Salt-Water Intrusion in the Lower Reaches of the Weihe River, Shandong Province, China

Honghan Chen[1], Yongxiang Zhang[2], Xinmin Wang[3], Zhongyu Ren[4], and Li Li[2]

Abstract: Mathematical statistical methods, such as trend-surface analysis, were employed to help describe the history, current situation, and regularity of the development of salt-water intrusion in the lower reaches of the Weihe River, China. Over-exploitation of fresh groundwater resources is the principal cause of salt-water intrusion. Pumping of fresh groundwater resources should be controlled systematically to prevent further salt-water intrusion.

Résumé: Des méthodes statistiques, comme l'analyse de tendance, ont été utilisées pour décrire l'histoire, la situation actuelle et la régularité de l'extension de l'intrusion saline dans les biefs inférieurs du fleuve Weihe (Chine). La surexploitation des eaux souterraines douces est la cause principale de l'intrusion saline. Le pompage des eaux souterraines douces doit être contrôlé systématiquement afin d'éviter une intrusion d'eau salée.

Resumen: Métodos estadísticos matemáticos, como el análisis de tendencias, se emplearon para describir la historia, situación actual y evolución, así como la regularidad en el desarrollo de la intrusión marina en la parte baja del río Weihe, en China. La sobreexplotación de los recursos de aguas subterráneas es la principal causa de esta intrusión. El bombeo de las aguas subterráneas dulces debe ser controlado sistemáticamente para prevenir una mayor intrusión en un futuro.

Introduction

Since the 1970's, with the economic development of the coastal areas of China, salt-water intrusion has been induced by over-exploitation of groundwater. In the mid-1980's, groundwater over-exploitation exacerbated the salt-water intrusion, and the rate of intrusion continues to increase steadily. Currently, serious problems occur in such places as the Gulf of Laizhou in Shandong Province (Xue Yuqun, 1991), Dalian in Liaoning Province, Qinhuangdao in Hebei Province (Han Zaisheng, 1988), and Ningbo in Zhejiang Province. The salinization of the fresh-water resources has seriously impeded the development of industry and agriculture and the improvement of the peoples' living standards in these areas. The purpose of this report is to describe the history, cause, and current status of salt-water intrusion in the lower reaches of the Weihe River in northeastern Weifang, Shandong Province, China. Location of the study area is shown in *Figure 1*. The total area is 1,208 km^2.

In the study area, the average annual temperature is 11.9-12.5°C, and the average annual precipitation is 551.5 mm; 60-70 percent of the year's total precipitation comes during June to August. The average annual evaporation is about 1,640 mm, chiefly during April to June.

The land surface of the study area slopes gently from south to north. The water-bearing deposits consist chiefly of alluvial and floodplain deposits in the southern and central regions and unconsolidated marine deposits in the northern part. Tectonic and geomorphic factors influence aquifer water-bearing characteristics. In general, three main aquifers occur; from south to north, their water-bearing capacities systematically change from poor to moderate to poor.

The general direction of fresh groundwater flow is from south to north. Over-exploitation for many years is responsible for the occurrence of two cones of depression in fresh water in southern Hanting and Cangyi and one cone of depression in salt water in northern Zaohu and Xiliyu. Salt water is pumped in order to obtain salt, by means of evaporation. A groundwater divide separates the southern fresh-water subsystem from the northern salt-water subsystem. These relations are shown in the hydrogeological section in *Figure 2*.

Salt-water Intrusion

Method and Observations

The current extent of salt-water intrusion is generally reflected by the distributions of hydraulic head and chloride concentrations. However, this approach is subjective and does not reveal the trend and regularity of the development and evolution of salt-water intrusion. In an attempt to use a more objective and quantitative method that more accurately reflects variations in time and space of salt-water intrusion, polynomial trend-surface analysis was applied (Du Qiren, 1979).

Polynomial trend-surface analysis utilizes the surface represented by a polynomial function and produced from a group of observation values to simulate the development and evolution of variable values in time and space. In general, the observation value consists of three parts, which can be expressed as:

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[1] Institute of Geotechnical Engineering, China University of Mining and Technology, Beijing, 100083, P.R. China.

[2] Department of Earth Science, Nanjing University, Nanjing, 210093, P.R. China.

[3] Department of Mathematics, Changchun University of Earth Science, Changchun, 130026, P.R. China.

