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IMPACTS OF FUTURE SEA LEVEL RISE ON SALT WATER INTRUSION IN THE CHANGJIANG RIVER ESTUARY ①

Yang Guishan (杨桂山)
(Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences; Nanjing 210008, PRC)

ABSTRACT: Sea level rise could increase the salinity of an estuary by altering the balance between fresh water and salt water. The implications of sea level rise for increasing salinity have been examined in the Changjiang (Yangtze) River estuary. By correlative analysis of chlorinity, discharge and tidal level and calculation of two–dimensional chlorinity, distribution of the Changjiang River estuary, the changes of the intensity and lasting hours of salt water intrusion at Wusong Station and the changes of chlorinity distribution in the South Branch of the Changjiang River estuary have been estimated when future sea level rises 50–100 cm. The intensity of salt water intrusion in the future will be far more serious than current trend.

KEY WORDS: sea level rise, salt water intrusion, chlorinity, the Changjiang River estuary

I. INTRODUCTION

The river mouth, located in the junction of ocean and river, is influenced by not only oceanic condition but also river condition. Salt water out of the mouth intrudes into the estuary region along with tidal current and results in chlorinity increasing. It directly influences water use in industry, agriculture and people's daily life. Salt water intrusion is a kind of natural calamity not to be ignored in the estuary region.

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The Changjiang River estuary region is one of the most densely populated and best developed areas, where there is the biggest city of China—Shanghai. Along the banks of the Changjiang River,especially in the southern bank of the South Branch, there are many large enterprises requiring a large amount of water resources of high quality. Since 1970, this region has been affected by salt water intrusion every year. Especially from the winter in 1978 to the spring in 1979, the drought resulted in chlorinity increasing that seriously influenced the water supply of Shanghai and the surrounding areas and caused large losses of industry and agriculture. The possible influence of global climatic warming on sea level has gained widespread attention. Accelerated sea level rise would increase salt water which enters into rivers.

How much will the relative sea level of the Changjiang River estuary rise? What effect will the sea level rise exert on salt water intrusion of this region? It is necessary to answer these questions, so as to promptly take preventive measures to reduce its harm.

The Changjiang River estuary is a deltaic estuary with multi-order bifurcations. Its discharge is plentiful and the hydrologic properties and riverbed development are very complicated (Fig.1).

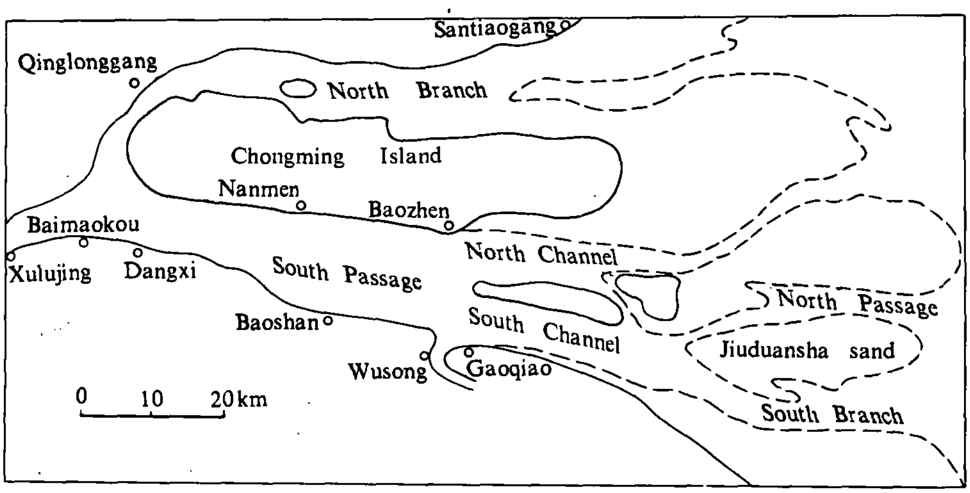

Fig. 1 The Changjiang River estuary

Salt water intrusion is mainly controlled by discharge, tidal level, topography of estuary, wind power, wind direction and sea current etc.. The principal factors are discharge and tidal level. In general, salt water intrusion damaging the production and life occurs in a dry season (from Dec. to March) every year in the Changjiang River estuary. In a dry season, the probability of mean daily chlorinity over 100 mg / kg at Wusong is over 40 percent. In a flood season (from May to Oct.), the Changjiang River estuary is almost controlled by fresh water (chlorinity below 100 mg / kg), and the probability of mean daily chlorinity over 100 mg / kg at Wusong is below 1.5 percent.

