CHINESE GEOGRAPHICAL SCIENCE
Volume 4, Number 4, pp.310–321, 1994
Science Press, Beijing, China

IMPACTS OF SEA LEVEL RISE ON COASTAL EROSION IN THE CHANGJIANG RIVER DELTA AND NORTH JIANGSU COASTAL PLAIN①

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ABSTRACT: At present, approximately 36% of coasts are experiencing net erosion in the Changjiang River delta and the north Jiangsu coastal plain. Future sea level rise will accelerate the process of coastal erosion. According to the ratio of the calculated value of coast retreat by Bruun rule to the estimated value by using measured data, the proportion affected by sea level rise in total coastal erosion has been estimated in this paper. When sea level rises by 20cm , the proportion determined by sea level rise will increase from 1.0% at present to 2.2% in the future in the coasts of abandoned Huanghe River delta and from 8.5%–9.6% to 13.5%–15.2% in the north and south banks of the Changjiang River delta. This result is lower than that from the similar research in the world, and this phenomenon is related with the special development process of the coasts in this area. The mechanism of accelerating coastal erosion by sea level rise is that sea level is will increase the intensity of tidal current, wave and storm surge and decrease the ability to reduce the force of waves on the tidal flat and coastal wetland due to the loss of their areas. Therefore, the length of erosion coasts will increase, the sedimentation rate of accretion coasts will decrease or even turn accretion into erosion, the width of tidal flat will reduce and coastal slope will increase. So the project of coastal protection of this area must be reinforced.

KEY WORDS: coastal erosion, Bruun rule, sea level rise

The coastline of study area stretches from the Guanhe River mouth in Jiangsu Province on the north to Gaoyang Mount in Zhejiang Province on the south, with a length of 925km, and the length of sea–river boundary of the Changjiang River mouth is 93km. This

① Project funded by the National Natural Science Foundation of China and the Chinese Academy of Sciences.

area is very susceptible to sea level rise because of its low and flat topography and projecting coastline, in which there are 4 sections of erosion coast, [1–4] i.e. two sections north of the Changjiang River mouth: abandoned Huanghe River delta and Lusi coast; two south of the Changjiang River mouth: Nanhui Cape–Zhonggang and Jingshanzui–Mt. Gaoyang coasts (Fig.1).

I. CHARACTERISTICS OF COASTAL EROSION

1. Wide Spread of Coastal Erosion

The coastline in this area is inclined to silt deposition, for example, the Changjiang River has an annual average silt load of 4.8×10^8t into the sea, the Huanghe River, the river with the largest silt load in the world, once flowed into the sea in this area during the period of 1128–1885 A.D., and huge radial sandbars outside the coastline protect the coastline from erosion. Although sediment supply exist in favourable conditions, yet coastal erosion is widespread in this area, and erosion coastline is about 36% of the total coastline. The typical form of coastal erosion alongside the abandoned Huanghe River delta is coastline retreat at different rate, while in Hangzhou Bay it is the lowering of tidal flat as the result of scouring, including high tide scouring and low tide scouring, due to the protection of solid sea dykes.

2. Continuous Increase of Overall Erosion Quantity

After a long process of natural adaption and human management, majority of the erosion coastline have attained a equilibrium profile under current hydrological and silt conditions. The retreat rate of coastline has decreased, for instance, the annual retreat distance of northern coastline was as much as tens and hundred meters early in the present century and now it is only about ten meters. But in recent decades, the area of coastal erosion increased continuously, as the result of global sea level rise and decrease of sediment load in the coastal area. A new 60km long erosion coastline has been formed, 40km between the Sheyang River mouth and North Xingyanggang, 20km west of Zhonggang. Based on the surveyed data of tidal flat elevation, the annual average total erosion from the Guanhe River mouth to the Changjiang River mouth is about $775\times10^4m^3$ in the period of 1954–1980, and it increased to $1058\times10^4m^3$ during 1980 to 1988 [5].

3. Evident Seasonal Variation of Coastal Erosion

The coast area has a middle–strong tidal action, and the tide range and velocity of tidal current is rather large. The velocity of falling tide is generally larger than that of

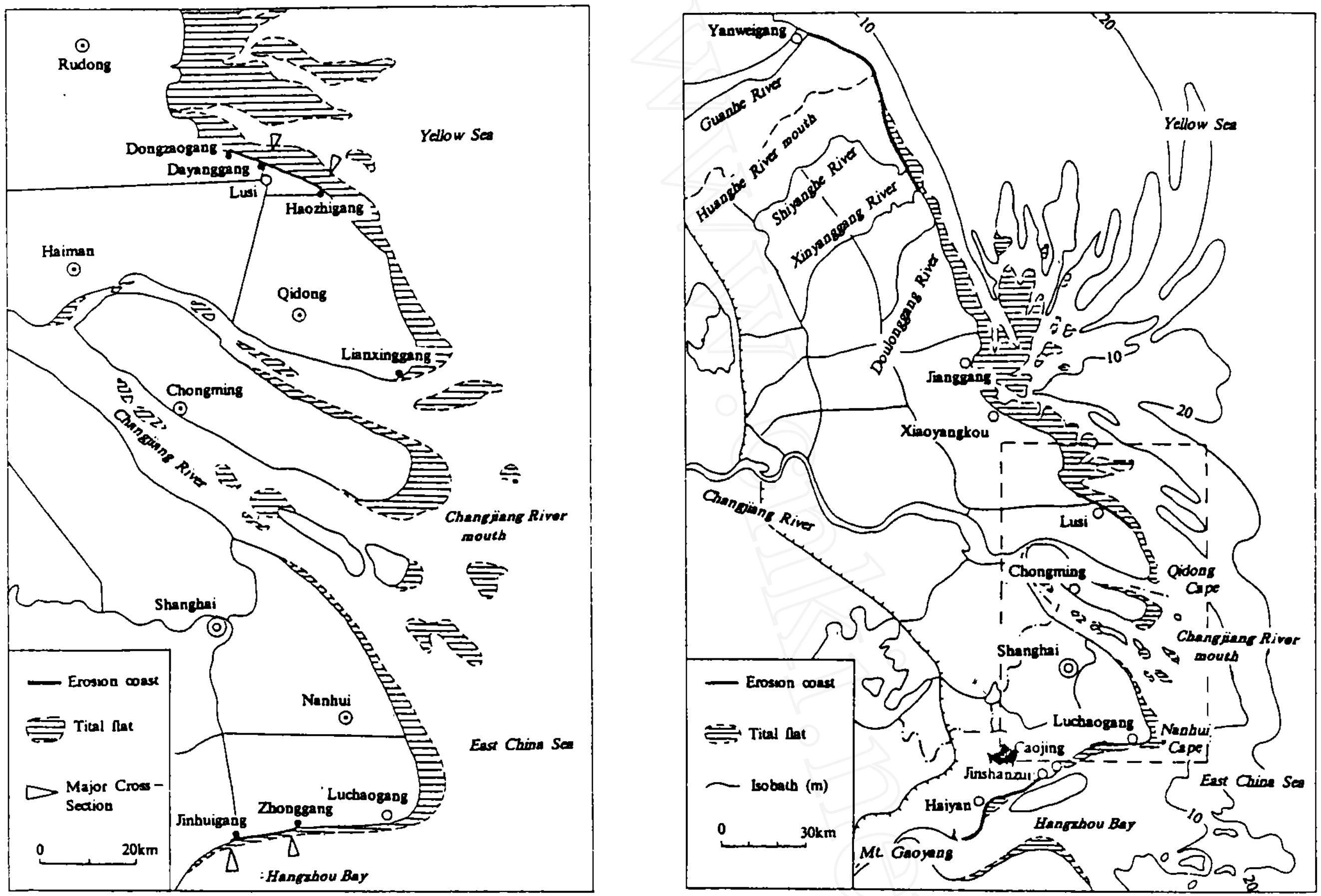

Fig.1 The distribution of erosion coasts in the Changjiang River delta and the north Jiangsu coastal plain

rising tide, and the time length of falling tide is longer than that of rising tide, resulting in the offshore movement of coast sediment and therefore coastal erosion. Wave action is a critical factor in seasonal variation of coastal erosion. Coastal erosion is strong in north sea area in the time of winter and spring when northern wave frequency is high and the maximum wave height is large, while in south sea area it is in the time of summer and autumn when southeastern wave action is strong.

