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FORECAST OF IMPACTS OF SEA-LEVEL RISE ON THE LOW COLONIZED ISLANDS AND THEIR SURROUNDING WATERS IN THE CHANGJIANG RIVER MOUTH

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ABSTRCT: As a worldwide authoritative, IPCC forecasted in 1990 that the world's sea level would most probably rise by 0.66 m by the end of the 21st century. Combined with the local depression caused by the sink of the earth's crust and the human activity, the relative sea level in the Changjiang River mouth will rise by about 1.0 m during the same period. Based on this figure, the article forecasted the impacts of sea-level rise on the safety coefficient of coastal structures and civil facilities, loss of wetlands, flood hazard as well as water intrusion. The results show that: 1) 40% as large as the present engineering mass should be added to the coastal structures in order to maintain the safety coefficient; 2) a dynamic loss of 60 km^2 of wetlands, as much as 15% of the present total area, would be caused; 3) to hinder the increase in flood hazard dynamic capacity to drain water must increase by at least 34 times as large as the present; 4) to maintain the present navigation conditions, about 100 million yuan (RMB) is needed to reconstruct over 3000 bridges and 30 sluices; and 5) the disastrous salt water intrusion caused by the sea-level rise could be encountered by the increase in water discharge from the Three Gorge Reservoir in the dry season.
KEY WORDS: sea-level rise; flood hazard; loss of wetland; salt water intrusion; Changjiang River mouth

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The threat against the coastal lowland caused by sea-level rise is one of the focuses of the world's attention. The best estimate value of global theoretical sea-level rise in the 21st century is 0.66 m(SCOR, 1991) by worldwide authoritative organization such as IPCC (Intergovernment Panel of Climate Change) *et al.* The crust of Changjiang Delta is subsiding. The average subsidence rate in the last 2000 a is 1.2 mm/a(PAN *et al.*, 1985). The islands of the Changjiang River mouth are accumulating lowland islands and their natural elevation is below the high tidal level of spring tide. Sea-level rise is an undoubtedly severe challenge to islands. Proper estimation for the latent loss of hazard is the necessary pledge to decrease hazard.

1 THE NATURAL, SOCIAL AND ECONOMIC CONDITIONS OF THE THREE ISLANDS

Chongming, Changxing and Hengsha are the largest islands in the Changjiang River mouth with their areas of 1111 km^2, 88 km^2 and 49 km^2(GSIRCI, 1996) respectively. They are formed from the sands of the Changjiang River. Their embryonic forms emerge from the water level at 618, 1644 and 1843 A.D. (GSIRCI, 1996). The relationship between the land elevations and the tidal levels is given in the Table 1.

According to the record of *Chongming County Annals* in the year of Zhengde in the Ming Dynasty, people began to settle in Chongming Island from 696

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Table 1 Comparison between tidal levels and elevations in the three islands (above the Wusong base) (m)

Island name	Average tidal level	Average high tidal level	Historical highest tidal level	Average land elevation*	Highest land elevation
Chongming**	2.07	3.33	5.67	3.77	5.1
Changxing	2.02	3.28	5.74***	2.78	3.2
Hengsha	1.94	3.25	5.74***	2.87	3.6

* Except the river system in the islands. ** The tidal level was obtained from Baozhen Station in the southern branch; the tidal level of northern branch is higher than that of the southern branch. *** From Wusong Station.

A. D.; Chongming Town was set up in the Five Dynasties, having over 1000-a history. The population census in 1990 indicated that the total population was 815 000, the population density was 653 persons/km^2, which was 5.7 times of the nation. Gross output value of industry and agriculture of the three islands was 410 million yuan (RMB) (GSIRCI, 1996). Land average output value (3.16 million yuan/km^2) was 12 times of the national average level. The average output value per capita (5030 yuan/person) was 2.2 times of the national average level.

2 THE TENDENCY OF SEA-LEVEL RISE

According to the studies of over ten scientists in the world during the half of this century, the rate of global sea-level rise is 1 – 2 mm/a (SCOR, 1991) in the last 100 a. In large delta, because of crust sinking and earth subsiding, the rate of relative sea-level rise was much faster than the rate of water dynamic rise. For example, the rate of relative sea-level rise reaches 11 mm/a (REN, 1995) in Wusong Station of the Changjiang River mouth in the last decades. As to the change of sea-level in the future, the best estimate value by IPCC in 1990 is that the global sea-level will have risen by 18 cm by 2030, 66 cm by 2100 (SCOR, 1991). Earth subsidence is an important factor affecting the relative sea-level rise of Changjiang Delta. However, the impact extent will be different in different developed regions (developed region > undeveloped region) (REN, 1995). The authors believe that the development of these islands in the next century will be acceleratd with the impact of Pudong's development and after large communicative engineering (such as the "southern tunnels and northern bridges" program). Therefore, the earth subsidence of the islands in the 21st century is unavoidable. By the rough estimate, the plus of theoretical sea-level rise, crust sinking and earth subsiding will make the relative sea-level of the islands rise by 1.0 m in the 21st century.