The Changjiang River estuary is a merotidal estuary with irregular semidiurnal tide. Affected by tidal change, there also occurs chlorinity of high value and low value in a day. There exists a strong correlation between tidal level and chlorinity (Fig.2)

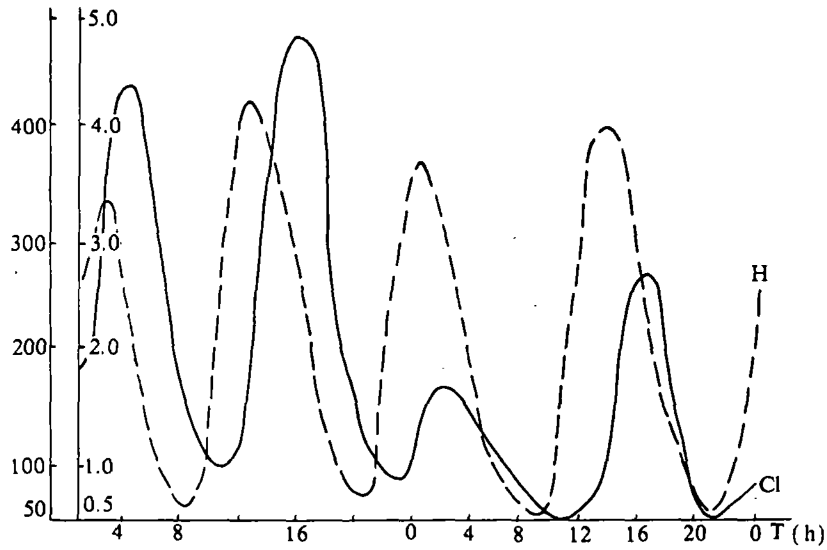

Fig.2 The process lines of chlorinity and tidal level at Gaoqiao

There are four outlets into the sea in the Changjiang River estuary. Owing to the sectional shape, runoff diversion and tidal features of the different bifurcations, there are different features of chlorinity distribution in each river channel.

Since the beginning of this century, the North Branch of the Changjiang River estuary has gradually withered and its runoff diversion has largely decreased. The North Branch becomes a flood channel dominated by the flood current, in which chlorinity is very high. At spring tides during the dry season, a great quantity of water body of high chlorinity inverts itself South Branch, which affects the water quality of the South Branch.

The South Branch is the main passage discharging the runoff of the Changjiang River. In comparison with the North Branch, the salt water intrusion of the South Branch isn't very serious, but chlorinity distribution is more complex. At the spring tide during the dry season, chlorinity gradually reduces from Baimaokou down to nearby Wusong along the southern bank and from Chongtou to nearby Nanmengang along the northern bank. This unusual distribution shows that chlorinity change in this river section is mainly affected by the inverted current of the North Branch. From Wusong or Nanmengang down to the lower reaches, chlorinity becomes regular distribution (chlorinity gradually increases from the upper reaches to the lower reaches). It indicates that chlorinity change in this section is mainly affected by the direct salt water intrusion from North and South channels.

II. PREDICTION ABOUT EFFECTS OF SEA LEVEL RISE ON SALT WATER INTRUSION

Sea level rise during the last century, claimed by most authors, was 10–15 cm. The global warming could accelerate sea level rise in the next century. However, too many points are still unclear, and the estimation of possible sea level change in the next century diverges with different authors, reflecting considerable uncertainty. The Changjiang River estuary region is located in the neotectonic subsidence area of the eastern part of China. In addition, surface subsidence rates due to groundwater extraction are quite rapid. It makes relative sea level rise in this region higher than the global mean value.

Predicting future sea level rise of the Changjiang River estuary, we must consider not only mean value of future global eustatic sea level rise but also the rate of crustal and surface subsidence. According to the estimations of future sea level rise generally reported in the literature, Table 1 gives three different scenarios of mean high tidal level at Wusong and Qinglonggang by the middle of the next century (the year 2050). Current trend of Table 1 is mean high tidal level of dry season at each station from 1960 to 1986; low, middle and high scenario of sea level rise are 50, 80 and 100 cm (relative to current trend).

