of the Bohai Bay, in Tianjin City, China, located between N38°45′ and N39°12′ and E117°12′ and E118°00′. Two rivers border the terrestrial portion (maximum W-E extent is ~25 km, with a total area of 743 km^2, explained in detail later) of the study area at the northern and southern boundaries. Both boundaries extend towards the offshore portion of the study area (maximum W-E extent is ~15 km, with a total area of 524.8 km^2, explained in detail later), creating an interface length of 45 km between the onshore and offshore areas (Fig. 1). Topographically, this coastal area is flat, and the elevation ranges from 0 to 5 m above sea level. The rivers at the northern and southern boundaries and the Hai River in the center of the study area have gentle hydraulic gradients of less than 1%. All are artificially controlled by water gates and have annual stage variations of less than 1.5 m. The Bohai Sea is a shallow inland sea, with an average depth of 18 m, and the depth within the study area is much shallower (<10 m). The level of the Bohai Sea fluctuates annually and is highest during the summer and lowest during the winter.

The study region has a typical sub-humid, warm temperate continental monsoon climate characterized by hot and rainy summers and cold and dry winters. The average annual temperature is approximately 12 °C. The average annual precipitation is approximately 500 mm/yr, 75% of which occurs in July, August, and September. Previous investigations suggested that a relatively small precipitation fraction of 2–20% is recharged into the aquifers underlying coastal plains (Guo et al., 1998; Tang, 2007; Zhang, 2012). The average annual variation in precipitation, the stage of the Hai River, and the level of the Bohai Sea are shown in Fig. 1.

The distribution of salinity in the surficial aquifer is illustrated in Fig. 2. It is based on data that include salinity contour maps and salinity distribution curves with depths from different data sources (Li, 1989; Sun, 1988; Tianjin Geology and Mine Survey Bureau, 2004; Zheng, 1989). In this area, the saline aquifer has a stable level with seasonal and annual fluctuations because it has not yet been exploited (Yang et al., 2011). This leads to the assumption that the historical salinity data are comparable to the present situation and justify the application. TDS represents the total dissolved salinity and the TDS values, which are calculated based on total salt content, vary from minimum values of 1 g/l near the surface to 35 g/l at the shoreline. An interpolated TDS concentration distribution suggests that the salinity ranges from ~27 to 35 g/l at the shoreline, 15–25 g/l at 5000 m from the shoreline, 5–20 g/l at 10,000 m from the shoreline, and 1–14 g/l at 15,000 m from the shoreline (as shown in Fig. 3a). Due to precipitation recharge into the aquifer, connate saline water was diluted; as depth increases, the concentrations of TDS first increase and then decrease (Fig. 3b). However, the concentrations of TDS increase with decreasing distance to the ocean. Fig. 3 shows the TDS distribution in the horizontal direction in the study area and in the vertical direction at specific points.

Beneath the Tianjin coastal plain, groundwater aquifers consist of the surficial saline aquifer and the lower fresh aquifer, both of which are hydraulically isolated by a clay layer (as shown in Table 1). The model domain focuses on the surficial saline aquifer system only, which is composed of Holocene and late Pleistocene sedimentary sequences, resulting from the deposition of continental alluvial, lacustrine, palustrine, and marine sediments (silt, clay, fine sand, and sandstone). Six marine transgressions in the Quaternary period saturated the sediments with saline water. Major marine transgressions and regressions and the resulting shifts of facies are the primary determinants of the sequences of high- and low-permeability sediments (Chen et al., 2012a, 2012b; Wang et al., 2012). The whole sequence can be grouped into five layers, including two continuous sandy layers that represent aquifers and three clayey layers acting as aquitards or aquicludes.

3. Model development

To quantify regional-scale submarine groundwater discharge into Bohai Bay, data from various sources are employed to develop and implement the three-dimensional finite element simulation model utilizing FEMWATER. Our model represents an average scenario, reflecting the typical annual groundwater flow situation.

3.1. Governing equations

Variable density groundwater flow is described by the following partial differential equations (Lin et al., 1997):

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \left[K \left(\nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho^*}{\rho_0} q \tag{1}$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{dS}{dh} \tag{2}$$

where F = the Storage coefficient (1/L), h = Pressure head (L), t = Time (T), K = the Hydraulic conductivity tensor (L/T), z = Potential head (L), q = Source and/or sink (1/T), ρ = Water density at chemical concentration C (M/L^3), ρ_0 = Referenced water density at a chemical concentration of zero (M/L^3), ρ* = Density of inflowing or withdrawn water (M/L^3), θ = Moisture content (dimensionless), α′ = Modified compressibility (compressibility × density × acceleration) of the solids (1/L), β′ = Modified compressibility (compressibility × density × acceleration) of the water (1/L), n = Porosity (dimensionless), and S = Degree of saturation (dimensionless). In equation (1), the unknown is h.

The hydraulic conductivity K can be calculated as follows: