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IMPACT OF FUTURE SEA LEVEL RISE ON FLOOD AND WATER LOGGING DISASTERS IN LIXIAHE REGION*

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ABSTRACT: Lixiahe region is one of the susceptible area to flood and waterlogging disasters in China due to its low topographic relief and having difficulty in draining floodwater away. The condition will be more serious if sea level rises in the future. The estimated results by some scientists indicate that the sea level could rise probably 20—100 cm by 2050. However, what the effect will future sea level rise exerts on flood drainage and on flood or waterlogging disasters? A hydrological system model has been developed to study the problem in the lower reaches of the Sheyang River basin. Predicted results from the model show that, if sea level rises, drainage capacity of each drainage river will decrease obviously, and the water level will also rise. From the change of drainage capacity of drainage rivers the trends of flood and waterlogging disasters are analyzed in the paper if the severe flood that happened in the past meets with future sea level rise. Some countermeasures for disaster reduction and prevention against sea-level rise are put forward.
KEY WORDS: sea level rise, flood/waterlogging disasters, Lixiahe region, river network, hydrological system model

I. INTRODUCTION

Flood and waterlogging in coastal regions are the common phenomena due to the nature of the areas and the characteristics of the climate. Most coastal-regions have a low topographic relief and confront a high tide from the ocean. As a result, these regions are prone to flood and waterlogging during the peri-

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od of rainstorm, particularly when rain events coincide with high tides or storm surges. There have been several such notable events happening in China in the past few years, such as the floods in the Changjiang (Yangtze) River Delta and the North Jiangsu Coastal Plain in summer 1991. Catastrophic flood and waterlogging could cause the losses of the people's life and the severe damage to their property.

Recently, sea level rise and its direct and indirect impacts on coastal regions have gained widespread attention by most geoscientists. The rise in sea level in some areas during the last century, claimed by some authors, has been more than 15 cm, which has caused the increase in property damage from periodic flood and waterlogging, the losses of tidal flat and wetlands, the frequent intrusion of salt water and the retreat of shoreline etc. Hence, if the sea level continues to rise in the next century, the condition in the coastal regions will be more serious. The continuous rise of sea level will cause the tidal rivers more difficult in draining water off the coastal regions to the ocean, which could increase the frequency and duration of flood and waterlogging for medium-sized and small cities and towns and low-lying parts.

Lixiahe region, facing the Yellow Sea in the east and bordering Grand Canal in the west, is located at the lower reaches of the Huaihe River basin and between Tongyang Canal and the General Irrigation Canal (Fig. 1). It includes the inner Lixiahe Plain (the plain to the west of the Tongyu River) and the Coastal Plain. With its favorable natural conditions and plentiful natural resources, it is an important agricultural region and is also a relatively developed area in China. Thus, it will be susceptible to sea level rise in the future.

The rise of sea level along the coast of the Yellow Sea has been higher than the worldwide average during the last century due to a rapid land subsidence rate. However, will the sea level continue to rise at a faster rate in the next century? How much will the sea level of the region rise? What effect will the sea level rise exert on flood and waterlogging disasters of the region? It is necessary to answer these questions to promptly take preventive measures to reduce the harm.

II. FLOOD AND WATERLOGGING DISASTERS AND THEIR CAUSES IN LIXIAHE REGION

1. Topographic Relief

The Lixiahe Plain was formed gradually since the Yellow River snatched and occupied the Huaihe River as its lower course to the Yellow Sea in 1194. The altitude of the land surface is from 1.0 m to 7.0 m. Most of the region is below 3.0 m.

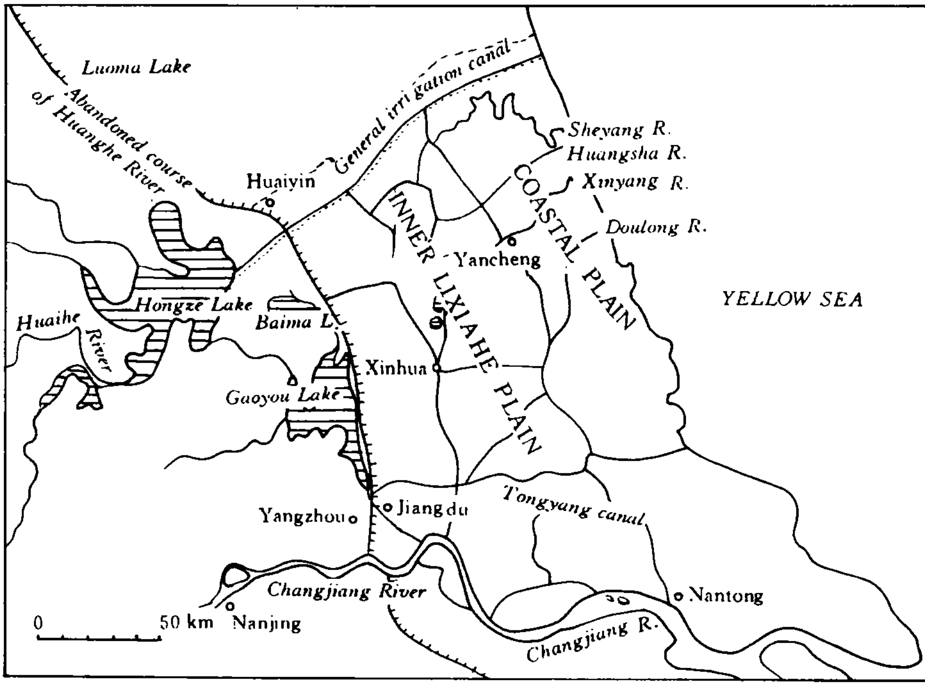


Fig. 1 Lixiahe Region

The inner Lixiahe Plain, with an area of 11,965 km^2, is a vast low-lying plain. The total area of arable land is about 6.38×10^5 ha, accounting for 57%. There are many linked low-lying lands with an elevation less than 2.0 m scattering in the center of the plain. The biggest ones are the Xinghua, Jianhu and Qingtong depressions. The area with an elevation below 2.0 m is about 3,400 km^2, accounting for 32%. The altitude on the fringe of the plain is higher than that in the center, with an average elevation of 3.5 m.

The coastal plain has a total area of 9,654 km^2, which can be divided into the south and north regions by the Doulong River. The north part, with an area of 5,415 km^2, is the flood water passage of the inner Lixiahe Plain. This part has the same topographic relief as the inner Lixiahe Plain, and the lowest point is only about 1 m. The south part has a high altitude from 4 m to 5 m.

2. Flood Mitigation Projects in Lixiahe Region

Since the founding of the People's Republic of China in 1949, the hazard reduction in Lixiahe Region has been put into consideration step by step by state government. After forty-year construction a complex system for flood prevention and logging water drainage has been formed by polders, dikes, rivers and ditches, and pumping stations, etc.. The system has been playing a vital role in reducing flood and waterlogging disasters in the region. The following water conservancy projects have been undertaken.

1) Drainage way construction. The main outlets of Lixiahe Region are these four rivers: the Sheyang River, the Huangsha River, the Xinyang River and the Doulong River. The project work includes dredging water ways and building a tidal lock at each river mouth, which has enhanced the maximum Changjiang drainage runoff to 1,800 m^3/s.

2) The project of directly pumping flood and logging water from the low-lying parts to the Changjiang River or the main drainage channels. There are many pumping stations distributed in the higher parts around the inner Lixiahe Plain. The main ones are the Jiangdu, Dongtai, Anfeng, Fu'an, Gaogang, and Jiangyan pumping stations, which can pump the logging water out from the region at a rate of 560 m^3/s during flood seasons

3) Polders construction. Most of the low-lying areas of Lixiahe Region have become polders, which have some pumps to drain the logging water off the areas as fast as possible. In the inner Lixiahe Plain there has a total polders area of 4.91×10^5 ha, with the total polder number of 2,494, and the total length of polder dike of 18,500 km and the number of sluices of 6,100. In addition, the pumping power of 4.4×10^5 kW has been installed in the inner Lixiahe Plain, which can discharge the logging water at a rate of 6,500 m^3/s to the rivers outside the polders.

3. Flood and Waterlogging Disasters and Their Causes

According to historical records flood and waterlogging happened very often, almost once every two years on an average, during the period when the Huanghe (Yellow) River took the Huaihe River as its lower course leading to the Yellow Sea from 1194 to 1855. After the Huanghe River returned to its present course in 1855 flood occurred once every three years on an average. Disastrous floods in the history often caused huge losses of the people's lives and the severe damage of their property. For example, in the 1931 flood, the Lixiahe Plain sank under a vast expanse of water, which caused about 900 thousand ha of arable land drowned, 3,120 thousand houses collapsed, 77 thousand people dead and 3 million homeless.

