Sea water intrusion and salt water intrusion in the coastal area of Laizhou Bay

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Abstract The characteristics, pattern, hydrodynamic and hydrochemical features, and the movement pattern of the salt water-fresh water interface of the sea water intrusion and the salt water intrusion, which occur in the coastal area of Laizhou Bay in Shandong Province, are analysed. The characteristics of the two kinds of intrusion are compared as well. A three-dimensional sea water intrusion model to describe the sea water intrusion with a transitional zone 1.5—6.0 km wide in the phreatic aquifer and a solute transport model describing the behavior of cations exchange in the process of sea water intrusion are established.

Keywords: sea water intrusion, salt water intrusion, cation exchange, salt water-fresh water interface, numerical simulation.

IN the early 1970s, sea water intrusion occurred in the coastal area of Laizhou Bay in Shandong Province. Later, salt water intrusion was observed. In the study area, sea water intrusion occurred mainly along the coast of Laizhou Bay, from Zhenzhu, Laizhou to the right side of Huangshuihe River in Longkou. Salt water intrusion occurred mainly in Tushan, Laizhou, via Changyi, Shouguang to southern part of the Xiaoqinghe River in Guangrao. These two phenomena are generally called saline-water intrusion abroad[1]. Sea water intrusion has long been a central issue in academic circles. The research achievement has been reviewed by Breuck[2] and Custodio *et al*.[1] Numerous papers have noted that there may exist ion exchange in the process of sea water intrusion, but few have had good field data to confirm it. The field observation network is very poor. “Only a few case histories of coastal aquifer monitoring have been published”[1]. The numerical simulation using a miscible transport model is limited to confined aquifers. Study of the sea water intrusion in our country began in the late 1980 s, and there is little comprehensive and systematic study. Since 1986, we have had systematic study of the two phenomena which did great harm to local production and living. Our study area includes coastal areas of three cities (Longkou, Zhaoyuan and Laizhou), the Hanting area of Weifang City, and Changyi County.

1 Geological setting

The basement of the study area is a metamorphic sequence of the Archaean-Proterozoic. The sedimentary cover consists only of the Early Cretaceous Qingshan Formation, Eocene Huangxian Formation, basalt and the Quaternary. The former is sporadically distributed on the border of the study area or scarcely exposed. In Longkou, Zhaoyuan and Laizhou to the north of Zhengzhu, the Quaternary comprises mainly the Upper Pleistocene and Holocene. The Upper Pleistocene which consists of alluvial or dilluvial mild clay, sandy clay, fine and medium sands, coarse sands, and gravels, usually 10—100 m in thickness, is the main phreatic aquifer in the study area, in which the TDS (Total Dissolve Solid) of groundwater is less than 500 mg/L. The sea water intrusion occurs mainly in this aquifer. In the south of Changyi, Hanting and so on, there are the Quaternary dilluvial, graves, sands clay and clay. TDS of groundwater increases gradually from less than 1 g/L to less than 2 g/L. In the northern part there are marine deposits consisting of clay, sandy clay, sands and coarse sands with gravels. At the depth of 80 m of the marine deposit, there are three brine aquifers deposited in the Holocene, Upper Pleistocene and Lower Pleistocene, respectively. TDS of the brine/salt water varies from 50.0 to 200.0 g/L.

2 Sea water intrusion

2.1 Characteristics

The main characteristics[3] of sea water intrusion in the study area are described below.

(1) At first, sea water intrusion is “spot intrusion” which was observed at some specific, isolated spots, each quite small in area (less than 0.5 km^2). Then it spread out gradually and covered a larger area by linking some isolated spots together. Eventually, it covered all the coast and developed into “planar intrusion”.

(2) The intrusion mode is controlled by geological condition. There are many intrusion modes, such

as "planar intrusion" observed in the Quaternary sediments area and the areas with homogenous and dense fractures, "finger-like intrusion" observed along ancient river channels, "vein-like intrusion" observed in bedrock areas only with sparse tectonic fractures and fault zone, "dendritic intrusion" observed in karst areas, etc.

(3) Sea water intrusion areas are related in distribution to negative water level areas where groundwater level declines substantially to lower than the adjacent sea level. The development of the negative water level areas provides conditions favorable for the sea water intrusion. Sea water intrusion develops just along such negative water level areas, but the expansion speed of the former is slower than that of the latter. For example, in 1989, the area of the negative water level areas was 262 km^2 in Laizhou, while the area of sea water intrusion was only 238.7 km^2.

(4) The specific distribution of sea water intrusion is related to the powerful pumping center. Generally, the salt water-fresh water interface is formed on the inland side adjacent to the powerful pumping center, and sea water intrusion stops here.

(5) There is a broad transitional zone about 1.5—6.0 km in width between sea water and fresh water. The situation that the transitional zone is narrow and can be considered as an abrupt interface, as described in ref. [4], has not been discovered in China till now.

(6) The sea water intrusion rate is affected by many factors such as groundwater discharge and pumping mode, precipitation and so on. It is not absolutely that "once occurred, expand rapidly"[3]. If the groundwater pumping is not restricted, but with less precipitation, the intrusion rate is really very fast. For example, in Laizhou, sea water intrusion increased in area by about 4 km^2 each year in the late 1970s, about 11 km^2 each year in the early 1980s, and reached or exceeded 30 km^2 after the middle 1980s. But if proper measures of "broadening sources of income and reducing expenditure" can be adopted, the intrusion rate can be slowed down, even the intrusion area can be decreased. For example, in Longkou, the intrusion area increased 19.4 km^2 in 1989. But the intrusion rate was slowed down after taking many efficient measures to restrict the groundwater pumping (figure 1).

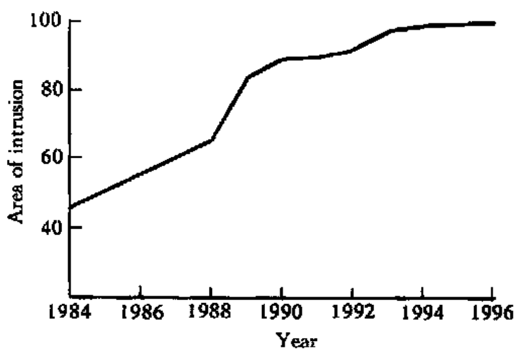

Fig. 1. A sketch map of variations of sea water intrusion area in Longkou.

2.2 Hydrodynamic and hydrochemical phenomena in the process of sea water intrusion

When sea water intrudes the fresh water aquifer (then we call it salt water), it begins to mix with fresh water. In the meantime, a broad transition zone (mixing zone) is formed under the hydrodynamic dispersion. Hydrodynamic dispersion causes the mixing of salt water and fresh water. On one hand, salt water moves toward land slowly and carries some quantity of salt. On the other hand, the flow along the transitional zone (we call it whirl flow) causes part of the salt to move toward the sea and flushes out part of the salt introduced, thus keeping some kind of salt balance and maintaining the width of the transition zone. In this condition, the width of the transitional zone depends on the intensity of salt water flow and fresh water flow within it, the aquifer coefficient of hydrodynamic dispersion and the hydraulic conductivity. When the fresh water increases, the flushing ability will increase, so the width of the transitional zone will contract; and *vice versa*. The existence of the pumping wells may decrease the discharge of the fresh water flowing to the sea, and causes salt water to move landward, thus the salt moving from the transitional zone to the sea decreases, and the transitional zone expands. If powerful pumping center is present, the outlet cannot be left for the fresh water to the sea. The fresh water will flow toward the pumping well and could not flow to the sea, and then the salt water body will increase. Finally, the salt water flows to the pumping well and mixes with the pumped fresh water. The pumped groundwater may be contaminated as brackish water or salt water. In this condition, groundwater flows toward the pumping well from all directions, and the above-mentioned whirl flow which flows to the sea and dilutes the salt water by taking away salt disappeared. Instead of the whirl flow, part of the fresh water flowing from fresh water region to the pumping well will take away salt, dilute the salt water and maintain the salt equilibrium. This hydrodynamic phenomenon is different from the whirl flow mentioned previously, in which the outlet for the fresh water to the sea exists. This phenomenon has not been reported so far, but has been confirmed by the monitoring results and the numerical simulation results of the three-dimensional observation network in Huangheying. For this reason, when groundwater abstraction does not exceed its recharge, there exists the outlet for fresh water to the sea and the whirl flow flushes out the salt introduced, then the sea water intrusion will not occur or not be severe. Excessive overpumping can lead to the elimination of the fresh water flow to the sea. Thus the fresh water flows to the pumping center, and flushs out part of the salt to keep the salt equilibrium. This is the reason why the salt water-fresh water interface formed on the inland side is not far away from the powerful pumping center, and its location does not move when the powerful pumping center does not move. This is also the dynamic interpretation of sea water intrusion on large scale caused by overpumping. The above-mentioned external influence can also broaden the width of the transitional zone. Besides, many other external influences such as the tide moving against the river, the fluctuation of phreatic surface, changes of precipitation replenishment can also affect the width of the transitional zone.

In the transitional zone, the concentrations of Na^+ and Mg^{2+} rise for the mixing of sea water and fresh water. On the other hand, the continental aquifer has a high Ca^{2+} content due to its previous saturation of fresh water relatively rich in Ca^{2+}. These provide good opportunity for cation exchange between groundwater and soil. We surveyed this phenomenon by the following methods: analysing chemical composition of the groundwater in the transitional zone, taking samples (soil sample, sea water sample and fresh water sample) to determine the cations exchange capacities (CEC) and the complex compositions, carrying out the cations exchange experiments between water and soil and carrying out the soil column experiment using sea water and fresh sediment. Our research work has verified that there exist cations exchange between water and soil, and the significant cation exchange exists between Na^+ and Ca^{2+}, the moderate one between Mg^{2+} and Ca^{2+}. Moreover, in the early phase of sea water intrusion, there exists almost no exchange between Mg^{2+} and Ca^{2+}. The soil shows intense adsorption to K^+ in the mixed water. In the transitional zone, the nearer the location is from the coast, the more completely the cations exchange between water and soil take place. It is also illustrated in our experiments that there exists almost no adsorption of Cl^- from the water to the soil in the process of sea water intrusion. In the process of the salt water advances landward, the above-mentioned cations exchange leads to the decrease of Na^+ and Mg^{2+}, the increase of Ca^{2+} the landward advancing transitional zone, and forming a special hydrochemical landscape that the concentration of Ca^{2+} in the mixed groundwater is greater than that both in local sea water and fresh water. On the Piper trilinear diagram, the groundwater appears as a Ca-Na or Ca-Mg mixed water in which no any anion-cation pair exceeds 50% in content[3, 5]. In long-term seriously intrusion area, the content of Cl^- in groundwater increases rapidly whereas the increase speed of the content of the alkaline metal ions is far slower than that of Cl^-. Therefore, sea water intrusion is not simple mixing of fresh water and sea water. It is accompained by physicochemical interaction. From land to the sea, the chemical composition of groundwater changes gradually from HCO_3-Cl-Ca-Mg water unaffected by sea water intrusion with TDS less than 300 mg/L to Cl-HCO_3-Ca-Na water or Cl-HCO_3-Ca-Mg water with TDS of 250—1000 mg/L. Only when the chloride content exceeds 90%, there is a rapid increase in Na^+ content. Finally, a Cl-Na water with TDS of 3—11 g/L is formed[3, 5].

2.3 Salt water-fresh water interface

There are mainly two types of salt water-fresh water interface[3, 6]. One is relatively distinct and steep. This interface occurs in a district with large pumping rate, stable flow rate and concentrated pumping wells. The other is a flat and unclear interface which occurs at locations where the pumping wells are scattered, the discharge of single well is small and unstable.

To observe the movement of the interface, a three-dimensional observation network has been set. The observation network consists of 31 special observation wells, 12 ordinary wells, and 3 pumping wells. Of the 31 special observation wells, 24 fall into 8 groups, each group consisting of 3 wells located at approximately the same site but at different depths——at the top, middle, and bottom of the aquifer (fig. 2). Refs. [2] and [5] reported the observation results of more than 2 years and 3 years, respectively. Observation of continuous five and a half years can further confirm the following results. The interface of January 1988 was located between No. 1 pumping well and well j3, and between No. 2 pumping well and well group 3. Wells j3, j5 and j6 together with well groups 3, 4, 5, 6, 7 and 9 were in the fresh water region (fig. 2). At that time, the chloride concentration in the groundwater of the transitional zone was relatively stable. In late May of 1988, the discharge of the productive wells increased greatly, and this caused the advancing of the salt water body landward and the increase of the chloride concentration (fig. 3, Well 2-1). But the location of the interface did not change for the location of the powerful pumping center did not change. In late Autumn of 1988, No. 3 pumping well put into operation. Though its pumping rate was less than 1/20 of No. 1 and No. 2 pumping wells, it also resulted in the interface moving slowly southward. The interface crossed well groups 3 and 4 and reached No. 3 pumping well (fig. 3, well 4-3); that is to say, the interface had moved about 140 m along the main observed section in a period of three years and three months. Because of the high permeability of the riverbed deposits of the Huangshuihe River and the united effect of Nos. 1, 2 and 3 pumping wells, the salt water did not invade along a straight line, but invaded along the Huangshuihe River and reached well j4 first, then invaded along the direction of j4-No. 3 pumping well and reached the No. 3 pumping well (210 mg/L, December 1991). At that time, well group 5 was still in fresh water region. After this, the above-mentioned water source was abandoned, and the powerful pumping center was moved 2 km southward away from Jiancun. Although the distance was far, the moving of the powerful pumping center resulted in the interface moving southward. It crossed well group 5 and approached well group 6 (fig. 2). In April of 1993, the interface moved 160 m southward, and the moving speed was accelerated (hereafter, this place was in the ground reservoir, so the observed data could not be used). In the five and a half years, there are three great changes: first, the pumping rate increased greatly, then pumping wells were added to the landside of the pumping center; at last, the pumping center changed its location. The observed data not only confirm the conclusion that the salt water-fresh water interface took shape on the inland side not far from the powerful pumping center

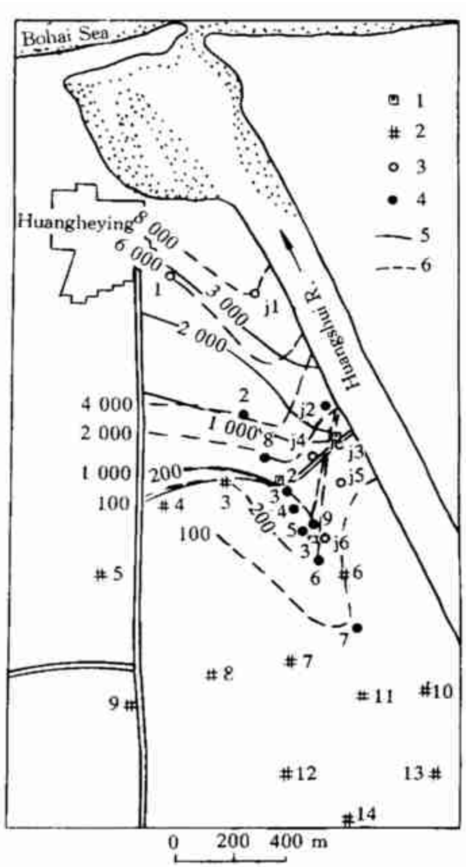

Fig. 2. A concentration contour map of chloride in Huangheying, Longkou. 1, Production well; 2, well; 3, observation well; 4, observation well group; 5, Cl^- concentration contour (January 1988); 6, Cl^- concentration contour (April 1993).

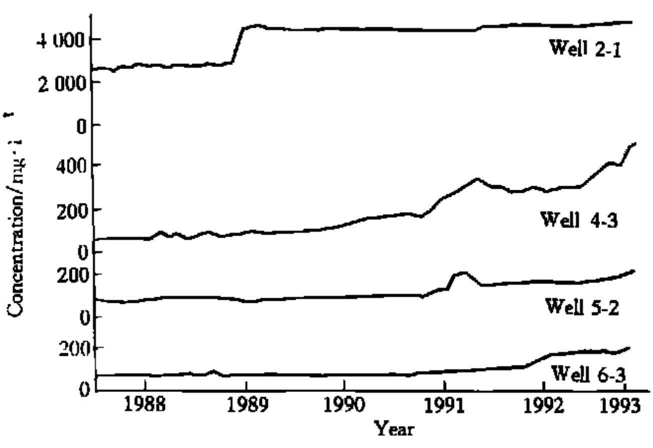

Fig. 3. The chloride concentration fluctuation graph of observation wells 2-1, 4-3, 5-2 and 6-3.

and the sea water intrusion stoped there, but also confirm the following conclusions from the above-mentioned three changes: (i) an increase in the flow rate of the powerful pumping center would aggravate sea water intrusion, but the sea water-fresh water interface would not move as long as the powerful pumping center keeps its site; (ii) if more pumping wells are added to the landside of the powerful pumping center, and even if the discharge is not very great and the center does not move, interface will still advance, though at a slow speed, (iii) the movement of the powerful pumping center will of course lead to the movement of the interface, but the specific intrusion course is controlled by geological situation and the state of water flow.

2.4 Numerical simulation

The abrupt interface model cannot be used for the very wide transitional zone. So a miscible transport model needs to be set up based on that the two fluids are soluble in each other. For such a situation, two problems need to be solved: one is how to consider the influence of precipitation infiltration on solute transport; the other is how to consider the influence of fluctuation of phreatic surface on sea water intrusion. These problems were evaded by considering the phreatic aquifer as a confined aquifer[7]. We have solved these problems and developed a sea water intrusion model for a phreatic aquifer[8]. In the model, boundary conditions are used to deal with the above two problems on phreatic surface. First, the hydraulic head H^* on the phreatic surface should satisfy

$$H^*(x_i, t) = x_3(x_1, x_2, t), \quad i = 1, 2, 3, \tag{1}$$

where x_i is Cartesian coordinate, $i=1, 2, 3$; x_3 is elevation. Second, according to the law of conservation of mass, the phreatic surface should satisfy

$$K_{ij}\left(\frac{\partial H}{\partial x_j} + \eta c e_j\right) n_i = \left(w - \frac{\rho^*}{\rho_0} S_y \frac{\partial H^*}{\partial t}\right) n_3, \tag{2}$$

where $K_{ij}(i, j=1, 2, 3)$ is the hydraulic conductivity tensor; $H=\frac{P}{\rho_0 g}+x_3$ is the reference hydraulic head, referred to as the fresh water head; P is pressure; $\eta=\frac{\varepsilon}{c_s}$ is the density coupling coefficient; $\varepsilon=\frac{\rho_s-\rho_0}{\rho_0}$ is the density difference ratio; c_s is the concentration corresponding to the maximum density ρ_s; e_j is the jth component of the gravitational unit vector; x_j is Cartesian coordinates, $j=1, 2, 3$; c is the concentration of a certain component in groundwater; w is the vertical precipitation infiltration and irrigation infiltration; ρ_0 is the density of fresh water; t is time; ρ^* is the density of groundwater in the zone where the water table fluctuates; when the water level declines, ρ^* approaches ρ_0, and S_y is specific yield; when the water level ascends, ρ^* becomes ρ and S_y is the difference of saturation; $n=(n_1, n_2, n_3)$ is the outward unit vector normal to Neumann boundaries Γ_2, B_2 and the phreatic surface Γ_{2-1}. If the influence of density is neglected, eq. (2) can be simplified into

$$-v_i n_i = \left(w - S_y \frac{\partial H^*}{\partial t}\right) n_3, \tag{3}$$

where v_i is the Darcy velocity of groundwater. Eqs. (1) and (2) are boundary conditions for phreatic surface that should be satisfied in the flow equation describing fluid motion. For the solute transport equation, the following boundary condition should be satisfied

$$\left(-D_{ij}\frac{\partial c}{\partial x_j} + u_i c\right)\varphi n_i + wc' n_3 = S_y \frac{\partial H^*}{\partial t} c n_3. \tag{4}$$

If the influence of density is neglected, the boundary condition (4) can be simplified into

$$-D_{ij}\frac{\partial c}{\partial x_j} n_i = \frac{w}{\varphi}(c - c'), \tag{5}$$

where D_{ij} is the dispersion coefficient tensor $(i, j=1, 2, 3)$; $u=(u_1, u_2, u_3)$ is the average pore velocity vector; φ is the effective porosity; c' is the solute concentration of the precipitation (the irrigation can be dealt in the same way, only different in concentration). Therefore, the complete three-dimensional sea water intrusion model for the confined aquifer can be expressed as:

the flow model:

$$\frac{\partial}{\partial x_i}\left[K_{ij}\left(\frac{\partial H}{\partial x_j}+\eta c e_j\right)\right]=S_s\frac{\partial H}{\partial t}+\varphi\eta\frac{\partial c}{\partial t}-\frac{\rho}{\rho_0}q, \tag{6}$$

$$H(x_i,0)=H_0(x_i), \tag{7}$$

$$H(x_i,t)\left.\right|_{\Gamma_1}=H_1(x_i,t), \tag{8}$$

$$v_i n_i\left.\right|_{\Gamma_2}=-v_n(x_i,t), \tag{9}$$

the solute transport model:

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right)-u_i\frac{\partial c}{\partial x_i}-\frac{\eta c}{\rho_r\phi}K_{ij}^0\left(\frac{\partial H}{\partial x_j}+\eta c e_j\right)\frac{\partial c}{\partial x_j}+\frac{cS_s}{\rho_r\phi}\frac{\partial H}{\partial t}+\frac{\eta c}{\rho_r}\frac{\partial c}{\partial t}=\frac{\partial c}{\partial t}+\frac{q}{\varphi}(c-c^*), \tag{10}$$

$$c(x_i,0)=c_0(x_i), \tag{11}$$

$$c(x_i,t)\left.\right|_{B_1}=c_1(x_i,t), \tag{12}$$

$$D_{ij}\frac{\partial c}{\partial x_j}n_i\left.\right|_{B_2}=q^D, \tag{13}$$

where S_s is the specific storage; q is the volumetric flow rate of sources or sinks per unit volume of the porous medium; H_0 is the initial head; H_1 is the prescribed head on the Dirichlet boundaries; v_n is the prescribed lateral flow rate per unit area on Γ_2 (it is positive for inflow); c^* is the solute concentration of the injected (or pumped) fluid; $\rho_r=\rho/\rho_0$ is the density ratio; c_0 is the initial concentration; c_1 is the prescribed concentration on the Dirichlet boundaries; q^D is the prescribed dispersion flux on B_2. For the phreatic aquifer, boundary conditions (1) and (2) should be added to the flow model, eq. (4) to the solute transport model. The flow model and solute transport model, together with the motion equation (14), are integrated to form a sea water intrusion model

$$v_i=-\frac{k_{ij}\rho_0 g}{\mu}\left(\frac{\partial H}{\partial x_j}+\eta c e_j\right)=-\frac{K_{ij}^0}{\mu_r}\left[\frac{\partial H}{\partial x_j}+\eta c e_j\right], \tag{14}$$

where k_{ij} is the intrinsic permeability tensor; K_{ij}^0 is the hydraulic conductivity under the reference condition; μ is the dynamic viscosity; $\mu_r=\frac{\mu}{\mu_0}$ is the viscosity ratio; μ_0 is the viscosity of fresh water (the reference viscosity). On sea water intrusion, generally $\mu\approx\mu_0$, $\mu_r=1$; g is the gravitational acceleration; in eq. (10), if $\Delta\rho_r$, $\frac{\partial H}{\partial t}$ and $\frac{\partial c}{\partial t}$ are neglected, it can be simplified into the equation presented in ref. [8]:

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right)-u_i\frac{\partial c}{\partial x_i}=\frac{\partial c}{\partial t}+\frac{q}{\phi}(c-c^*). \tag{15}$$

Numerical simulation considers not only the correspondent solution, but also the effect of the network size. Wide network will lead to numerical dispersion, so we changed the interval of the network from the initial 60—280 m to 40—60 m and simulated once again[8].

The above-mentioned model is only suitable for simulating single stable ion such as Cl^-. In order to describe the cations exchange between water and soil in the process of sea water intrusion, we must rebuild the mathematical equation on the basis of the chemical reaction and set up a new solute transport model for the description of the transport behavior of exchange cations Na^+, Mg^{2+} and Ca^{2+}. This model was presented in ref. [8]. Due to having described the behavior of the main ions in groundwater, the model provided a new method for the study of the evolution of groundwater chemical environment.

3 Salt water/brine intrusion

3.1 Characteristics

Salt water/brine intrusion has many similarities to sea water intrusion. For instance, they are all affected by geological condition and hydrological situation. Salt water and brine advanced rapidly along valley of the Bailanghe River, encroaching southward in tongue-like shape. There are perennial water in the valley of the Weihe River because of its great runoff. Thus the salt water intrusion was hindered for the top supply of the river water, and the intrusion was far slower than that on two sides of the valley. The distribution of salt water/brine intrusion is related to areas where groundwater level has declined substantially (Weifang-Hanting cone of depression, Changyi cone of depression). The intrusion rate is affected by many factors such as the pumping rate, pumping mode, precipitation and so on. However, salt water/brine intrusion is distinguished from sea water intrusion in many aspects. First, due to the long-term hydrodynamic dispersion, there exist brackish water (TDS 1—10 g/L) and salt water (TDS $>$ 10 g/L, the upper limit is the TDS of the brine in the aquifer) in the area between the brine (TDS $>$ 100 g/L) or the salt water (TDS 50—100 g/L) and the fresh water (TDS $<$ 1 g/L), and there are a dynamic equilibrium among them (fig. 4). Excessive pumping of the fresh groundwater will destroy the equilibrium and lead to the landward advancing of such types of groundwater. A certain kind of groundwater will not advance forward evenly for the different pumping rates, pumping modes and hydrogeological conditions in different places. Because of the different advancing speeds, the interface advances fluctuatingly and different water has its respectively advancing speed. For example, the different areas of TDS $>$ 50, 50—3, 3—1 g/L in groundwater were 306, 278, 212 km^2 respectively in June 1985, and 492, 380, 182 km^2 respectively in April 1992. So it is significantly different from the sea water intrusion, which began from isolated spot intrusion and then spread out and linked together.

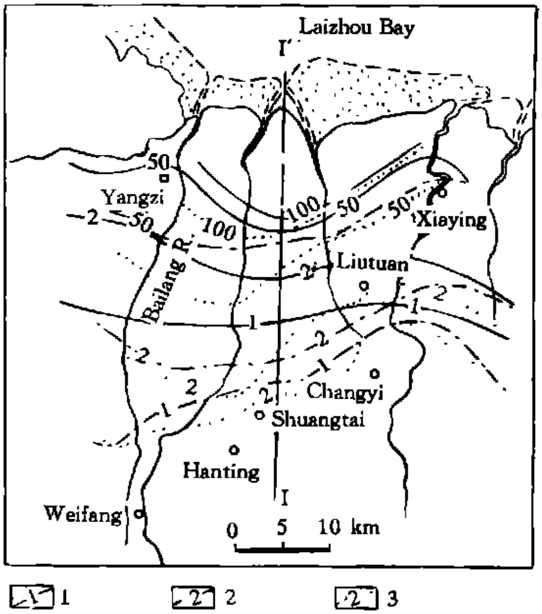

Fig. 4. The TDS contour map of groundwater in Hanting-Changyi area. 1, 1983; 2, 1990; 3, 1992.

Secondly, an obvious transition zone is formed in the process of sea water intrusion. But in the salt water intrusion region, as mentioned above, there exists a gradually changed transition status of groundwater in the long history before intrusion. The salt water/brine intrusion only led to the broadened distribution area of brine, salt water and brackish water. Lastly, the specific distribution of salt water/brine intrusion is also related to the powerful pumping center. But there are cones of depression both in fresh water region (such as the Changyi cone and the Weifang-Hanting cone) and the brine-salt water region (such as the Changbei cone and the Yangzi cone) for that there exist not only fresh water pumping but also brine and salt water pumping in making salt. The locations of these cones make the groundwater flow complicated (fig. 5). For instance, a groundwater divide is formed between the cone in brine-salt water district and that in fresh water district, which constrains the movement of salt water crossing the divide toward the center of the cone in fresh water district. The complicated groundwater

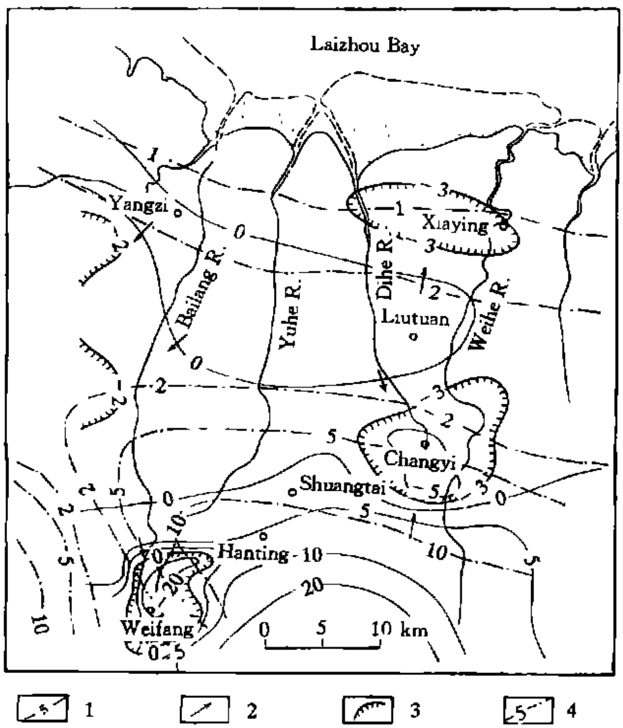

Fig. 5. The groundwater level contour map in Hanting-Changyi area. 1, Ground water level contour of 1990; 2, direction of groundwater flow; 3, cone of depression; 4, groundwater level contour of 1983.

flows, which are affected by many factors, make the course and speed of the salt water intrusion more complex than those of the sea water intrusion. Till now, the case that "the salt water-fresh water interface formed on the landside not far away from the powerful pumping center, and the sea water intrusion stopped there", which is common in the process of sea water intrusion, has not been observed. Though the groundwater level in the center of the cone in fresh water district has declined to lower than −7.5 m (the Changyi cone) or −27.0 m (the Weifang-Hanting cone) and the salt water has reached the border of the cones, the intrusion speed is relatively slow and there is a distance to the center of the cone. The intrusion speed in the area of the Weifang-Hanting cone, whose hydraulic gradient is steep, is faster than that in the area of the Changyi cone, whose hydraulic gradient is gentle.

3.2 Hydrochemical characteristics

In the brine, the relative contents (milliequivalent) of Na^+, Mg^{2+}, Cl^- and SO_4^{2-} are 76.11%, 21.53%, 90.60% and 9.25%, respectively. In the local modern sea water, the values are 76.04%, 19.19%, 90.21% and 9.30%, respectively. These two groups are very close. The salt water has the similar condition. But they differ from the local fresh water greatly. These demonstrate that the brine and the salt water are enriched from the ancient sea water. The contents of Na^+, Mg^{2+}, Cl^- and SO_4^{2-} (meq/L) in the brine are 5.0—5.9 times higher than those of the modern sea water, but the contents of K^+, Ca^{2+} and HCO_3^- are only 3.0—4.6 times higher than those of the modern sea water. This illustrates that in the enriching process, some chemical reaction occurred. On the figures of the relationship of the groundwater components, the spots of HCO_3^-, SO_4^{2-} and Ca^{2+} in the brine are all located under the sea water line. This illustrates that the increase of HCO_3^-, SO_4^{2-} and Ca^{2+} decline relatively in the enriching process. In the meantime, the saturation indexes SI of calcite, dolomite and gypsum in the groundwater in the brine region are bigger than 1. So there may exist the deposits of these minerals in the enriching process. The calcite and gypsum found in the drilling core of the brine aquifer proved such a conclusion.

On the contact zone between the marine deposits and the continental deposits, when the groundwater flowed from the continental deposits to the marine deposits, Ca^{2+} and Mg^{2+} in groundwater exchanged with Na^+ sorbed in the marine deposits, which resulted in the increase of Na^+ content and the decrease of Ca^{2+} and Mg^{2+} contents in the groundwater. In the mixed groundwater of the contact zone between salt water and fresh water, the carbonates are generally unsaturated. The produced Ca^{2+} was depleted in the cations exchange, whereas the produced HCO_3^- are enriched in the groundwater. Therefore, a HCO_3-Na or HCO_3-Cl-Na water zone was formed (region C in fig. 6), which extends parallel to the coast in a direction of NE-SW with width of 3.5—5.5 km and TDS of 550—950 mg/L. Obviously this kind of water was formed in the long history. When salt water intrusion occurred for the excessive groundwater pumping, Na^+ in salt water was exchanged with Ca^{2+} and Mg^{2+} adsorbed by the soil grain in the process of the above-mentioned cation exchange. Thus the inverse cation exchange causes the decrease of the relative content of Na^+, the increase of Ca^{2+} and Mg^{2+} in groundwater, and the formation of Cl-HCO_3-Na-Ca water or Cl-HCO_3-Na-Mg water with TDS of 1—3 g/L (region D in fig. 6). The above-mentioned cations exchange lead to formation of many types of groundwater from land to the sea, located at regions A, B, C, D and E on the Piper trilinear diagram, respectively. Finally, the Cl-Na brine was formed at region F in fig. 6. Fig. 7 illustrates such pro-

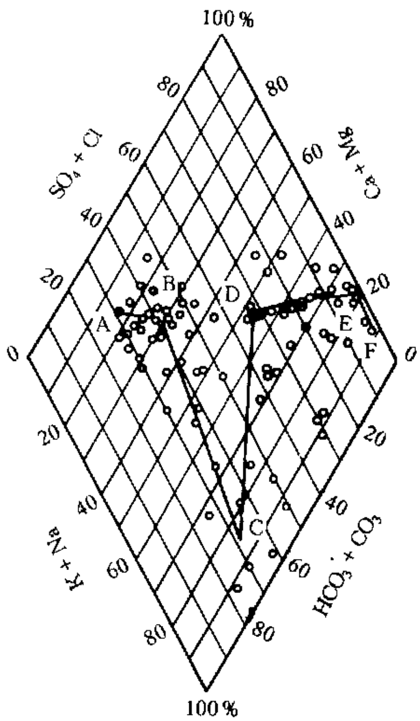

Fig. 6. Pipe trilinear diagram of groundwater composition (milliequivalent content) in the Hanting-Changyi area.

cess. Because the quantity of Ca^{2+} in aquifer exchang for Na^{+} in salt water is limited in the process of salt water/brine intrusion, and the Ca^{2+} content is much greater in brine than in sea water, the phenomenon that Ca^{2+} content in groundwater in the transitional zone is much greater than that in salt water and brine, impossibly appears in the salt water/brine intrusion.

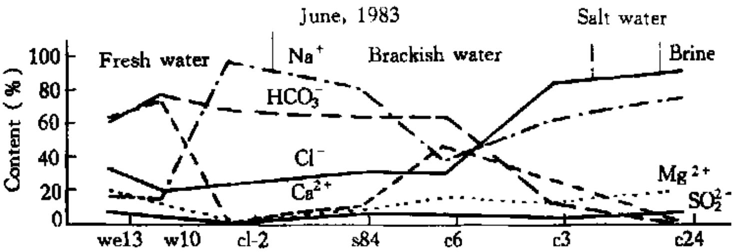

Fig. 7. The generalized hydrochemical section from the brine region to the fresh water region.