The four curves in Fig.2 show the anomaly of monthly average elevation to annual average elevation of tidal flat in the north and south banks of the Changjiang River delta using surveyed data, in which negative anomaly means erosion month, and positive anomaly means sediment month. the seasonal variations of two cross–sections in Zhonggang and Jinhuigang on the south bank is quite evident. Erosion of tidal flat is very strong from July to November, which is resulted from the strong hydrodynamic action in the north bank of Hangzhou Bay, where the tidal level is high, tidal current fast, tide range large, and southeastern wave prevailing. The seasonal variation of Dayanggang cross–section on the north bank is the smallest among the four cross–sections, erosion dominates from January to May, sediment from August to December. Tidal action is quite strong here. North wind dominates in winter and spring, and onshore wave causes strong erosion (wave lifting sand, tidal current taking it away). Southeastern wind dominates in summer and autumn, offshore or alongshore wave is favourable to sediment. The seasonal variation of Haozhigang cross–section is very complex. It seems that it has some transitional characteristics of above two kinds of coastlines, which is related to its situation in an open coastline, its NW–SE strike of coastline, and relatively strong tidal current and wave action.

II. IMPACT OF SEA LEVEL RISE ON COASTAL EROSION

1. An Estimate by Bruun Rule

The concept of sea level rise causing coastal erosion was systematically put forward by Bruun in 1962. After studied many cases of coastal erosion in 40 countries, he listed 6 different reasons for coastal erosion, among which sea level rise was listed as a reason in all cases [6]. In the last 30 years, Bruun theory has been tested by experiment in laboratory and field observation, and become the conventional method to calculate the coastline change. The retreat distance of coastline in this area, calculated by this method, is listed in Table 1.

The calculated retreat distance in the table is generally larger than the results of many coastline abroad. For example, when sea level rises by 1cm, the coastline in South Carolina in the United States retreats 2m, Florida 10m.[7] That is because the sediment of coastline in this area consists of silt and mud, and the gradient of tidal flat is very small. In