[4] China Urban Water Resources Center, Ministry of Construction, Beijing, 100007, P.R. China.

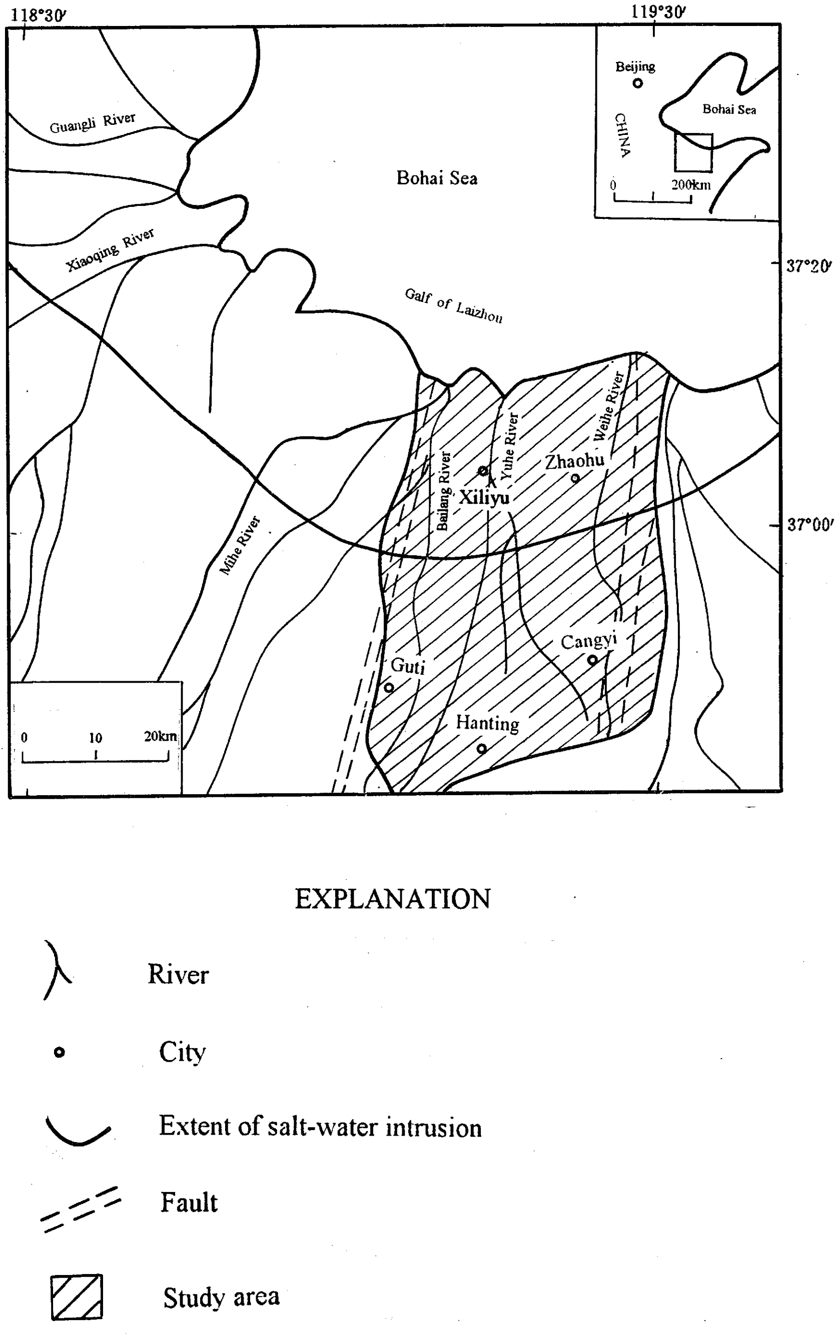


Figure 1. Location of study area.

$$\hat{H} = H + \Delta H + \varepsilon \tag{1}$$

where $\hat{H}$ is the observation value; H is the trend value; ΔH is the residual value; and ε is the random error. The value of ε is so small that it can be omitted, and equation 1 becomes:

$$\hat{H} = H + \Delta H \tag{2}$$

Therefore, the observation value $\hat{H}$ consists of two parts, trend value H and residual value ΔH, which stand for the general evolution trend regularities and abnormal changes caused by the partial factors, respectively.

Theoretically, the surface represented by a linear polynomial trend-surface function is a plane. The surface represented by a quadratic polynomial trend-surface function is an ellipsoid, and that by a cubic polynomial trend-surface function is a saddle-shaped surface. However, when the power of the polynomial function is higher than four, abnormalities occur. Experience has shown that the cubic trend-surface function, which is applied in this article, can simulate the

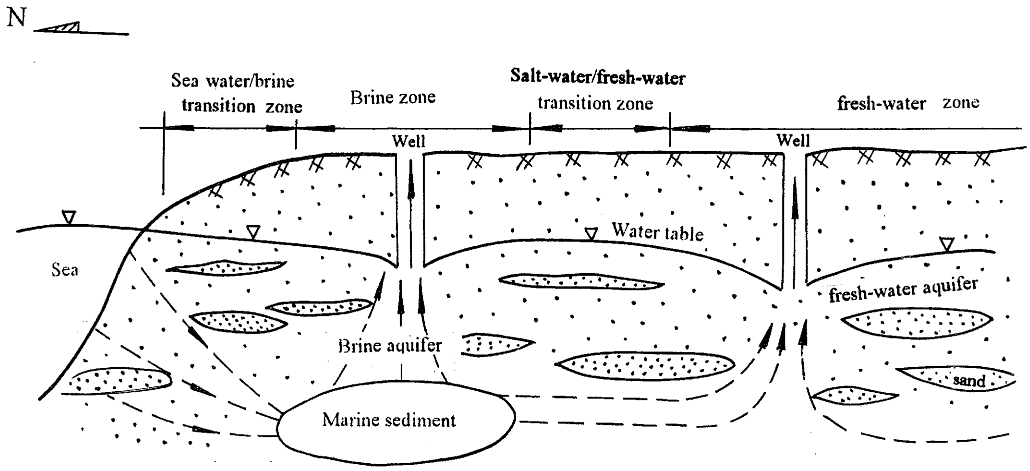
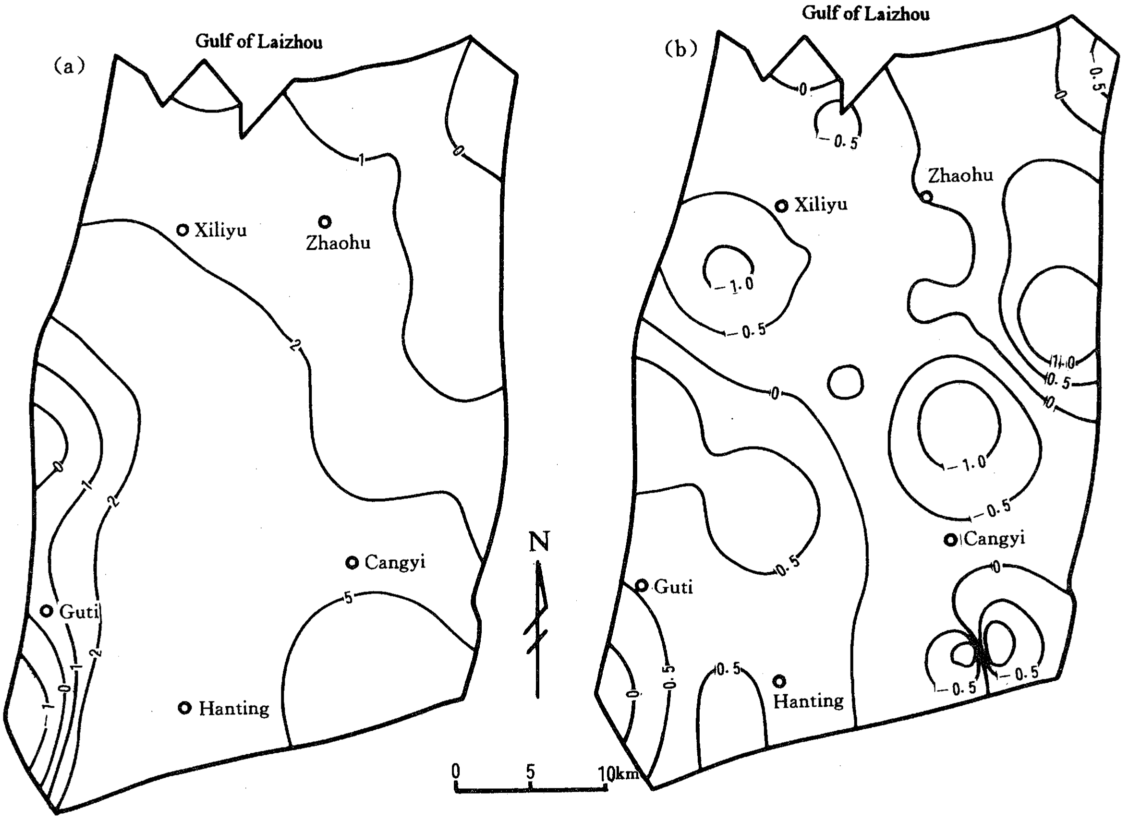


Figure 2. Generalized hydrogeologic section. Not to scale.



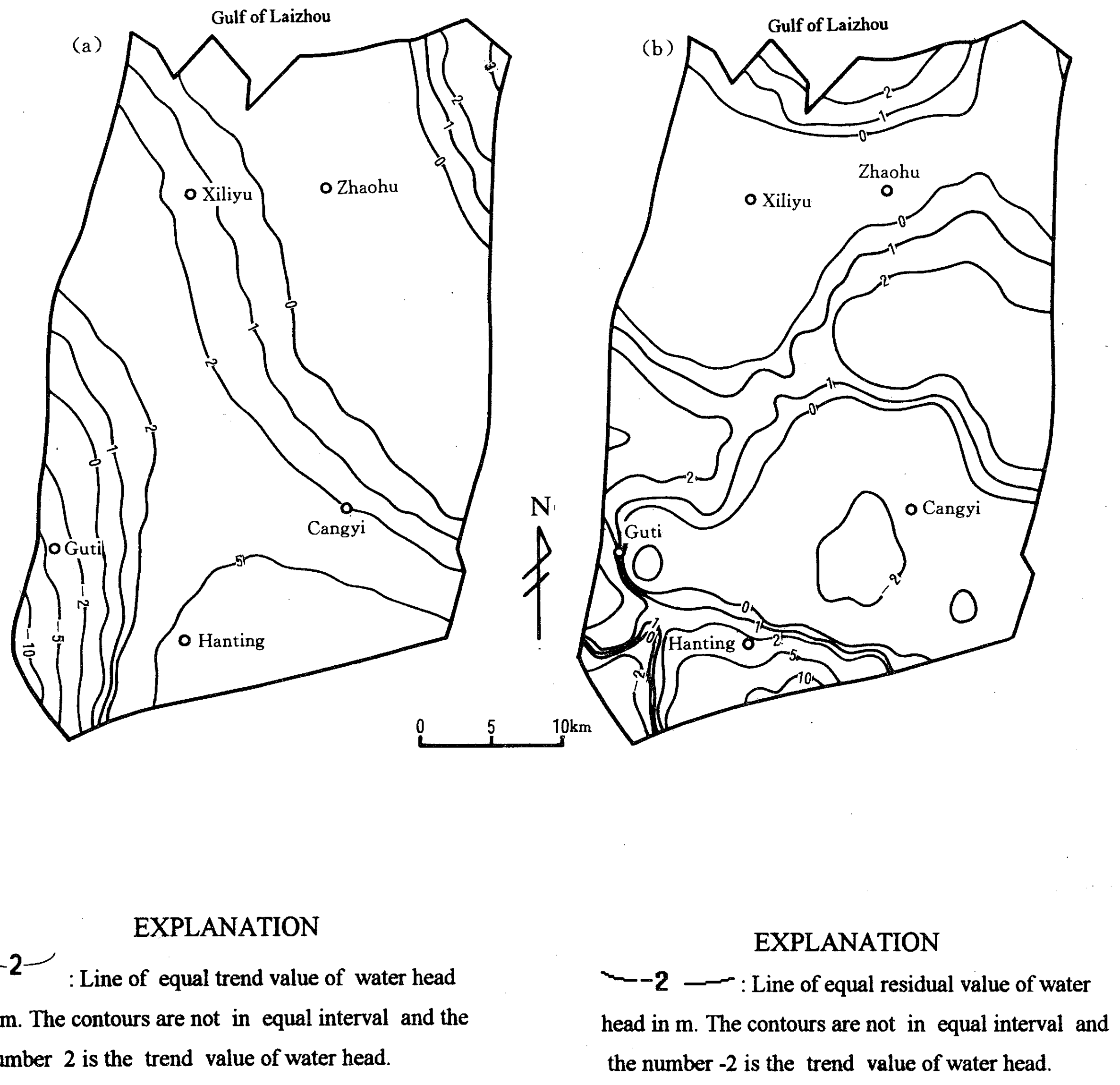
EXPLANATION

2 : Line of equal trend value of water head in m. The contours are not in equal interval and the number 2 is the trend value of water head.

EXPLANATION

0.5 : Line of equal residual value of water head in m. The contours are not in equal interval and the number 0.5 is the residual value of water head.

Figure 3. Trend-surface map of groundwater head, June 2, 1983. a) Trend values. b) Residual values.



EXPLANATION

2 : Line of equal trend value of water head in m. The contours are not in equal interval and the number 2 is the trend value of water head.

EXPLANATION

-2 : Line of equal residual value of water head in m. The contours are not in equal interval and the number -2 is the trend value of water head.

Figure 4. Trend-surface map of groundwater head, June 2, 1992. a) Trend values. b) Residual values.

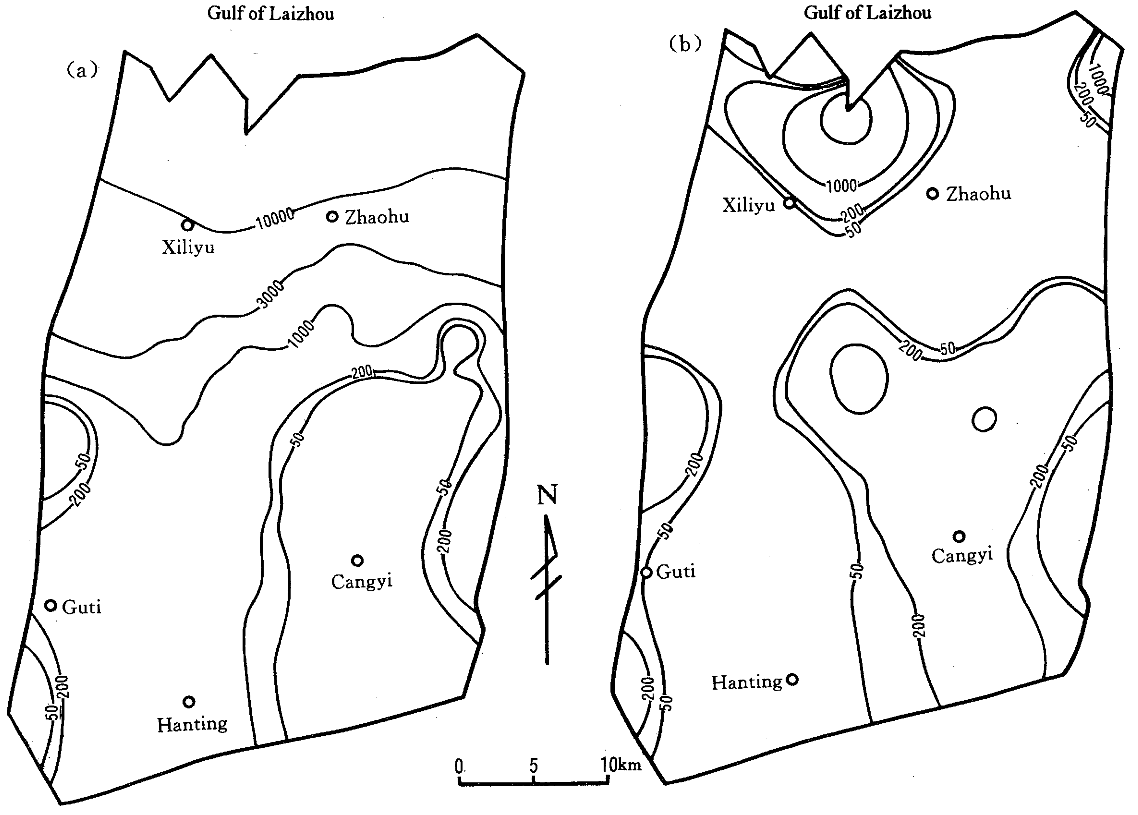
development and evolution of laws of variable values in time and space. In this method, contour maps of cubic trend values of groundwater head, contour maps of trend values of Cl^- concentration, and residual contour maps were analyzed for the water-abundant seasons and water-deficient seasons during 1983-92. These parameters are shown in *Figures 3-6.*

In general, the hydraulic head is higher in the south and the east than in the north and the west. During 1983-92, the head steadily declined throughout the area.

