Seawater Intrusion Trend Forecast in Laizhou Bay Based on FEFLOW

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KEYWORD: Seawater Intrusion; Numerical Simulation; Model Prediction; Laizhou Bay

ABSTRACT: Seawater Intrusion is that seawater or saltwater intrude into the continent along the aquifer . Under the effects of the natural and artificial factors, the hydrodynamic conditions of aquifer in the coastal area has been changed ,which break the equilibrium between the seawater and the freshwater, hence the salt-fresh interface moves on the continent. Laizhou Bay suffers the most serious seawater intrusion in China. Based on analysis of the geological and hydro-geological condition in the study area, a flow and mass transport model has been developed to study the seawater intrusion in the area. Using FEFLOW software based on the finite element theory, this article solves the mathematic model and calibrates the model by long-term observation data of hydraulic head. Using the calibrated model it forecasts the evolution tendency of seawater intrusion. The modeling results showed that after 30 years total invasion of seawater intrusion in the area of about 4124 km^2, and the serious invasion area of 2678 km^2.

INTRODUCTION

Seawater intrusion is a global issue, exacerbated by increasing demands for freshwater in coastal zones and predisposed to the influences of rising sea levels and changing climates(Werner et.al,2013).Saline water intrusion threatens drinking water supplies, a large proportion of which are derived from groundwater, in the coastal region of China. The Bohai Sea area, especially Laizhou Bay, experiences the most severe seawater intrusion in North China (Meng et.al., 1997; Han et.al.2011). Seawater intrusion decreases the quality of drinking water by raising salinity to levels exceeding acceptable drinking water standards. This causes environmental contamination and soil secondary salinization. Local economies and social development can be considerably constrained by this increase in seawater intrusion, which affects industry and agriculture. With the development and extensive application of computer, using advanced groundwater model software to establish regional groundwater model on groundwater environmental impact assessment and predict the groundwater quality change trend, has become an important aspect of regional groundwater and its environmental research(Hu and Jiao, 2010;Sherif, et.al 2012; Nocchi, et.al 2013). At present, through the analytic method, the finite element method and finite difference method for extension and application of transition zone model, received a good application effect（Sadeg and Karahanoglu，2001； Kerrou and Renard, 2010；Abd-Elhamid and Javadi，2011）.

This paper is using FEFLOW software to establish the regional hydrogeology conceptual model, which based on analysis of the geological and hydro-geological condition in the study area and generalized boundary conditions, the structure of the aquifer system and groundwater flow characteristics. Using the existing groundwater level observation data, the model is calibrated to get initial flow field simulation area groundwater natural circumstances. Finally according to the characteristics of seawater intrusion, on the basis of the numerical model of groundwater seepage coupling solute transport equation, get the groundwater solute transport model. And then Using this model to predict the process of seawater intrusion, ultimately determine the scope and degree of the seawater intrusion.

conceptual model of groundwater system

Study area

The study area is located in the southern and eastern of laizhou bay. And the administrative districts include the city of Laizhou, Pingdu, and Weifang with a total area of about 10361.2km^2(Fig1). The study area is the most typical and serious region suffering

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from the geo-hazard of the seawater intrusion in China. Because of the influence of holocene epoch saltwater intrusion, dry climate, sea level rise and human activity, the Laizhou bay area has become the most serious and typical area of seawater intrusion in China(Yin, et.al. 1991, Han, et.al. 2001)

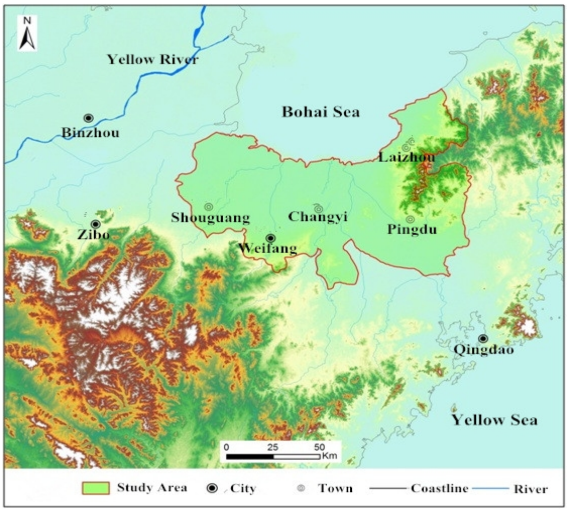

Figure 1. Study area

Aquifer system structure

The aquifer in the study area is mainly quaternary pore water, and the bedrock fissure water only distribute in the southern and eastern mountains in the study area. Groundwater recharge source is mainly supplied by atmospheric rainfall infiltration and the rivers in southern mountains, Which discharge Laizhou bay form south to north. Due to three major transgression regressive, formed the main three layers of water-resisting layer based on sandy clay deposits, which divided the groundwater into four levels: Vadose zone - the second confined aquifer in phreatic aquifer, the first confined aquifer, and the third confined aquifer(Fig 2). According to the hydrogeological conditions in the study area, a generalized geological model is divided into ten layers: the first and the second layer for the silty clay layer, layer thickness 3 ~ 7 m; the third and the fourth layer for the sill layer, layer thickness 3 ~10 m; the fifth and the sixth layer for the silty sand layer, layer thickness 7 ~18 m; the seventh and the eighth layer for the silty clay layer, layer thickness 4 ~14 m; the ninth and the tenth layer for the coarse sands layer, layer thickness 3 ~ 7 m.

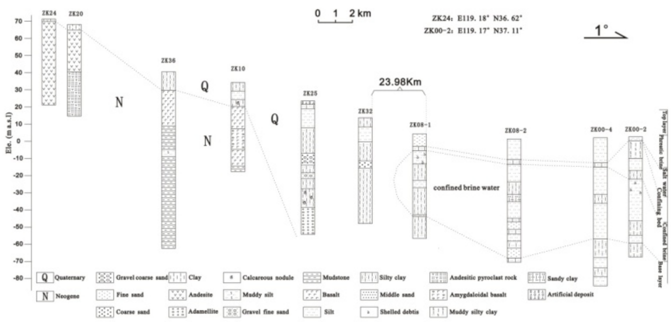

Figure. 2 A schematic presentation of a cross section in the Laizhou Bay stratum

Conceptual model and boundary conditions

According to the hydrological geology characteristics of the evaluating area and the existing each kind of information, the boundaries to evaluate the simulation range was established. The model outer boundaries were delineated as constant head boundaries. The northern boundary is along the coastal line of Laizhou Bay(about 205.2 km). The hydraulic heads in the north boundary was considered as zero (Dirichlet/first type boundary condition) as the domain is bounded by the LaizhouBay from the south to east. The southern boundary along the administrative boundaries of Shouguang Weifang Changyi and Pingdu(about 238.4 km) was considered to be first type spatial dependent boundary condition at which the water table elevation is controlled by the average water

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level in the main river. The eastern boundary is along the the administrative boundaries of Laizhou and Pingdu (about 202.7 km). The western boundary is along the the administrative boundaries of Shouguang (about 88.4 km). Initial hydrogeological parameters used in the simulation work main basis have hydrogeologic data and similar regional hydrogeological parameters, at the same time, according to the hydrogeological conceptual model simulation area, its permeability coefficient is the generalized partitioning. Figure 3 reprsents the Initial distribution of potentiometric heads considered in numerical simulations.

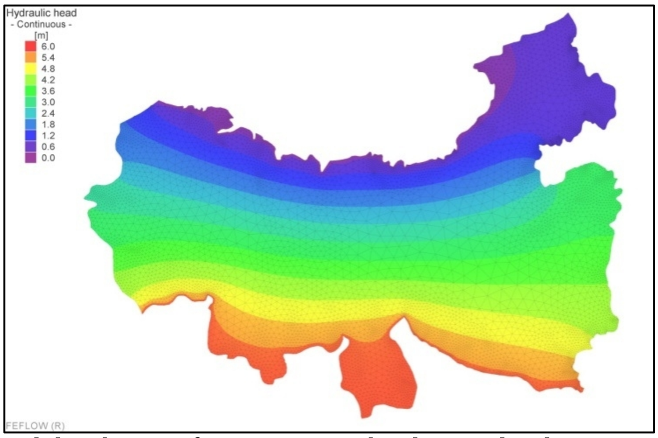

Figure 3. Initial distribution of potentiometric heads considered in numerical simulations.

Numerical modeling

Mathematical model

Through the analysis of the hydro-geological conceptual model, on the basis of seepage flow continuity equation and Darcy's law, establishing simulation area hydrogeology conceptual model of groundwater system corresponding to the mathematical model of unsteady flow in three dimensions:

$$\frac{\partial}{\partial x}\left(\mathrm{K}_{xx}\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mathrm{K}_{yy}\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial H}{\partial z}\right)+w=m_s\frac{\partial H}{\partial t}$$

$$H(x,y,z,0)=H_0 \qquad (x,y,z)\in\Omega$$

$$K\frac{\partial H}{\partial n}\Big|_{S_2}=q(x,y,z,t) \qquad (x,y,z)\in S_2$$

$$H(x,y,z,t)=H_1 \qquad (x,y,z)\in S_1$$

Here, Ω represents Groundwater seepage area in L^2; H_0 represents the initial ground water level in L; H_1 represents the specify ground water level in L; S_0 represents the Dirichlet boundary; S_1 represents the Neumann boundary; m s represents storage coefficient in L^{-1}; Kxx, Kyy, Kzz represents the main direction of permeability coefficient of x, y, z respectively in LT^{-1};w represents source items, including evaporation, rainfall infiltration, wells pumping water in T^{-1}; q(x, y, z, t) represents the flow of different time on different boundary in L^3T^{-1}.

The three-dimensional mathematical solute transport model of hydrodynamic dispersion equation is as follows:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_{yy}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z}\right)-\frac{\partial(m_x c)}{\partial x}$$
$$-\frac{\partial(m_y c)}{\partial y}-\frac{\partial(m_z c)}{\partial z}+f$$

$$C(x,y,z,0)=C_0(x,y,z)(x,y,z)\in\Omega\ ,t=0$$

Here,

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$\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_{yy}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z}\right)$ represents dispersion term; $-\frac{\partial(m_x c)}{\partial x}-\frac{\partial(m_y c)}{\partial y}-\frac{\partial(m_z c)}{\partial z}$ represents convection item; represents the increment of the solute due to chemical reaction or adsorption; *Dxx, Dyy, Dzz* represent dispersion coefficient; μ_x, μ_y, μ_z represent the actual water flow rate; *C* represents solute concentration in ML^{-3}; C_0 represents initial concentration in ML^{-3}; Ω represents the area of the seepage of the solute.

Numerical simulation model and Calibration strategy

The density-dependent numerical model was developed using the FEFLOW code (ver. 6.2) working under the steady-state conditions. The finite element method was adopted for its flexibility and ability to simulate complex geometric forms and to refine the nodal mesh around points and/or single lines (observation points, coastline, etc.). Geolithological, hydrogeological and hydrochemical data processing was carried out in a GIS environment (ArcGIS) that can be totally interfaced with FEFLOW; this was very useful in developing the conceptual model, creating the numerical model and analyzing simulation results.

The aquifer was discretized to equilateral triangle mesh by using the Advancing Front method with 8473notes and 15888 elements. ArcGIS was developed to handle the ground elevation data from ASTER GDEM data, related geological data was available for other altitude data through Co-kriging interpolation. The regionalization of the structural surfaces of the model and the parameters was carried out using the TinSpot function in ArcInfo to ensure that the target values are set exactly to nodal points of the mesh generated by FEFLOW. A three-dimensional mesh consisting of more than 158840 linear prismatic elements with a triangular base, for a total atea of about 10361 km^2(Fig.4).

The method of "big model cut into small model" was adopt to obtain the initial flow field, which delineates Laizhou Bay area boundary according to the natural boundary. In this method, the northern boundary was along the coastline, the southern boundary was along the Jinan, Zibo, Linyi hilly areas, the western boundary was along the Yellow river, and the eastern boundary was along river. The natural state of regional groundwater model was described to determine the artificial boundary value in the study area.