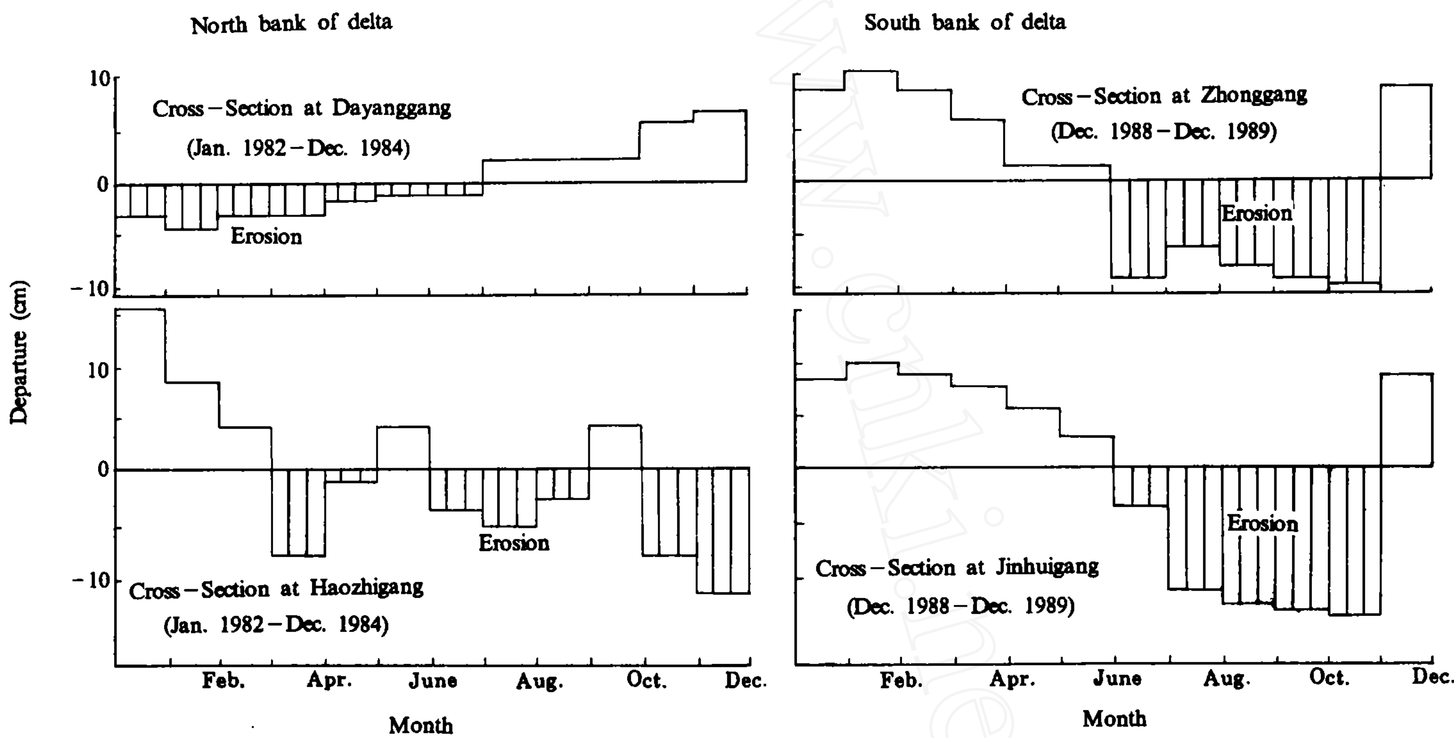

Fig.2 The monthly change of the elevation of tidal flat in the Changjiang River delta

addition sea dyke engineering has been constructed along all the coasts, and the location of most coastlines is decided by human engineering. Only part of coastline in the abandoned Huanghe River delta can retreat in natural way. When coasts "move onshore in original conditions", as Bruun pointed out, to sea dykes, coastal erosion display itself as lowering and width decreasing of tidal flat.

Table 1 Retreat distance of coastline as sea level rise calculated by Bruun Rule

Coast	Retreat distance of coastline as sea level rise by 1 cm (m)
Guanhe R. mouth–Sheyang R. mouth	2.8–7.7
Sheyang R. mouth–North Xiaoyanggang	11.2–33.4
North Xiaoyanggang–Qidong Cape	8.3–9.1
North Luchaogang–Jinhuigang	2.6–16.7
Jinhuigang–Gaoyang Mount	2.2– 3.6

It is under certain conditions to apply the Bruun Rule to the estimation of impacts of sea level rise on coastal erosion in the study area. The rule is only applicable to special coastlines, besides, there exists a kind of longitudinal movement of silt in this area, which exclude itself as a closed tidal flat system. To many erosion and stable coastlines, Bruun Rule should be revised before application according to the parameters of tidal flat morphology of silt coastline and size fraction of sediment.

2. The Role of Sea Level Rise in Coastal Erosion

Sea level rise have a big share of total impacts of all factors on coastal erosion. According to Bruun's analysis, sea level rise contributed to 15%–20% of total erosion in serious erosion coastline. As the rate of sea level rise increases in the future, its share in total coastal erosion will also increase.

From the case of coastal erosion in ocean city, Maryland, the United States, Everts estimated that 20%–25% coastal retreat was caused by sea level rise. According to EPA (Environmental Protection Agency of U.S.A.)'s mid range low scenario of sea level rise and Bruun's Rule, the coastal retreat would be 22m in 2025, and total retreat would be 57.6m considering all other factors[8]. In the case, the share of sea level rise in coastal erosion could be raised to 38% in 2025.

Because the extent of sea level rise is also dependent on ground subsidence, the impact of sea level rise on coastal erosion in different places will be different. In the abandoned

Huanghe River mouth with serious coastal erosion, the rate of sea level rise is now 0.15 cm/ a, and the rate of coastal retreat is 0.4 m/ a on average by Bruun's Rule. By comparison with actual coastal retreat rate, we found that the share of sea level rise in coastal retreat is only 1.0%, which shows that the coastal erosion in this area is mainly caused by sediment deficiency and relative strengthening of wave and tidal current action when the Huanghe River returned to the north route.