3 FORECAST OF IMPACTS OF SEA-LEVEL RISE

3.1 Impacts on Seawall and Coastal Protective Structures

Seawall is an important engineering measure to protect the residents in the islands from the disaster of ocean outflow. By the record of *Water Conservancy Annals of Chongming Town* (in 1987), since 1301, in almost 700 a, there were 17 times of great ocean outflow, about once per 40 a. "In July of 1390 (the 23rd year of Hongwu in Ming Dynastry), ocean outflow, the houses along the shore were all submerged, nine tenths people were drowned"; "In leap June of 1569 (the 3rd year of Longqing in Ming Dynastry), from thirteenth to sixteenth, agitation, the depth of water in the flat land was more than 10 m. In the city, people moved by canoe; countless people were drowned". "On August third, 1905, hurricane, night tide suddenly outflow, all the streets and houses of the city were submerged, over 10000 people were drowned". After 1949, the government called in islands residents to renew the old seawall, to structure new bank on a large scale. Then a perfect protective system has been set up surrounding these islands, which effectively resist tidal attack. According to the statistics of Shanghai resources comprehensive investigation, there were 294.6 km seawall (63% of total seawall length of the whole city). The top width of the seawall is 5 km, the elevation is 7.8 – 8.0 m, landside 1:2, seaside 1:3. As auxiliary facilities of seawall, there are over 300 stone lump spur dike (total length is 45.5 km); 146 km stone lump concrete slope protection; 122 km stone lump protection ridge.

Sea-level rise reduces the seawall security standard. If former security standard can be maintained, the seawall must be broadened and heightened. Fig. 1 indicates that the section area of seawall must be added according to the following formula.

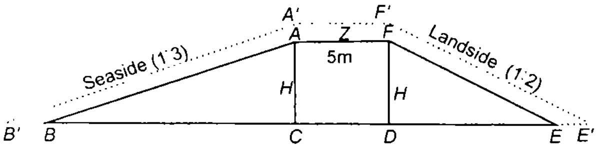

Fig. 1 A model of seawall adjustment as response to sea-level rise

$$S = A'B'E'F' - ABEF$$
$$= (A'B'C + A'CDF' + F'DE') - (ABC + ACDF + FDE)$$
$$= 5/2\ (X^2 + 2XH) + 5X\ (m^2)$$

In the formula, X is the extent of sea-level rise (m); H is the present elevation of seawall (m).

The seawall dike of Shanghai is usually 3.5 m high (zero state of Wusong). If calculated by 8.0 m high of seawall top, then $H = 4.5$ m. Calculated by the former estimate, $X = 1.0$ m. Then put the two figures into the formula, the score is $S = 30.0$ m^2. The added seawall section area is 41.1% of the former. Calculated by the 294.6 km of present seawall total length, the added soil quantity is 8 840 000 km^3. Calculated by labor price in 1995, the cost of added seawall soil and labor will be about 10 yuan/m^3. Only seawall cost 100 million yuan.

Sea-level rise deepens the water out of bank and intensifies the wave energy. Therefore, in order to maintain primary seawall security coefficient, the spur dike, slope protection and protective ridge out of bank must be heightened and strengthened. The specific added investment to be calculated is very complicated. Try to calculate it by the added ratio of seawall cubic meter of earth, there are 1×10^6 m^3 stone lump structure, 50 000 m^3 concrete structure must be added. By estimate, the accumulated investment will be as much as the cost of adding seawall.