Since 1949, the flood and waterlogging disasters happening in Lixiahe Region have been more than fifteen times, of which the most serious ones occurred in the year of 1954, 1956, 1962, 1965 and 1991. Most flood events happened in the 1950s and the 1980s and the beginning of the 1960s and the 1990s.

In the summer of 1991, a catastrophic flood occurred in Lixiahe Region. The maximum 15-day precipitation in some 6,000 km^2 of the area had a return period of over 100 years. In the plum-rain period from May 21 to July 16, the total rainfall in Xinhua Rain Gauge was 1,301 mm, and Gaoyou 1,080 mm and Dongtai 1,046 mm. The highest water level in Xinhua Hydrostation reached 3.34 m, which was 0.26 m higher than the historical highest water tage before 1991 during the instrumental period. Analytical results from the NOAA (National Oceanic and Atmospheric Administration of America) satellite image of July 19 showed that some 3,700 km^2 of the area had been inundated. The inundated area had an average water depth of 0.7 m. Xinhua County was the most serious flooded area in Lixiahe Region, 68% of its polders had been drowned because of the polder dike broken. The economic losses totaled US$ 0.7 billion.

Heavy monsoon rains and typhoon rains are the main and important causes for flood and waterlogging in Lixiahe Region. Monsoon rains are the continual rains with storms lasting for a long period, generally from mid-June to early-July. Sometimes they last for about two months from mid-May to mid-July. Flood and waterlogging caused by monsoon rains happened on an average once in six years, major flood once in ten years. Typhoon rains are sudden heavy rains over a short time-span. Typhoons penetrate into the area once or twice each year. Statistic data indicate that maximum daily precipitation more than 200 mm hit the area 8 times in ten years, and that more than 150 mm hit the region 17 times in ten years.

Another important reason for the increasing incidence of flood is the tide wave action resisting the flood water being freely discharged. The flood and logging water of Lixiahe Region is mainly discharged by the four rivers mentioned above. Since the high tidal level just down the tidal lock is always higher than the water level at the upper river of the sluice because of the tidal wave action, the sluice can be opened to discharge floodwater in the low tide period of the irregular semidiurnal tide at the estuary. During flood period, the water surface gradient of the main rivers is only from 0.0000005 to 0.000001. The water, rising fast and falling slow, may keep high level for a long time, which could result in the farmlands inundated.

Polder's combination and human blind reclamation of lake and river shores are also important reasons of the disasters. Since 1958 the water surface area has decreased by about 1,000 km^2, and it lost a storage volume of about 1.2×10^9 m^3. Due to the reclamation of lakes, the lake area shrank by bout 800 km^2 within twenty-five years, from 992.6 km^2 in 1965 to 209 km^2 in 1990, accounting for 80% of the deceased water area.

III. CHANGES OF FUTURE RELATIVE SEA LEVEL ALONG THE COASTAL AREA OF THE REGION

Predicting future relative sea level (RSL) rise, we must consider not only mean value of future global eustatic sea level (ESL) rise but also the rate of earth crust and surface subsidence.

The coastal area of the Yellow Sea locates 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.

Predicted results show that, if the climate system is sensitive to the accelerated emissions of greenhouse gases and the ground surface subsides at a fast rate in the future, the sea level will rise at a high scenario; on the contrary, if the climate system is not sensitive to the emissions of greenhouse gases and the ground surface subsides at a slow rate in the future, the sea level will rise at a low scenario. Actual rising of sea level will be probably between the low and high scenario as the middle scenario in Table 1. By the years of 2025 and 2050 in the next century, the rises in sea level in the coastal area of Lixiahe Region could be around 21 cm and 51 cm respectively.

Table 1 Future relative sea level rise in the coastal area of Lixiahe Region

Year	High scenario	Middle scenario	Low scenario
2000	14	8	4
2025	46	25	10
2050	101	51	21

IV. MODELING THE IMPACT OF FUTURE SEA LEVEL RISE ON FLOOD DRAINAGE IN THE TIDAL RIVER NETWORK OF SHEYANG BASIN

A hydrological system model has been built to simulate the changes of discharge capacity in the lower reaches of the Sheyang River basin after future sea level rise. The studied area locates in the northern part of the Coastal Plain, which has a total area of 3,020 km^2. The area of arable land is about 1.35×10^4 ha. Most lowlands are controlled by polders, with an area of 1,103 km^2, and an elevation of polder dike from 3.5 m to 4.0 m and the drainage power of 5.4×10^4 kW that can discharge the logging water at a rate of 900 m^3/s.