The rate of sea level rise in this area will be 0.19–0.42 cm/ a in 2025 according to several scenarios. The coastal retreat caused by sea level rise could increase to 2.2–4.9 m/ a while the actual rate of coastal retreat could decrease from 40 m/ a to 22.8 m/ a (calculated by the regressive rate of coastal erosion in the last 130 years). Thus, the share of sea level rise in coastal erosion could increase to 2.2%–9.6%, which is still lower than many cases. In the edge of the abandoned Huanghe River delta, the retreat speed is 10.3 m/ a after the share of sea level rise (2.2 m/ a) in coastal retreat (10.3 m/ a) could reach 21.4%. This coast is now in the situation of erosion development, so that the share will increase in the future.

As to the coastlines in the Changjiang River delta and north bank of Hangzhou Bay, they could retreat no more because of the missing of supralittoral zone and engineering control of sea dykes. Coastal erosion in the future will be the gradual lowering of tidal flat, and sea level rise can cause the submergence and loss of tidal flat. The surveyed lowering rate of tidal flat caused by coastal erosion is 3.53 cm/ a (1980–1985) on average in the coastline from Dongzhaogang to Haozhigang, 3.14 cm/ a (1986–1989) on average in that from Nanhui Cape to Jinhuigang. Comparing with the rate (0.3 cm/ a) of relative sea level rise in the Changjiang River delta at present, the share of sea level rise in tidal flat loss is 8.5%–9.6%. Suppose the tidal flat of two sections in the Changjiang River delta could keep the above erosion rate, and because the rate of sea level rise will possibly increase in the future, the share of sea level rise in tidal flat loss will increase remarkably (Table 2). Because of lack of surveyed data, this share in north bank of Hangzhou Bay is not estimated. Since this section has abundant sediment source and has been stable during a long period or has a little erosion, the impact of sea level rise may be similar to above two coasts.

3. Seasonal Variation of Tide level and Tidal Flat Elevation

Because of the influence of monsoon climate, there is a clear seasonal variation of offshore tidal level, tide range and wave conditions in the Changjiang River delta. The monthly average tidal levels are all highest in July–September, lowest in January–March, the maximum monthly variation is as large as 0.35–0.52m, in three stations of Lusi, Luchaogang and Jinshanzui. The seasonal change of hydrodynamic conditions along sea-shore could also bring about the changes of sedimentation in tidal flat. Sediment belt moves onshore in the season with weak hydrodynamic conditions, while the erosion belt moves onshore in the season with strong hydrodynamic conditions. The distance of movement in sedimentary coast of middle Jiangsu is as large as several hundreds and 1000 meters. The tidal flat elevation in south part of study area is higher in winter and spring, lower in summer and autumn, maximum monthly range reaching 20cm; while the tidal flat in north part is usually lower from January to May, higher from August to December, the maximum monthly variation is 10cm. But the seasonal change of tidal flat near Haozhigang is much complicated, showing some transitional characteristics from north to south.

Table 2 Estimation of the share of sea level rise in tidal flat loss along the Changjiang River delta

Period	Coast	Middle-Range High Rise		Middle-Range Low Rise	
		Average rate (cm/ a)	Share (%)	Average Rate (cm/ a)	Share (%)
1990-2000	Section 1	0.72	20.4	0.35	9.9
	Section 2		22.9		11.1
2000-2025	Section 1	0.95	26.9	0.43	12.2
	Section 2		30.3		13.7
2025-2050	Section 1	1.23	34.7	0.52	14.7
	Section 2		39.2		16.6

Note 1: Section 1 is from Dongzhaogang to Haozhigang

Section 2 is from Nanhui Cape to Jinhuigang

Note 2: The rate of sea level rise was predicted according to Xie Zhiren (1992)

The following regression equations can be formulated using data of monthly average tide level (W) of three tide survey stations and monthly average elevation of tidal flat (H) of four sections in the delta:

$$W_{Lusi} = 0.60 + 1.39H_{Dayanggang\ section} \qquad (r = 0.34)$$
$$W_{Lusi} = 2.55 - 0.40H_{Haozhigang\ section} \qquad (r = -0.25)$$
$$W_{Luchaogang} = 5.90 - 1.77H_{Zhonggang\ section} \qquad (r = -0.82)$$
$$W_{Jinshanzui} = 4.76 - 1.41H_{Jinhuigang\ section} \qquad (r = -0.84)$$