3.2 Impacts on Intertidal Flats

The islands of the Changjiang River mouth connect with the tidal flats. Seen from history, the lands of these islands are all developed from tidal flats or people's enclosing for cultivation. Sea-level rise impacts on coast are submerge and section adjustment. Because deposit coast including beach and tidal flats is generally inclined to sea, with sea-level rise, the line that sea face intersects flats face certainly moves to land. The horizontal distance of movement is $Y_1 = X/\tan\theta$ and the flat face slope distance is $Y_2 = X/\tan\theta$ (X — the extent of sea-level rise, θ — the flats' gradient). When θ is very small, Y_1 approximates Y_2. The BRUUN formula which is about beach section adjustment after sea-level rise in fact is horizontal movement to land based on the supposition that longitudinal offering sands is balanced (i.e. the quantity of imported sands is equal to that of exported sands); the formula is similar to Y_1 (BRUUN, 1962). As for the application of Bruun law, there is no unanimous knowledge. Carter introduced the condition of many scholars testing Bruun law in the sandy coast. The result indicates that beach section, the rate of sea-level rise and complicated changes of deposit make very large limit in applying this law (CARTER, 1988). JI Zi-xiu *et al.* think that this law in principlely suits to scouring and steady muddy flat coast, but it must be modified with using deposit size and tidal flat gradient (JI *et al.*, 1993).

It's difficult to quantitatively give each section accumulating law of the islands tidal flats in the background of sea-level rise in the next century. The reason is there is some uncertain factors. At first, the development law of the Changjiang River mouth can't be quantitative and the process of sometime scouring and sometime deposit, here scouring and there deposit can't be well forecasted. Second, we can't accurately answer the question that how much sands carried by river will be decreased after Three Gorges Reservoir is built in the next century and how to adjust the river mouth flat land after sands are decreased. Third, there are some measures to protect flat and coast along the islands, so the natural scouring receding of coast natural scouring is prevented by man. On this occasion, sea-level rise only means increasing protective cost not coast receding. But we can semi-quantitatively make some estimate. At present, the natural steady coast segments chiefly lie in the west of northern branch coastline of Chongming, they are about 1/4 of total length of islands coastline. Engineering steady coast segments sporadically lie in the middle of Chongming and the coasts of Changxing and Hengsha, they are about 1/3 of total length of islands coastline. Intensively erosive receding coast segments lie in Tuanjiesha – Xijiagang section in the east of southern coast of Chongming and the new east three dams in the west of southern coast of Chongming and the west of northern and southeast of Changxing, they are about 10% of total islands coastline. The natural accumulating coast segments are Dongwangsha in the east of Chongming, the east segments of the northern coast of Chongming and the west and northeast parts of Changxing, they are about 1/3 of total coastline. In the next century, at the background of sea-level rise, in the present natural accumulating coast segments, the accumulating rate may be decreased, accumulating function may turn to scour. The present steady coast segments may turn to scour. Moreover, the present erosive coast segments may intensify scour. Either for erosive coast segments or for accumulating coast segments, we can estimate the net loss area of tidal flats (decrease or scour rate reducing), caused by sea-level rise, according to the gradient of each coast segment tidal flats and the forecast value of sea-level rise, the formula is $Y = X/\tan\theta$. The calculated scores are arranged in Table 2.

Therefore, in the condition of 1.0 m relative sea level rise of the islands, area loss of tidal flats will be 60 km^2, being equal to 15% of present tidal flat area (397 km^2) of the islands.

3.3 Impacts on Flood Hazard

In the aspect of water, there are two mechanisms of the islands being submerged, one is that they are submerged by tidal water (seawall breach), the other is that rain water concentrate and can't be drained away in time because of low land. The latter is similar to the mechanism of the flood hazard of Taihu Basin. The perpetual water system area of islands is about 10% of land area, the paddy field area is 23% of land area, plus the structure of streets and houses etc, the unosmotic land area in the rainy season is about 40% of land area. the Changjiang River mouth belongs to subtropic zone. According to the statistic data of 30a, yearly average rainfall of Chongming, Changxing and Hengsha is 1034 mm, 1064 mm and 1074 mm. The maximum rainfall is 1538 mm (Houjiazhen Station). About half of rainfall in a year is concentrated in the three months of summer. The maximum 1-h rainfall is 76 mm and the maximum 1-d rainfall is 163 mm. About 20% of Chongming land area and over 90% of Changxing, Hengsha land area are below the average hightidal level (Table 1). Because of the smooth land, low elevation, concentrated rainfall and the big ratio of unosmotic land

Table 2 Forecast on net area loss tidal in the three islands caused by 1.0 m relative sea-level rise in the 21st century