3.3 Numerical simulation

Due to the high TDS of the brine and salt water, the conventional motion equation, flow equation and advection-dispersion equation are not applicable. The effect of fluid concentration on density, and viscosity, motion equation, flow equation and solute transport equation should be considered.

4 Summary and future direction

Sea water intrusion and salt water intrusion are a phenomenon caused by excessive pumping of fresh water, i.e. salt water-fresh water interface moves landward and the water table is lowered to a level at which the hydraulic head in the fresh water body becomes lower than that of the nearby sea water or salt water body. Affected by many factors, their intrusion pattern, hydrochemical characteristics and movement of the salt water-fresh water interface are obviously different. The expanding mode from spot to plane in the sea water intrusion is replaced by the fluctuating advancing mode in salt water intrusion. In salt water/brine distribution area, the transitional zone had already formed, the salt water intrusion only led to its broadening. Therefore, the steep interface appears seldom in salt water intrusion, unlike the sea water intrusion which develops the obvious transitional zone quickly. The concentrating process of the brine and salt water is accompanied by the deposition of calcite and gypsum. There are dissolution of calcite and cations exchange in the contact zone between the salt water and fresh water. After salt water intrusion, the inverse cation exchange happens. All of these make the salt water intrusion more complex than sea water intrusion. So we not only distinguish the two phenomena, but also put different emphasis on our research.

The whirl flow is very important. Especially, the flow regime and salinity balance in the condition that no outlet is left for the fresh water to flow to the sea, are the dynamic base to explain the movement of the salt water-fresh water interface and large-scale sea water intrusion after large-scale overpumping. Owing to the higher TDS in water, it is necessary to seek for new flow equation, solute transport equation and motion equation for the salt water intrusion.

To study the two phenomena, observing carefully the vertical change of hydraulic head and salinity will be necessary. The best way is to set up a three-dimensional observation network consisting of short or point-screened piezometers and to make a long-term observation. Observing in the ordinary observation well will just "lead to meaningless or even confusing results"[1].

The present study of sea water intrusion focus on single aquifer distribution area and less on the multiple aquifer or complex structure aquifer distribution area. The characteristics of sea water intrusion, the hydrochemical features and the characteristics of the movement of the salt water-fresh water interface in the multiple aquifers or aquifers with complex structure and the aquifer with multiple semipervious lens inside will be emphasized in the further research. We must pay our attention to the influence of the beds of different permeabilities on the movement of the salt water-fresh water interface, and the influence of the interlayers or lens of sandy clay and clay, as well as leakage on the sea water intrusion. Numerical simulation should try to establish the models to describe the sea water intrusion in multiple aquifers or the aquifer with multiple semipervious layer.

(*To be continued on page* 992)

Quasisymmetric boundary correspondence and Grötzsch problem

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Abstract Two necessary and sufficient conditions for the validity of the conjecture $K_0(h)=K_1(h)$ are given, which are independent of the complex dilatations of extremal quasiconformal mappings, where $K_0(h)$ is the maximal conformal modulus dilatation of the boundary homeomorphism h, $K_1(h)$ is the maximal dilatation of extremal quasiconformal mappings that agree with h on the boundary. In addition, when the complex dilatation of an extremal quasiconformal mapping is known, the proof of the result simplifies Reich and Chen Jixiu-Chen Zhiguo's result.

Keywords: **quasisymmetric boundary correspondence, extremal quasiconformal mapping, Grötzsch problem, Teichmüller mapping.**

LET U denote the unit disc. Suppose that h is a quasisymmetric boundary correspondence of ∂U onto itself (the boundary value of a quasiconformal mapping of U onto itself). Let S be a closed subset of ∂U. Denote by $Q(h, S)$ the class of quasiconformal mappings of U onto itself that agrees with h on S, and by $K(f)$ the maximal dilatation of f. Set

$$K_1(h, S)=\inf_{f\in Q(h, S)} K(f).$$

We say f_1 is extremal in $Q(h, S)$ if $f_1\in Q(h, s)$ and $K(f_1)=K_1(h, S)$. Denote by $Q^*(h, S)$ the class of extremal quasiconformal mappings in $Q(h, S)$. We write $Q(h)=Q(h, \partial U)$, $Q^*(h)=Q^*(h, \partial U)$, and $K_1(h)=K_1(h, \partial U)$.

(*Continued from page* 991)

For salt water intrusion, three-dimensional observation network for long-term observation is lacking in China. It is necessary to set up such observation network in typical areas. In the process of brine (salt water) formation and intrusion, there exist complex dissolution, deposition, cations exchange and absorption. So it is the next objective to establish the salt water intrusion model which can describe the above-mentioned phenomena. Some problems have not been solved till now such as the mathematical description of deposition. Only when such problems are settled, it is possible to provide scientific method for the description of hydrochemical environment evolution in the process of salt water intrusion.

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