Out of four equations, three are negatively correlated, i.e., high tide level corresponds with low elevation of tidal flat. The correlation of first two equations is not significant, which is caused by no synchronization of strongest tidal current and wave action in north bank of the delta. On the contrary, the correlation of last two equations reaches 99.9% significance, showing that hydrodynamic conditions have a good consistence with sediment movement of tidal flat in the south banks. According to the estimation of last two equations, when average tidal level (approximately to sea level) rises by 0.5m, the average elevation of tidal flat will be 0.31–0. 36m lower than that in present erosion situation. So it can be inferred that the share of erosion loss is about 38.3%–41.9% in the tidal flat loss caused by sea level rise.

III.MECHANISM OF COASTAL EROSION INTENSIFICATION CAUSED BY SEA LEVEL RISE

Sea level rise is not only an environmental problem in the future but also a severe problem at present. About 60% of the sand coast all over the world is in the process of retreat, and about 70% of beach has erosion, while it is 90% in the United States [9]. If a series of engineering and biological measures of tidal flat and sea dyke protection were not adopted, there would be more coasts to retreat as erosion intensifies. These phenomena are closely connected with global sea level rise. It is the change of hydrodynamic conditions along the coast caused by sea level rise that precipitates the process of coastal erosion.

1. Sea Level Rise Increases Tide Range and Strengthens the Scouring of Tidal Current

The intensity of tidal current is dependent on velocity of rising and falling tide and tide range. The typical bell shape of the Changjiang River mouth, Hangzhou Bay and south tidal way in North Jiangsu can cause gradual deformation of the progressive tide wave when it enters above areas. The gradual increase of proportion of standing wave in tide wave results in the maximum flow velocity of rising and falling tide occurring around half–tide level. Sea level rise will raise tide level and further intensify the deformation of tide wave along the coast of the Changjiang River delta. And the further increase in phase difference of tidal level and tide current will make tide range much larger. There is a good linear correlation between distribution of tide level and that of tidal range in the area. The results of regression analysis of long–term monthly average data of tide level and tidal range in three stations of Lusi, Luchaogang and Jinshanzui show that when average tide level (approximately to sea level) rises by 1cm , tide range in Lusi Station increases 0. 61cm. Luchaogang Station 0.34cm, and Jinshaozui Station 0.69cm. The rising of tidal level, increasing of tide range and increasing of flow velocity of tidal current because of decrease of basal friction, strengthen the scouring effect of tidal current.

2. Sea Level Rise Increases the Water Depth along the Coast and Strengthens the Action of

Wave and Storm Surge

According to the theory of wave dynamics, wave energy has a direct proportion relationship with the square of wave height, and so does the speed of wave energy transmission with the square root of water depth. Thus, if sea level rise can make the water depth along the coast increase by onefold, the strength of wave action can increase by 5.6 fold. Besides, sea level rise can make plunge line move onshore. A rough estimate shows that the plunge line of tidal flat in the north bank of the Changjiang River delta (gradient around 0.1%) can move about 500m onshore and 100–200 m in south bank (gradient 0.3%–0.5%) when water depth increases 50cm. Once the plunge line moves to and reaches coast or sea dyke, the surf full of air will exert great pressure upon constructions on the coast and make them damaged. The engineering for coast protection in abandoned Huanghe River mouth has already faced the problem. Because of the impediment of sea dykes, moving on shore of plunge line will make upper tidal flat much narrow or disappear, and sediment coarse. In addition, as sea level rises, the frequency and intensity of storm surge will increase correspondingly, and then the storm surge, which usually takes important part in coastal erosion, will inflict greater damage on sea dyke and coast.