Table 1 The projection of mean high tidal level by the year 2050 (m)

	Current trend	Low scenario	Middle scenario	High scenario
Wusong	3.00	3.50	3.80	4.00
Qinglonggang	3.23	3.73	4.03	4.23

The article mainly deals with the intensity of salt water intrusion and lasting hours of characteristic chlorinity (100, 200 and 250 mg/ kg) at Wusong, and chlorinity distribution in the South Branch, corresponding with future sea level rise, for the water supply of Shanghai is affected by water quality at Wusong.

1. The Change of Intensity of Salt Water Intrusion at Wusong

Judged by discharge data of the Changjiang River, mean discharge of the dry season in a humid year (20% frequency equivalent), a normal year (50% frequency equivalent), a general dry year (75% frequency equivalent) and a special dry year (90% frequency equivalent) are about 15,000, 13,000, 11,000 and 9,000 m^3/s respectively. By analyzing measured data of chlorinity to discharge and high tidal level (Fig.3), we get the following correlation equations:

$$CL = 4.3EXP(0.68H / Q_m) \quad (1)$$

$$CL = 8.3EXP(1.17H / Q_m) \qquad (2)$$

where *Cl* is mean daily chlorinity at Wusong; *H* is mean daily high tidal level at Qinglonggang (because the chlorinity change at Wusong is mainly affected by the inverted

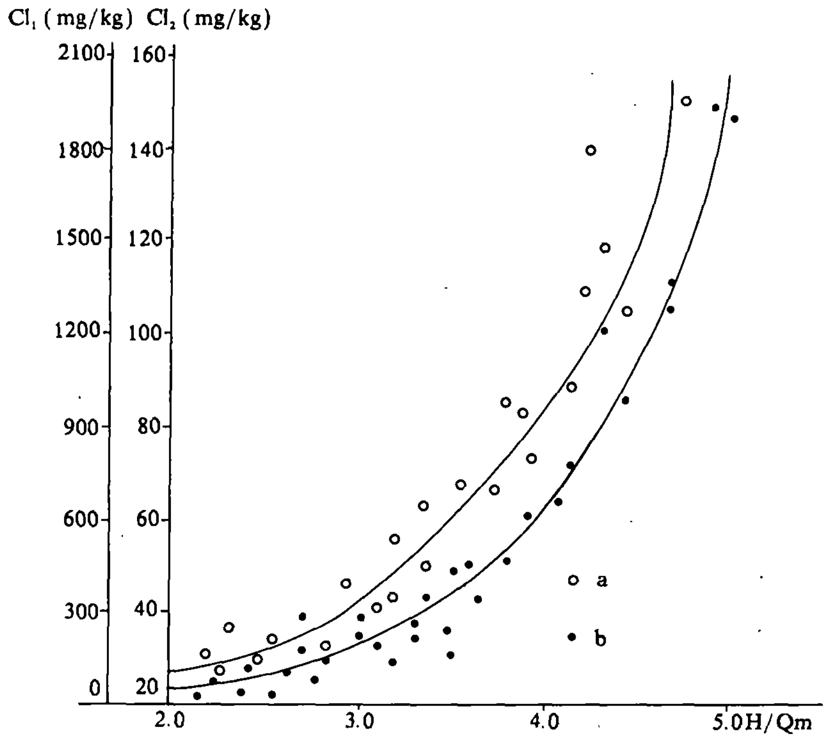

Fig.3 Relative Curve Between *Cl* and H / Q_m

current of the North Branch); Q_m is a ratio of mean daily discharge to the mean value of the dry season in a characteristic year. Correlation coefficient of the two equations are all over 0.90. In equation (1), the discharge range of selected period (from 20 Jan. to Feb. 1983) was 12,000 to 17,000 m^3/s; the mean discharge of dry season was about 13,250 m^3/s. In equation (2), the discharge range of operating period (from 10 Dec. 1978 to 10 Jan. 1979) was 7,000 to 12,000 m^3/s; the mean discharge of the dry season was about 8,830 m^3/s. In this way, we have estimated the effect of sea level rise on chlorinity change at Wusong in different discharge conditions (Table 2).