Many rivers densely distribute in the studied area (Fig. 2). The main drainage channels are those as the Sheyang, Huangsha, Yunmian and Liming rivers. The Sheyang and Huangsha rivers are also the discharge ways of the inner Lixiahe Plain, which can drainage 60% of the flood water.

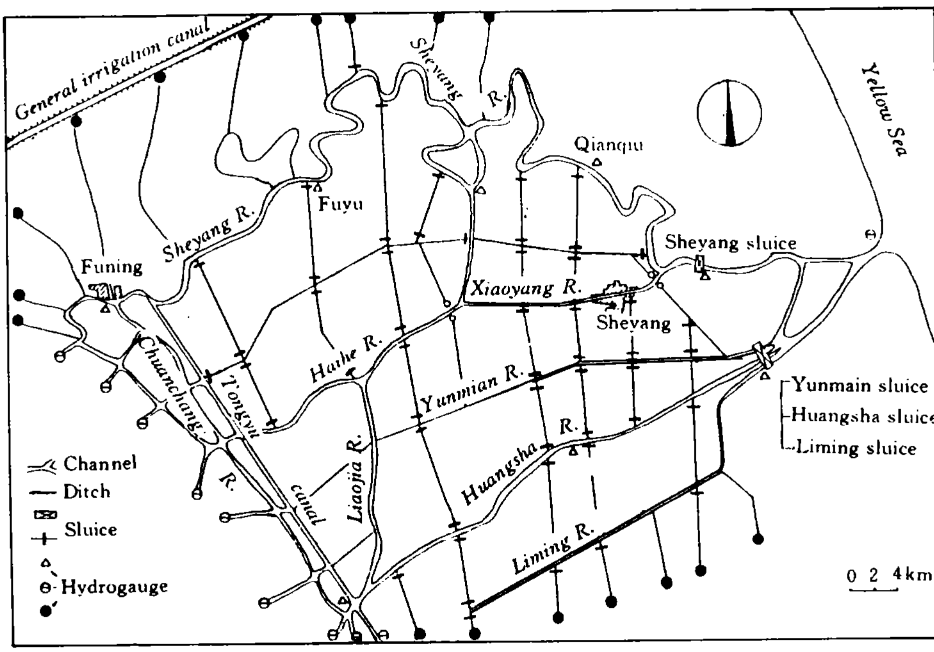


Fig. 2 The network channels in the computational area

1. The Hydrological System Model

The model, mainly simulating the movement of floodwater in the river network of the lower reaches of the Sheyang River basin, consists of five submodels, which namely are:

1) Model for unsteady flow in network channels. The equations for this model are as follows:

$$\frac{\partial Q}{\partial x} + B_T \frac{\partial Z}{\partial t} = q_L \quad (1)$$

$$\frac{\partial Q}{\partial t} + 2u\frac{\partial Q}{\partial x} + (gA - Bu^2)\frac{\partial Z}{\partial x} - u^2\frac{\partial A}{\partial x}\bigg|_z + g\frac{n^2|Q|Q}{R^{\frac{4}{3}}} = 0 \qquad (2)$$

$$\sum_{i=1}^{m} Q_i = 0, Z_1 = Z_2 = \ldots = Z_m \qquad (3)$$

where x is Cartesian coordinate; t is time; Q is discharge; Z is water stage; B is water surface width; B_T is storage width; n is Manning roughness coefficient; R is hydraulic radius; A is cross-sectional area of the river; u is mean velocity in the cross section; g is acceleration of gravity; q_L is continuous lateral inflow (outflow) per unit length along river bank; m is river numbers at a node.

Using the four-point implicit scheme by Preissmann, the partial differential equations are discreted as finite differential equations. A combined multiple-steps method has been used to solve the discrete equations.

2) Model for network channels. A method called series-parallel connection is used to skeletonize the river network in the studied area. By using the method, many small-scale ditches with small narrow river and low discharge can be combined to form several relative big rivers.

3) Model for boundary conditions. Water level and tidal stage hydrographs are used as the west and east boundary conditions respectively. The hydrological statistics method is applied to design water stage and tidal stage hydrographs of different frequencies. Discharge hydrograph are given in the south and north boundaries. Most rivers have no water quantity exchange to the adjacent basins, so we used zero discharge condition.

4) Model for rainfall and runoff. The precipitation and runoff relationship curves $P+Pa\sim R$ are used to calculate the runoff production in the embanked and non-embanked areas.

5) Model for hydraulic projects and their managements. The sluices around the polders can only be opened when the water level in the ditches inside the polders is higher than the water level in the main drainage rivers. The tidal sluices lead the flood water to flow to the ocean.

2. Test and Calibration of the Model

In the process of unsteady flow computation, step length of space $\triangle x=$ 500—3200 m, and step length of time $\triangle t=900$ s and Manning roughness coefficient $n=0.015$—0.030.

Test results show that the model has a high accuracy to simulate the runoff production in plain area and runoff concentration in network channels.

Table 2 is the comparison of measured and computed daily discharge volumes of the four sluices gates (Sheyang, Huangsha, Yunmian, Liming) on July 20, 1981.

Table 2 Comparison of measured and computed discharge volumes of the four sluices ($\times 10^4$ m^3)

Results	Sheyang R.	Huangsha R.	Liming R.	Yunmian R.	Total
Computed	1560.73	848.65	343.84	270.40	3023.64
Measured	1575.60	856.90	313.63	298.08	3046.21
Rel. Err.	−0.9%	−1.2%	9.6%	9.3%	−0.7%

3. Predicting the Changes of Water stage and Discharge after Sea Level Rises in the Next Century

3.1 *Assumptions*

Because of the uncertainty of the estimates of future sea level rise in Table 1, the author assumes that the mean value of low-middle scenarios of 40 cm is the low limit of sea level rise by 2050, and that the mean value of middle-high scenarios of 80 cm is the high limit of sea level rise by 2050.

Future sea level does not result in the sedimentation of river channels. The riverbed topography of each river hardly changes.

The tidal hydrograph in the Yellow Sea does not change its shape. That means, if sea level rises 0.40 m, the high and low tidal level will also rise 0.40 m.

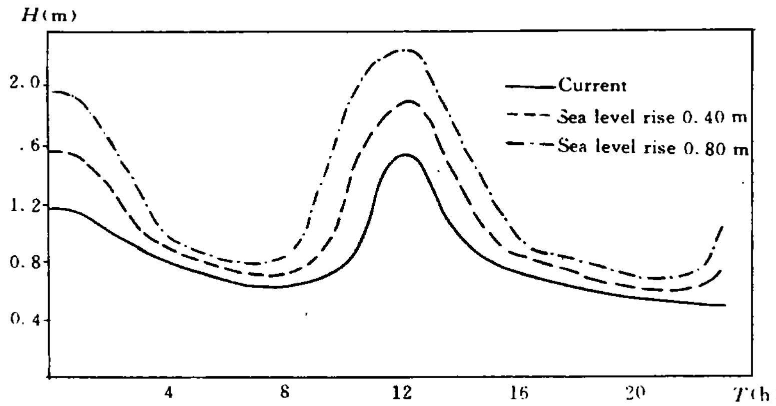
3.2 *Computation schemes*

Tidal frequencies are designed as 10%, 50% and 90%, which represent high tide, normal tide and low tide. Water levels at Funing hydrostation are designed as 0.50 m, 1.00 m and 1.75 m, which represent drought, normal and flood of the region. In flood season, the mean areal rainfall is designed as 150 mm.

3.3 *Response of water stage to future sea level rise*

High and low tidal stages at the estuary of each drainage river will rise correspondingly with sea level rise. The extent of rise in high tide will be higher than that of the rise of sea level. However, the rising value of the low tide is lower than that of sea level. The tidal range will increase (Fig. 3). The rise in sea level rise of 0.40 m and 0.80 m could cause the 0.40 m and 0.80 m increase of average high tidal level just down the Sheyang sluice gate and the

0.08 m and 0.19 m increasing of average low tidal level at the same location.