3. Decrease of Coastal Wetland Area Will Lessen Resistance of Tidal Flat to Wave Action

There are dense salt marsh plants in many wet lands in the Changjiang River delta, which is favourable to the development of coast and tidal flat. It not only increases the resistance of tidal flat to tidal current and wave action but also promotes the expansion of tidal flat. According to field observation, the silt sediment rate can be as large as 10 cm/ a in reed tidal flat of Chongming County and *Spartina anglica* tidal flat of Qidong County. Vegetation in tidal flat is more important to the coastlines in the Changjiang River mouth and the north bank of Hangzhou Bay, because the season when plants grow exuberantly is just that with the strongest hydrodynamics. So vegetation in tidal flats can achieve significant effect on sedimentation accelerating and tidal flat protection. If the vegetation regresses or disappears because of sea level rise, coastal retreat will be accelerated by stronger erosion.

In addition to sea level rise, there are many other natural and human effects to cause coastal erosion in the area. They accelerate coastal erosion by reducing run off and sediment into the sea and strengthening hydrodynamic action along the coast.

IV. TENDENCIES OF REGIONAL COASTAL EROSION

Sea level rise can accelerate coastal erosion, which has been a common knowledge among researchers. Suppose the ocean tidal wave system, overall flow field and general circulation of atmosphere have no change in the future, and there are no other big catastrophic events to interfere the tendencies of coastal erosion in the Changjiang River delta and coast plain in North Jiangsu can be predicted as follows, according to the impact of sea level rise and other existed or possibly occurring natural and human factors.

1. Tendencies of Longitudinal Coastal Change

The general tendencies of longitudinal coastal change is the expansion of erosion coast and increase of overall erosion quantity. Because silt moves offshore, wave erosion will be significantly strengthened along the coast in abandoned Huanghe River delta, and the supralittoral zone outside sea dykes will gradually disappear, but the erosion velocity of the coast, which has been retreating for a long period, will gradually decrease. The coast between the Sheyang River mouth and the Doulonggang River mouth, which is now a transitional coast from sediment to erosion, will have stronger erosion in the future. At the rate of 1km per year of erosion coast development in the last twenty years, all the coast will finally become erosion coast from north to south after twenty years. The coast from Doulonggang to Dongzhaogang has the largest sediment rate in the whole area, but sea level rise will gradually reduce sediment rate in the future, at same time, wave action will become stronger when the radiant sand bar off the shore shrinks. The coast from Dongzhaogang to Qidong Cape will have mixed results. Erosion in the coast west of Lusi will stop, but the coast around and on the south of Haozhigang will develop into a strong erosion area because moving southward of the Changjiang River mouth will reduce sediment of northward transportation. The coastal change in the Changjiang River mouth and on its south has long been controlled by the factors like the abundant sediment supply from the Changjiang River and strong tidal action in Hangzhou Bay. Because the water conservancy project in the upper and middle reaches of the Changjiang River and reclamation of tidal flat in the river mouth area will reduce sediment load into the sea in the future, and sea level rise will cause stronger tidal action, the speed of eastward movement of sand island in the river mouth such as Chongming and Nanhui Cape will decrease and even stop.

The coast with a light sedimentation on the north bank of Hangzhou Bay at present will gradually reduce sediment and even turn to erosion, while erosion coasts will enlarge their erosion scale including scouring down of tidal flat and moving onshore of low tide line.

2. Tendencies of Horizontal Coastal Change

As the sea level rises, there will occur horizontal changes of coast in this area as follows: (1) Width of tidal flat generally decreases, part of low tide flat turns into sublittoral zone (including coast of Doulonggang–Dongzhaogang which is still in the process of sedimentation), resulting in shrinkage of tidal flat and great decrease of coastal wet land (2) Because high–tide line is determined by sea dykes or artificial vegetation for tidal flat protection, the base of sedimentation rises, causing gradual increase of tidal flat gradient. (3) Because of strengthening of tidal action and moving onshore of plunge line, the convex or straight shape of tidal flat cross sections in coasts of Haozhigang –Qidong Cape and Zhonggang–Caojing will be eroded into concave shape like that of tidal flat around abandoned Huanghe River delta and Luchaogang. (4) Sediment in high–tide flat will become coarse and some mud flat may be developed into silt beach or sand beach. (5) Because of rising of tide level and strengthening of storm surge action, sea dyke design standards of most coastline should be upgraded, including the height of sea dykes, protection of sea dyke slopes and improvement of sea dyke structure.

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