Calculated results shows that the effect of sea level rise on chlorinity change at Wusong will occur in the dry season of a dry year. In the dry season of a humid or normal year, chlorinity change at Wusong is hardly affected by sea level rise. Even if sea level rise to a high scenario value (100 cm), chlorinity isn't over two times of the current trend, and the mean daily chlorinity at Wusong is below 100 mg / kg. But in the dry season of a dry year, the chlorinity in the year 2050 won't conform to general standard of drinking water (chlorinity below 250 mg / kg). Especially in the lowest discharge month of the special dry year, the chlorinity at Wusong will exceed the water quality standard of agriculture irrigation (chlorinity below 1,100 mg / kg) due to sea level rise. It will greatly influence economic development and people's daily life.

Table 2 Effect of sea level rise on chlorinity change at Wusong

Discharge (m^3/ s)	Chlorinity (mg / kg)				
	7,000	9,000	11,000	13,000	15,000
Scenario (m)					
3.23 (current trend)	976	338	172	40	30
3.73 (low)	2,041	601	276	57	40
4.03 (middle)	3,178	848	365	70	48
4.23 (high)	4,269	1,066	441	81	55

2. The Change of Lasting Hours of Characteristic Chlorinity at Wusong

According to the quality standard of water supply and status of water use in the Changjiang River estuary region, we choose three characteristic chlorinity: 100 mg / kg is a sign of salt water intrusion in the estuary region; 200 mg / kg is the high limit of water use for some large enterprises; 250 mg / kg is the quality standard of drinking water. Calculating lasting hours of chlorinity over each characteristic value at Wusong (Tn), mean high tidal level of dry season (H) at Wuson and a ratio of mean discharge of dry season different years to mean discharge of dry season for years (Q_m) at Datong. We obtained the following relational equations:

$$T_{100} = 209(H / L^{0.4} Q_m)^3 \quad (3)$$

$$T_{200} = 16.4EXP[2.10H / (L^{0.4} Q_m)] \quad (4)$$

$$T_{250} = 8.4EXP[2.38H / (L^{0.4} Q_m)] \quad (5)$$

relational coefficient are all more than 0.94 (Fig.4). As mentioned above, the chlorinity change at Wusong is greatly affected by the inverted current of the North Branch which is relating to the topographic change of the upper section in the North Branch. Therefore, the topographic factors must be considered in analyzing their interrelation. In these expressions, L is the isobath length of minus ten meter (−10 m) down from 121° 05′ E nearly the outlet of the current diversion of the South and North Branch. The longer this isobath length is, the more runoff diversion of the North Branch is, so the inverted current intensity of the North Branch decreases conversely; $Q_m = Q_i / Q$, the range of Qi is 7,000–16,000 m^3/s, $Q = 13,250\ m^3/s$.