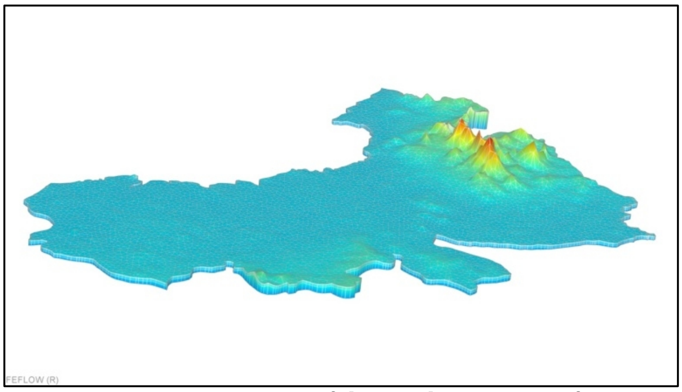

Figure 4. 3D view of the Laizhou Bay aquifer.

Forecasting

The forecasting was considering the natural initial state, which was has never invaded seawater invasion and the intrusion continues to 30 years, to predict the scope and degree of seawater intrusion in the simulation. The effects of hypothetical aquifer exploitations were assessed in terms of the evolution of hydraulic head and salinity values. These forecasts concern the next 30 years and take into consideration the local climate trend. As a result of Cl- in the transition and transformation process of groundwater is relatively complex, the forecast evaluation does not consider the effect such as adsorption, chemical reaction, only consider the typical pollutants in the diffusion process and principles of convection, dispersion.

Using FEFLOW run solute transport model, with the hydrogeological parameters and solute transport parameters. The concentration of Cl^- in seawater is set to 3500 mg/L, for 30 years. The results of the simulation of drawing work was done using FEFLOW software, and the data post-

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processing job was done by ArcGIS software, and the Cl^- concentration boundary was 250 mg/L (invasion) and 1000 mg/L (serious invasion) is bounded.

In 30 years simulation period, due to the difference hydraulic head and the Cl^- concentration between the seawater and fresh water, seawater intrusion developed intensified toward to southern inland and the seawater in deep aquifer moved to inland constantly. On the other hand, because of the density of water head and water resistance is less than the density of the water. The direction of seawater deviates counterclockwise gradually from south to north, and the risen from deep to shallow after the return to the sea, which forming a brackish-water transition zone. The brackish-water transition zone was move toward south at the early stage of the simulation, after 3 months gradually achieve the equilibrium state. The farthest goes on about 15 km.

Figure 5 shows seawater intrusion after 30 years. Seawater intrusion moves along the whole northern migration, its migration distance is about 27 km respectively, total invasion area is about 4124 km^2, of which the invasion of area of 1446 km2, serious invasion covers an area of 2678 km^2.

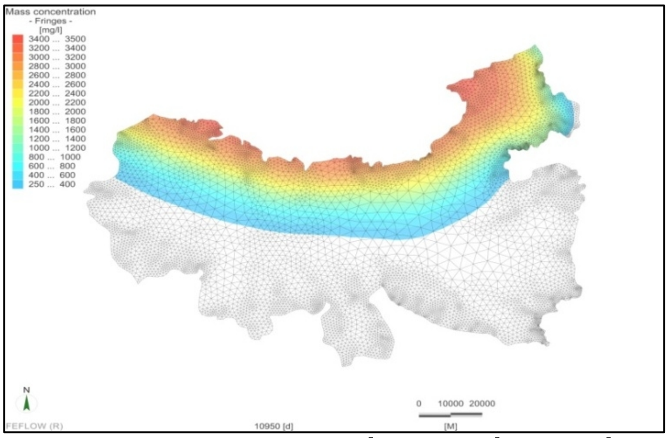

Figure 5Seawater intrusion prediction simulation results

Conclusions

Seawater intrusion has brings to the economic construction and social development in the coastal area serious harm. Precisely divide the range of seawater intrusion and forecast dynamic development of seawater intrusion, could be used to prevent and reduce the seawater intrusion to provide reasonable and scientific basis.

This paper presents a new approach to simulate seawater intrusion in coastal aquifers, in three-dimensional horizontal views, incorporating the concept of equivalent freshwater head. A flow and mass transport model has been developed to study the seawater intrusion in the area, based on analysis of the geological and hydro-geological condition in the study area. Using FEFLOW software based on the finite element theory, this article solves the mathematic model and calibrates the model by long-term observation data of hydraulic head. In addition to use the calibrated model it forecasts the evolution tendency of seawater intrusion. The modeling results showed that after 30 years total invasion of seawater intrusion in the area of about 4124 km^2, and the serious invasion area of 2678 km^2, its migration distance is about 27 km.

Acknowledgements

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