Item	East flat of Chongming	North bank of Chongming		South bank of Chongming	Changxing Island and Hengsha Island					Total
		East part	West part							
Average slope(‰)	0.5	2.7	6.4	18.5	1	2.3	5.3	8.5	16.4	
Length of line(km)	11.5	37.8	44.6	78.5	1.6	8.8	9.4	11.9	48.2	
Water line retreat distance (m)	20000	370	156	54	1000	435	189	118	61	
Area loss(km^2)	23	14	7	4.2	1.6	3.83	1.77	1.4	2.94	59.7

Note: There are complicated longitudinal changes and too many segments in Changxing and Hengsha, it's difficult to arrange them in succession, so different grades are accumulated.

area, the threat of flood hazard is very severe. According to the record of water conservancy annals of Chongming town, "on the night of July 15th, 1461, because of rainstorm, spring tide (high water level, accumulated water is difficult to drain away), houses were submerged, over 4000 residents were dead". "In the summer of 1755, rain continue for several ten days ... with starved bodies everywhere." "In the last ten days of July, 1947, rain was continuous... the whole area was submerged, the accumulated water is 2 m deep, the harvest was greatly decreased." "In the summer of 1954, due to continuous rainstorm, fields were submerged, the accumulated water of inland was to water logging."

Under the estimate of 1.0 m relative sea-level rise in the last of next century, the average sea level of Chongming, Changxing and Hengsha will reach 3.07 m, 3.02 m and 2.94 m. Average high tidal level of three islands will reach 4.33 m, 4.28 m and 4.25 m (Table 1). Calculated by this, all the land of Changxing and Hengsha, over 80% of the land and 95% of the fields of Chongming will below average high tidal level. At present, underground water level is generally 0.6 – 0.8 m(GSIRCI, 1996). Sea-level rise will raise the underground water level. Too high underground water level not only prevents the growing of crops but also causes flood hazard easily in rainy season. Therefore sea-level rise will intensify the threat of flood hazard of the islands. By 1985, there have been 11 draining water pumps, 28 pumps, the controlled area is 2333 ha, besides these, there have been 39 draining and irrigating pumps and 92 pumps, the controlled area is 780 ha. By the rough estimate, the chance that the draining water passage arise negative gradient will be 4 – 5 times of the present; on the other hand, the field area below high tidal level of these islands in the next century is about 4 – 5 times of the present. Deduced by this, if the standard of controlling flood and draining water reaches the present standard, the ability of drawing and draining of these islands in the next century must be added by 3 – 4 times of the present.

3.4 Impacts on the Facilities of Bridges, Sluices and Culverts

By the record of water conservancy annals of Chongming Town, in 1985, there were 140 road bridges, 293 dry river bridges and 3090 Mingou bridges. Calculated by the price in 1975, average cost of road bridges is 290 000 yuan, average cost of Mingou bridges is 10 000 yuan. There are 23 sluices along the coast in Chongming. Calculated by 11 sluices built in the 1970s, the average cost is 670 000 yuan. There are 56 culverts in Chongming. Calculated by the price from 1961 to 1963, the average cost is 12 000 yuan. By the rough estimate, it will take 25 000 yuan to rebuild these facilities of traffic and water conservancy. At the background of 1.0 m relative sea-level rise, all of these facilities can't reach the present standard, especially the navigable ability of bridges and sluices will be evidently limited. Lots of fund must be invested to reach the present standard.

3.5 Impacts on Salt Water Intrusion

There are great quantity of runoff of the Changjiang River pouring into the river mouth to make the salinity of the water around these islands usually fit for the demand of the water used in daily life and agricultural and industrial production. But in very dry season, these islands still are subjected to being surrounded by salt water and form hazard. For example, in the early of 1979, the river basin was very dry (historical minimum water discharge was 4620 m^3/s on January 31st in Datong Station, which was 44% of average water discharge in January for years in succession.) and lots of water was drown to agăinst drought along the river from Datong, the quantity of the fresh water that factually ran into the river mouth from January to April was only about half of average year' s. Runoff is weak then sea-water is energetic. These islands are surrounded by salt water for a long time. The salinity of the water factory of Wusong which lie in the opposite bank of Baozhen in the middle of Chongming exceed drink water standard for over two months. The maximum salinity is 7.16‰① (Fig. 2 indicates the distribution law of the salinity in the Changjiang River mouth, the salinity of most segments of these islands is higher than that of Wusong Station) . Salt water intrusion made severe hazard to manufacture and daily life in the Changjiang River mouth region including these islands. The historical maximum salinity of Baozhen Station is 21.3‰ (XU *et al.*, 1994).