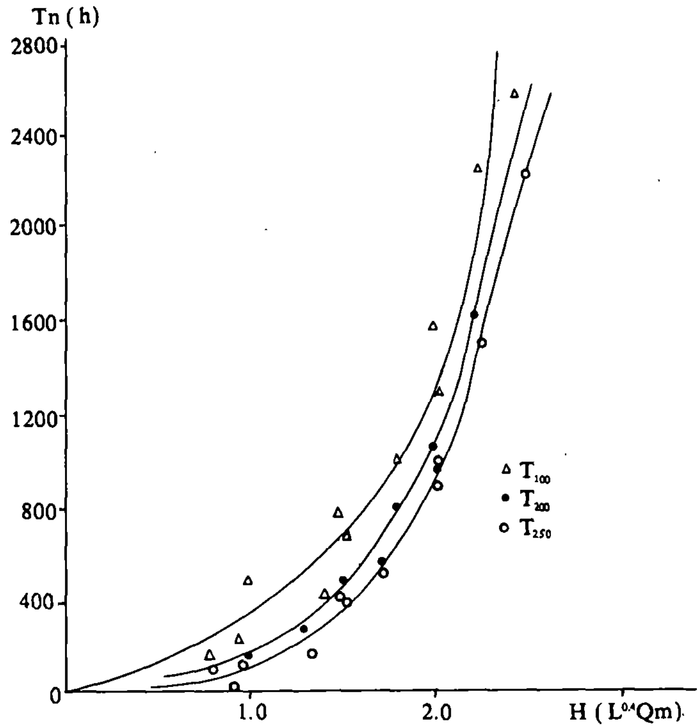

Fig.4 Relative Curve Between T_n and $H / (L^{0.4}Q_m)$

Assuming that the change of L in future is the same as present, with the help of equation (3)–(5), we have estimated the effect of sea level rise on lasting hours exceeding some characteristic chlorinity at Wusong (Table 3). In the dry season of a special dry year, affected by sea level rise, chlorinity at Wusong is more than 250 mg / kg in the whole dry season. In a general dry year, when future sea level rise is low scenario value predicted, the water plant nearby Wusong can't supply water in the whole dry season, and it will seriously threaten water supply of this region. In the dry season of a normal or humid year, the effect of sea level rise on lasting hours of chlorinity over 250 mg / kg is relatively small. Even if future sea level rise is high scenario value predicted, the lasting hours of chlorinity over 250 mg / kg at Wusong is less than 25 percent of the whole dry season.

3. The Change of Chlorinity Distribution in the South Branch

To study the effect of sea level rise on chlorinity distribution of the Changjiang River estuary, we use ADI method to set up two-dimensional mathematics model of chlorinity distribution of the Changjiang River estuary ①. The calculated scope is from Xuliujing to the isobath of minus twenty meters (−20 m) near the outlet. The period calculated is the spring tide period from the 12th to the 17th of Feb. in 1987. Mean discharge at Datong Station is about 7,000 m^3/s, which is equivalent to the mean discharge of the lowest value month in a special dry year.

Table 3 Effect of sea level rise on lasting hours exceeding some characteristic chlorinity at Wusong (h)

Discharge (m^3/s)	11,000			13,000			15,000		
Chlorinity (mg/kg)	100	200	250	100	200	250	100	200	250
Scenario (m)									
3.0 (current trend)	1,609	1,037	923	577	312	237	326	142	97
3.5 (low)	2,555	2,070	2,021	916	510	413	360	203	146
3.8 (middle)		the whole		1,172	684	576	460	252	168
4.0 (high)		dry season		1,369	833	720	537	291	219

3.1 Basic Equation

Continuity equation

One-dimension:

$$B\frac{\partial H}{\partial t}+\frac{\partial \theta}{\partial x}=0 \tag{6}$$

two-dimension:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(Hu)+\frac{\partial}{\partial y}(Hv)=0 \tag{7}$$

Motion Equation

one-dimension:

$$\frac{\partial \theta}{\partial t}+u\frac{\partial \theta}{\partial x}+\theta\frac{\partial H}{\partial x}A+g\frac{\theta|\theta|}{AC_f^2R_h}=0 \tag{8}$$

two-dimension:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial h}{\partial x}-fv+\frac{gu\sqrt{u^2+v^2}}{C_f^2H}=0 \tag{9}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial h}{\partial y}+fu+\frac{gv\sqrt{u^2+v^2}}{C_f^2H}=0 \tag{10}$$

Chlorinity Conservation Equation two-dimension:

$$\frac{\partial (CH)}{\partial t}+\frac{\partial}{\partial x}(uHC)+\frac{\partial}{\partial y}(vHC)=\frac{\partial}{\partial x}[(D_xH)\frac{\partial c}{\partial x}]+\frac{\partial}{\partial y}[(D_yH)\frac{\partial c}{\partial y}] \tag{11}$$

①Support for this model is provided by Associate Professor Han Naibin (Nanjing Institute of Water Conservancy)

Where x and y are Cartesian coordinate; t is time; H is water depth above average water level; u and v are mean velocity component of vertical line in x and y axis; Q is discharge at Datong; A is cross-sectional area of the river; B is river width; R_h is hydraulic radius; g is acceleration of gravity; C_f is Chezy coefficient; $f = 2\omega\sin\varphi$ (here ω is angular velocity of the earth rotation, φ is latitude); C is mean chlorinity in vertical line; D_x and D_y are integrated diffusion coefficient in x and y axis.

3.2 Boundary Conditions

In the two-dimensional model of tidal current, velocity of normal direction in land boundary $V_n = 0$. In down boundary (the isobath −20 m), the model is controlled by the tidal level. We use relevant water level calculated by one-dimensional model as the boundary condition of the upper boundary (Jiangyin Station in Jiangsu Province) of two-dimensional model. The upper boundary (Guichi Station in Anhui Province) of one-dimensional model is controlled by discharge; We use relevant water level calculated through two-dimensional model as the boundary condition of down boundary (Jiangyin Station) of one-dimensional model.