In 1983, the hydraulic head was high in the south and low in the north (*Fig. 3*). The residual contour map for 1983 shows negative values southwest and east of northern Cangyi. The formation of a cone of depression in the Weicheng area was responsible for the increasing size of the depression area, to about 3.5 km^2. Groundwater over-exploitation in the Cangyi area resulted in the formation of a depression cone north of eastern Cangyi, which underlies an area of about 100 km^2. This cone is elliptic in form, with its longer axis in an east-west direction. The high value of hydraulic head in the southeast is mainly caused by the lateral flow of groundwater that is recharged in the southern mountain area, and by groundwater recharge in the eastern Weihe River valley (*Fig. 4*).

By 1992, each cone of depression had expanded further. The area of the cone in Weicheng grew to about 80 km^2, and the one in northern Cangyi to about 150 km^2. Moreover, due to the over-exploitation of salt water, the hydraulic head declined sharply. By 1992, a broad depression, 1.5 km in width, 12.5 km in length, and about 75 km^2 in area, had appeared, creating a groundwater divide between the two major depressions.

The distribution of Cl^- concentration indicates generally high values in the north and low values in the south, as shown in *Figure 5*. In 1983, high values of Cl^- concentration were



EXPLANATION

1000 : Line of equal trend value of chloride concentration in mg/l. The contours are not in equal interval and the number 1000 is the trend value of chloride concentration.

EXPLANATION

50 : Line of equal residual value of chloride concentration in mg/l. The contours are not in equal interval and the number 50 is the residual value of chloride concentration.

Figure 5. Trend-surface map of chloride concentration, June 2, 1983. a) Trend values. b) Residual values.

mainly in the northern marine deposition plain, where the average Cl^- concentration was greater than 5 g/L. The area of salt water was elliptical and was about 90 km^2 in area, 5.5 km in width, and 15.5 km in length. At the two ends of the ellipse axis, groundwater was diluted by river water of the Weihe River from the east and the Yuhe River from the west. In addition, the high Cl^- concentration in the estuary of the Weihe River suggests that the salt-water intrusion occurred along the river bed. The Cl^- concentration, generally greater than 800 mg/L in this area, was caused by contamination by agriculture, industry, and sewage. In the southern part of Gudi and Cangyi, the water quality was better, and the Cl^- concentration was generally less than 20 mg/L. A transition zone existed between the fresh-water system and the salt- water system and was about 3-6 km wide and 113 km^2 in area (*Fig. 5*).