Water level 1.[illegible] m at Funing, tide frequency 50%

Fig. 3 The changes of tidal hydrograph just down the Sheyang sluice gate after sea level rise

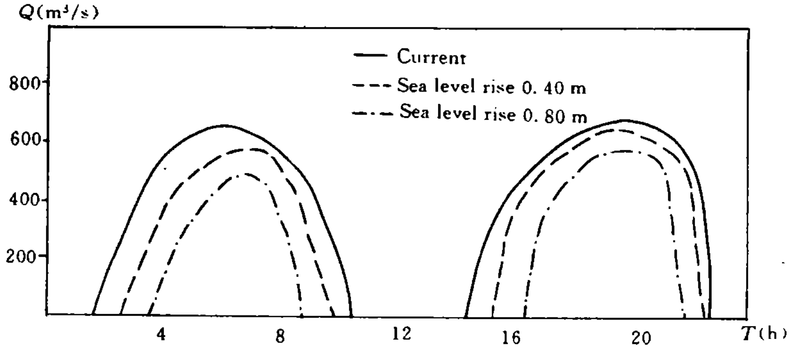
The rising value of water level in the drainage channels will decrease along distance from the sluice gates to the upper streams. For example, if sea level rises 0.40 m, the increasing value of average water level at Tongyang water-gauge will be 4 cm less than that at Sheyang sluice. The change of water level in the ditches of polders is very complicated. It relates not only to the rise of sea level but also to the drainage modules of polders.

3.4 *Response of discharge to future sea level rise*

If the sea level rises, the drainage capacity will decrease markedly. This is mainly caused by a reduction of discharge duration and a decrease of discharge (Fig. 4). With sea level rise of 0.80 m and 0.40 m, the mean drainage capacity from the this area to the Yellow Sea may decrease about 52% and 26% respectively (Table 3).

Table 3 **Reduction rates of total drainage volume of the four sluices after sea level rise**(%)

Tide frequency (%)		10			50			90		
Water stage in Funing (m)		0.50	1.00	1.75	0.50	1.00	1.75	0.50	1.00	1.75
Sea level rise	0.40 m	26	19	17	33	23	15	48	33	14
	0.80 m	55	39	31	68	47	55	93	63	33



Water level 1.0 m at Funing, tide frequency 50%

Fig. 4 The change of discharge hydrograph of the Sheyang sluice gate after sea level rise

V. PRELIMINARY STUDY ON THE TREND OF FLOOD AND WATERLOGGING DISASTER IN LIXIAHE REGION

Future sea level rise could not only directly cause the losses of tidal flat and wetlands along coastal shores but indirectly exasperate the flood and waterlogging disasters in Lixiahe Region. The decreasing of discharge capacity of the drainage channels will be the main cause for aggravation of the disasters.

In several serious flood and waterlogging disasters since 1949, floods in 1954 and 1991 caused by plum-rains are the two most serious ones. Because the main outlets were not controlled by tide sluices in 1954, we select the flood in 1991 as a typical flood to forecast the effect of future sea level rise on the disaster.

1. The Coastal Plain

The direct impact of future sea level rise on this region is the inundation of tidal flat and wetlands. Statistic data indicate that, if sea level rises 0.50 m, the losses of tidal flat and wetlands could be 302 km^2 and 100 km^2 respectively, and the sea level rise of 1.00 m could cause 17% of tidal flats and 55% of wetlands lost. Due to the difference of terrain between southern and northern parts of the Doulong River, the effects of sea level rise on flood and waterlogging disasters in these two parts will be different.

1.1 *Northern area of the Doulong River*

This area has a lower topographic relief, it is a typical flooded and waterlogging area because the flood water level is always higher than the land elevation. If sea level rises in the future, the flood stage in the four main rivers, which run through the area as drainage passages of flood water in Inner Lixiahe Plain, could rise, and the disasters could become more serious. The predicted results by using the model mentioned above show that, if flood is similar to that of 1991 and sea level rises 0.40 m, the water levels just upstream of the Sheyang and Huangsha sluice gates could raise by 0.13 m and 0.19 m. It means that the heights of polder dykes should increase more than 20 cm, which could make the economic loss in polder areas after sea level rise 0.40 m less than that in 1991. The lowest design height of polder dykes should increase to 3.90 m from 3.50 m at present if sea level rises 0.80 m.

1.2 *Southern area of Doulong River*

According to estimation, the sea level rise less than 1.00 m will have little effect on the water draining from this area because of a higher terrain of the area and a larger tidal range along the area's coast.