In the two-dimensional diffusion model of chlorinity, normal gradient of chlorinity in land boundary is zero, which means $c / n = 0$; boundary condition of down boundary (nearby the isobath −20 m) is chlorinity of sea water.

3.3 Preliminary Conditions

In the two-dimensional model of tidal current, the effect of preliminary condition on calculative results isn't obvious. So we assume:

$$h(x,y,0) = 0$$
$$u(x,y,0) = 0$$
$$v(x,y,0) = 0$$

In the two-dimensional diffusion model of chlorinity, the range of chlorinity is very extensive (from sea water of down boundary to fresh water of upper boundary). For saving calculative time, we identify preliminary chlorinity in sections, and then rapidly get space distribution of chlorinity.

3.4 Test Calculation

In the process of calculation, step length of space, $s = 1{,}000$ m, step length of time, $t / 2 = 240$ s, $C_f = H^{1/6} / n$ (where rough coefficient $n = 0.0007H + 0.009$), D_x and D_y are 10 m^2/s.

Fig.5 is test curve of the tidal level at Gaoqiao station. There is little difference between the measured value and the calculated value of tidal level. Fig.6 is test curve of chlorinity at Baozhen Station, the calculated value of chlorinity can completely conform to the demands of model calculation.

3.5 Analysis of Calculated Results

Because the calculated region is unclosed, it is difficulty to decide boundary condition for future sea level rise, so we assume:

a. River bed topography hardly change;

b. Discharge change from the upper reaches of the Changjiang River is similar;

c. There is little change in chlorinity of down boundary.

Using this two-dimensional model, we have estimated chlorinity distribution in the South Branch for current trend, 50 cm and 80 cm rise in sea level (Fig.7). In the lowest discharge month of a special dry year, chlorinity from Xuliujing to the outlet would exceed 250 mg / kg for 80 cm rise in sea level during the spring tide period of the dry season. Chlorinity increase resulting from sea level rise will be different in distribution (it can be seen in Fig.7), and the highest chlorinity for sea level rise is found in South Passage. The section from Baimaokou to near Baoshan is the second; South Channel is the lowest. The main reason for this is that, South Passage is close to the outlet and so the effect of direct intrusion of salt water on this section is more serious than other river course. Baimaokou down to near Baoshan mainly affected by the inverted current of the North Branch. Although South Channel is affected by the two, the intensity of them is smaller than the upper or lower river course.