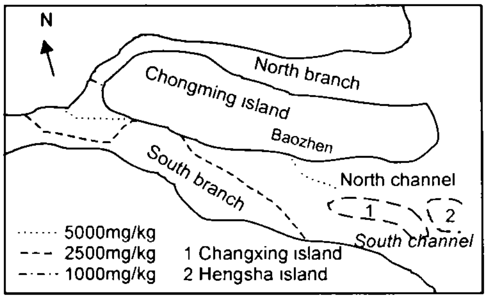

Fig. 2 Distribution of chlorine isogram in the Changjiang River mouth (based on the maximum chlorine from Feb. 16 to Apr. 10, 1987)

Saline soil of seashore is in a big proportion of present cultivated land in these islands. For example, the area of seashore saline soil of Chongming is 180 km^2, which is 31% of total cultivated land area ②. Moreover, there are about 400 km^2 seashore saline soil of tidal flats in these islands. Slat water intrusion will cause the salinity of underground water in these islands to rise, which will affect on development and usage of tidal flats. The increase of salt quantity of tidal flats in these islands

① SHEN Huan-ting *et al.*, 1990. Furecast study on the impacts of Three Gorge Engineering on salt water intrusion in the south bank of the south branch in Yangtze Rivev mouth.

② CHEN Jia-lian *et al.*, 1992. Report of soil resources of Chongming Island.

is harmful to farming but favor to sea water aquiculture.

About the impact of sea-level rise on salt water intrusion in the Changjiang River mouth, XU Hai-gen *et al.* calculated by GU Hao-wei formula, the results indicated that in the condition of 0. 3 m, 0. 5 m and 1. 0 m sea-level rise, salt water wedge would move 3. 3 km, 5. 5 km and 12 km(XU *et al.*, 1994) to upper reaches. These results are generally similar to the score that made from COLA formula by HU Chang-xin. Investigation proves that there is evident negative relativity between the distance of saltwater intrusion and the water from upper reaches. Saltwater intrusion in the Changjiang River mouth generally takes place in Dec. to Mar. next year. After Three Gorge Reservoir is built, the work of storing water function will increase 1000 – 2500 m^3/s (XU *et al.*, 1994) water discharge pouring into the Changjiang River mouth in winter, which will offset the action of salt water intrusion caused by sea-level rise in a certain extent. The impact of runoff change on the relative change of salinity becomes more evident closer to upper reaches within the Changjiang River mouth. Such as in the Yinshuichuan Station in mouth gate, the change scope of monthly average salinity (8. 85‰ – 20. 90‰) is 1∶2. 36. The water discharge in dry season of normal year increases by 1000 – 2500m^3/s, which only relatively decreases the salinity by 4% – 10%. The change scope (0. 01‰ – 1. 59‰) of monthly average salinity at Baozhen in southern branch is 1∶159, the historical maximum salinity is 2130 times as the minimum monthly average salinity. Fig. 3 suggests that there is negative relationship between monthly average salinity from Dec. to May at Baozhen Station and the last monthly average water discharge at Datong Station(Water pouring into Changjiang River mouth will take 20 – 30 d from Datong Station to the Changjiang River mouth by the estimate of sectional average velocity in dry season) . In the figure, the dot at the right of the dotted line is on behalf of the record of maximum salinity. From the figure, the small decrease of water discharge will cause salinity to rise immediately when the downfall from Datong is smaller than 10 000 m^3/s. Therefore, the hazard of salt water intrusion in southern branch system will greatly reduce if 2500 m^3/s water discharge from Three Gorge Reservoir can be received in very dry season.

Generally, the challenge caused by sea-level rise in the 21st century will be within the bearable ability of these islands. The more developed economy of these islands gives pledge to against kinds of hazards. Therefore, people's life and social economy development will normally be in progress if the result of sea-level rise is given enough attention and positive measures are made.

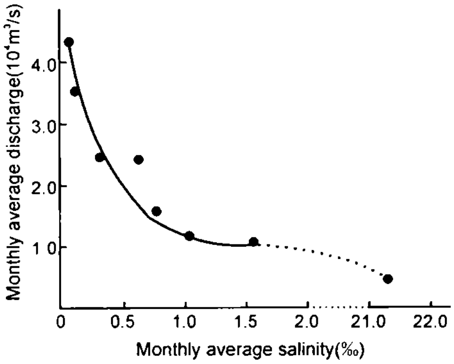

Fig. 3 Relationship between monthly average salinity from Dec. to May at Baozhen Station and the last-month monthly average water discharge at Datong Station

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