2. The Inner Lixiahe Plain

2.1 *Sea level rise* 0.40 *m*, *the* 1991*'s flood reoccurs*

The 1991 disastrous flood mainly happened in the second period of the plum-rains from June 28 to July 16. In this period, the rainfall in the storm centre of Xinghua County reached 970 mm, and the areal mean precipitation was 704 mm, which produced about 7.0×10^9 m^3 of runoff. Calculated results indicate that about 3.5×10^9 m^3 net produced water were stored in the Lixiahe Plain on July 15, which caused the rising of water stage to 3.34 m (08 hour, 15 July). If sea level rises 0.40 m, the four main channels could only drain 2.0×10^9 m^3 flood and logging water off in the same period, and the flood water storing in the area will increase to 4.0×10^9 m^3, which could cause the following affects:

1) The highest water level in Xinhua hydrological gauge will be up to 3.43 m, if no more farmlands inundate.

2) The inundated area will increase about 360 km^2, if the water level does not change.

2.2 *Sea level rise* 0.80 *m*, *the* 1991*'s flood reoccurs*

Sea level rise 0.80 m could cause the drainage capacity of the four main rivers decreasing by 35% if the flood of 1991 reoccurs in the future. From the decrease rate we can calculate that the drainage amount from the area will decrease by about 1.0×10^9 m^3, which could cause the impacts as follows:

1) The highest water level in Xinhua hydrological gauge will be up to 3.57 m, if no more farmlands inundate.

2) The inundated area will increase about 840 km^2, if the water level does not change.

VI. COUNTERMEASURES FOR DISASTER PREVENTION AND REDUCTION AGAINST FUTURE SEA LEVEL RISE

The harmful effect on Lixiahe Region caused by future sea level rise should be considered in designing water conservancy projects since it is a relatively economic developed and densely populated area. Some measures are put forward as follows:

1) **Dredging the Four Main Drainage Waterways and Other Drainage Channels in Order to Expand the Flood-Drainage Capacity.** The discharge capacity of the four waterways and other dranage courses has decreased a lot due to the siltation of the riverbed since the construction of tidal sluice gates at the mouth of each river. The rising of sea level will cause the condition more serious. For example, if sea level rises 0.80 m, the mean discharge capacity of the Sheyang River sluice will decrease by 52%. Hence, it is an important measure to evacuate the drainage ways. In the upper and middle parts of these rivers, the narrow courses should be widened soon. In the lower parts, the meandering ways should be straightened, and the tidal sluices and power equipment should be repaired. In the meantime, a large artificial channel should be digged in the south part of the Coastal Plain.

2) **Further Constructing the Polders.** During the 1991'S disastrous flood, about 45% of the polder dikes could not withstand the flood and half of the polders did not have enough pumps to drain the logging water off the region. So we should continue to construct the polders. The constructing height of the polder dikes in the next few years should be higher than the highest water stage in 1991. To prevent the effect of future sea level rise, we must enhance the design standard of height of polder dikes and enlarge the drainage capacity of the present pumping system. Before 2050 the height of polder dikes should be 20—40 cm higher than the design height by water conservancy prejects without considering the sea level rise.

3) **Continuing to Build the Pumping Stations Around Upper Part of the Inner Lixiahe Area.** The principle of water conservancy in Lixiahe region is "pumping on upper, retarding on middle and discharging on lower". Pumping on upper is an important means to reduce the risk of flood and waterlogging

disasters. There have been many pumping stations being built on the upper parts of the region. But the discharge capacity of these stations has still not meet the requirement for water conservancy planning. Additional stations should be built soon. Increase of the pumping discharges will reduce the pressure of floodwater on low-lying area after future sea level rise.

4) **Increasing the Storage Capacity of Lakes and Marshes.** Because floodwater storaging in the centre is very important to flood reduction in Lixiahe Region, it is necessary to keep some storage areas. Now, the region only has an area of lakes and marshes of 210 km^2. It is less than the minimum area of 700 km^2 by water conservancy planning. The lower benefit farmlands around lakes or marshes should return to lakes or marshes.

5) **Fulfilling Town's flood-Prevention System.** Recently, the newly built industrial and living areas have expanded to lowland due to the rapid development of township industry. There almost have no flood-prevention measures in these areas. In the 1991's flood, most of these areas inundated. For example, about 10.2 km^2 was drowned in the newly built area of Shaoyang town of Xinhua County, accounting for 86.6%. If future sea level rises 0.40 m or 0.80 m and the 1991's flood happens again, the inundated area could be larger than now. Thereafter, the town's flood-prevention system should be fulfilled soon.

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