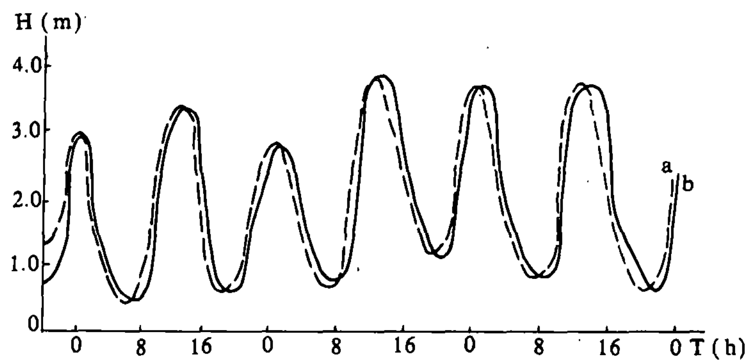

Fig.5 Test curve of tidal level at Gaoqiao Station

a. Calculated value b. Measured value

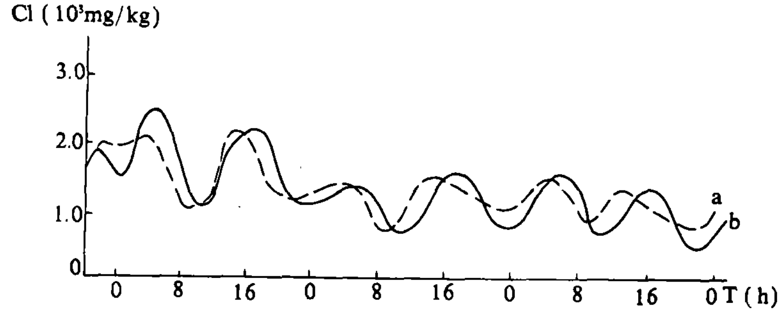

Fig.6 Test curve of chlorinity at Baozhen Station

a. Calculated value b. Measured value

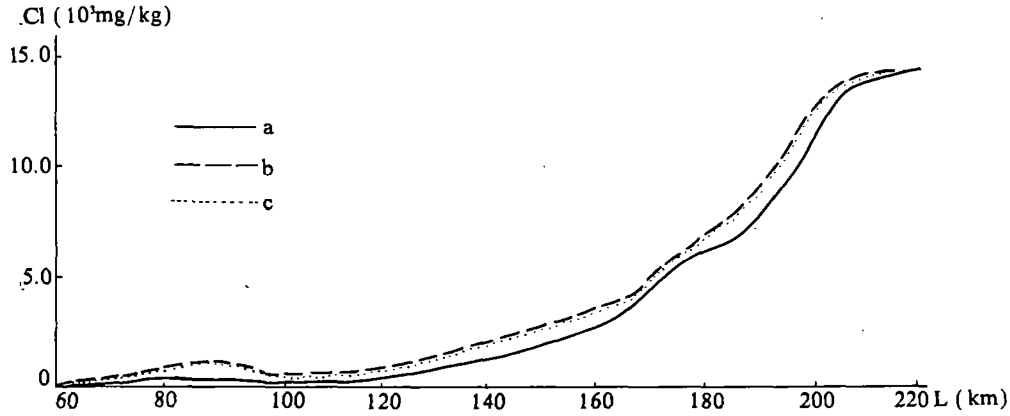

Fig.7 Impacts of sea level rise on chlorinity distribution in the South Branch
a. Current trend b. Sea level rise of 0.8m c. Sea level rise of 0.5m

III. THE MEASURES PREVENTING SALT WATER INTRUSION

The Changjiang River is the only stable and reliable water source of water supply for Shanghai, so it is necessary to take feasible measures to reduce harm of salt water intrusion due to the future sea level rise.

1. Combining with the Realignment of the Changjiang River estuary, Damming the North Branch

During spring tide period of dry season, the inverted current of the North Branch is main source of salt water intrusion in the South Branch. By Damming the North Branch, the effect of inverted current of the North Branch will be completely eliminated. It can greatly decrease chlorinity of the upper reaches from Baoshan in the South Branch and play a important role in ameliorating water quality of this section (Table 4, according to Shanghai Institute of Water Conservancy and Design).

Table 4 Effect of damming the North Branch on water quality of the South Branch

Station	Measured value (from the 17th to 18th of Feb. in 1987)		Calculated value after damming the North Branch	
	Chlorinity (mg/ kg)	Lasting hours of chlorinity over 250 mg/ kg	Chlorinity (mg/ kg)	Lasting hours of chlorinity over 250 mg/ kg
Danxi	407	24	54	0
Baoshan	306	17	194	5
Nanmengang	416	24	184	6

2. Building Regulate Reservoir in the River Floodland to Store Fresh Water

Although future sea level rise will increase salt water intrusion, serious effect will still occur in dry season, especially in dry year. In flood season, chlorinity will be low even if sea level rise over 100 cm. So we can build some regulate reservoirs in the river floodland to store fresh water before dry season coming. It can alleviate fresh water shortage in dry season. From the evolution trend of the whole estuary, the floodland of the South Branch is basically stable and the condition of building regulate reservoir is very favorable. If the water intake of water supply for Shanghai is located in the river section upper from Xuliujing, because effect of salt water intrusion isn't serious in this section, it is unnecessary to build regulate reservoir. But in the river section from Xuliujing to Baoshan, if the North Branch isn't dammed, it is necessary to build a great reservoir in this section. If water intake is located in the river section down from Baoshan, we can't guarantee water supply in dry season unless a great regulate reservoir will be built.

3. Exploiting Reasonably Groundwater so as to Alleviate Shortage of Water Supply in Dry Season

Making use of regulate function of groundwater, we can concentrated backbill water in flood season and appropriately exploit groundwater so as to alleviate fresh water shortage in the dry season. Exploiting groundwater often causes some environmental problems, for example, surface subsidence, salt water intrudes into groundwater and so on. So we must keep balance backbilling and exploiting in order to guarantee perpetual use of groundwater.

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