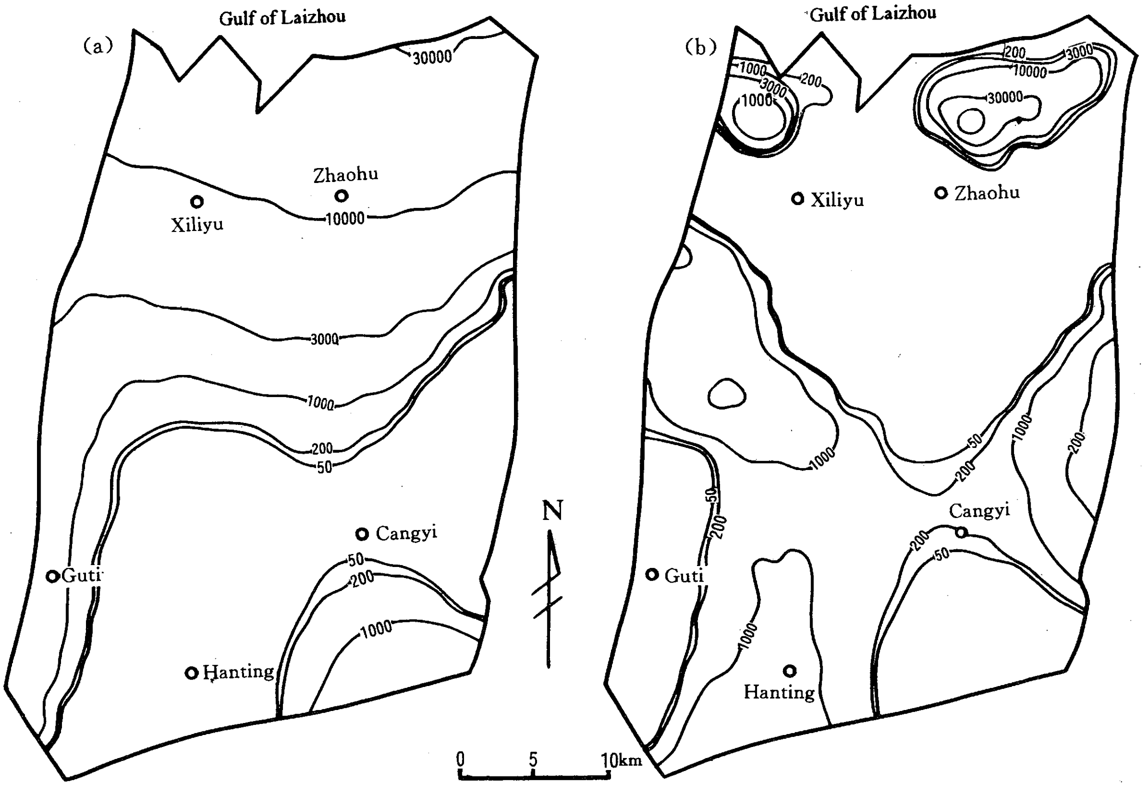
In 1992, the salt-water intrusion area was extensive, the rate of salt-water intrusion in the west was different from that in the east, and the distribution of Cl^- was not uniform (*Fig. 6*).

A comparison of Cl^- maps of 1983 (*Fig. 5*) and 1992 (*Fig. 6*) indicates that the transition zone between the fresh-water system and the salt-water system expanded. By 1992, its width was about 8.0-9.5 km, and its area was 295 km^2. Salt-water intrusion occurred only in a few places in the early 1980's, but by 1992 intervening regions were also invaded by salt water.

Interpretation

The analysis of trend surface shows that salt-water intrusion in the lower reaches of the Weihe River is substantial. The interpretation is based on input and output components of the groundwater system in this area.

Since the end of the 1970's, with rapid economic development, groundwater exploitation by industry, agri-



EXPLANATION

3000 : Line of equal trend value of chloride concentration in mg/l. The contours are not in equal interval and the number 3000 is the trend value of chloride concentration.

EXPLANATION

200 : Line of equal residual value of chloride concentration in mg/l. The contours are not in equal interval and the number 200 is the residual value of chloride concentration.

Figure 6. Trend-surface map of chloride concentration, June 2, 1992. a) Trend values. b) Residual values.

culture, and a growing population has increased dramatically. *Table 1* shows the magnitudes of the various components of the water balance during 1983-92. The data show that the fresh-water component of the groundwater system had a negative balance. On the one hand, the over-exploitation of fresh-water resources caused the lowering of hydraulic head in the fresh-water subsystem and the formation of cones of depression, which enhanced salt-water intrusion. On the other hand, the over-exploitation of the northern salt-water subsystem caused the formation of a cone of depression in salt water, which induced recharge of both seawater and fresh water. The effect was to reduce chloride concentrations. The formation of a cone of depression in salt water is favorable for slowing down the rate of salt-water intrusion, but it is not favorable for the protection of salt-water resources. The issue is, therefore, how

Table 1. Annual water balance, 1983-92.

Component		Amount (x 10^4 m^3/yr)
Fresh-water recharge, from infiltration of:	Precipitation	15,323
	River water	152
	Irrigation water	1,076
Subtotal		16,551
Fresh-water pumpage		20,761
Salt-water pumpage		880

to control the fresh-water withdrawals and salt-water resources in order to prevent salt-water intrusion in this area.

Conclusions

The basic cause of salt-water intrusion is the over-exploitation of fresh-water resources. This condition is responsible for the higher head in the salt-water subsystem than in the fresh-water subsystem, and for the development of a groundwater flow field that is favorable for salt-water intrusion. In order to prevent salt-water intrusion, the fresh-water resources should be exploited by maintaining a balance between groundwater pumpage and groundwater recharge, that is, the average pumpage of several years should be less than the average groundwater recharge. Meanwhile, a more rational distribution of pumping wells should be considered.

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