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Review

Coastal erosion in China under the condition of global climate change and measures for its prevention

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Abstract

The general characteristics of coastal erosion in China are described in terms of the regional geography, the form of erosion, the causes of erosion, and the challenges we are facing. The paper highlights the relationship between coastal erosion and sea level rises, storm waves and tides, and the influence of global climate changes on coastal erosion along the coastal zone of China. The response of the risk of coastal erosion in China to climate changes has obvious regional diversity. Research into and the forecasting of the effects of climate changes on coastal erosion are systemic work involving the natural environment, social economy, and alongshore engineering projects in the global system. Facing global warming and continual enhancement of coastal erosion, suggestions for basic theoretical study, prevention technology, management system assurance, and strengthening the legal system are presented here.

Keywords: Global climate changes; Sea level rise; Coastal erosion; China

1. Introduction

The global average sea level has been rising over the last 100 years, and with global warming the annual rate of sea level rise is expected to be two to five times the present rate. By 2100, the sea level is projected to be approximately 50 cm higher than it is today. Two-thirds of the world's major cities, which contain 60% of the population and have higher levels of economic development, are located in coastal zones [1]. For instance, more than 8 out of 10 Australians (85%) live within 50 km of the coastline [2]. Anticipated climate changes will greatly amplify risks to coastal populations, and by the end of this century, the global sea level rise will lead to the inundation of low-lying coastal regions, inducing more frequent flooding during storm surges and beach erosion [3,4]. Saltwater could penetrate further up rivers and estuaries and infiltrate coastal aquifers and contaminate urban water supplies.

Coastal erosion is a global problem. If the sea level rises in tandem with the occurrence of greater and more frequent storms, coastal flooding and erosion problems will become exacerbated in vulnerable coastal areas [5]. At least 70% of the sandy beaches around the world are recessional [6]. In the United States of America, approximately 86% of the United States east coast barrier beaches (excluding evolving spit areas) have experienced erosion during the past 100 years [7]. Widespread erosion is also well documented in California [8] and the Gulf of Mexico [9].

In China, coastal erosion has become a major concern for future socio-economic developments in coastal cities. Shoreline retreat in low-lying areas around the Shandong Peninsula has been greatly accelerated [10]. A maximum coastal retreat of 300 m $year^{-1}$ has been estimated at the Luanhe River mouth and an average erosion of

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25 m year^{-1} for its offshore sandbars accompanied by a rapid decrease in sandbar size [11].

A sea level rise and the negative environmental effects caused by human activities aggravate the risk of coastal erosion and increase the environmental burden in these areas day by day. The trend of global warming is hard to reverse, and it appears that the global climate change will not be under control in the near future. Therefore, research institutions, coastal zone management organizations and local ocean departments in the coastal states or areas have been focusing their attention on coastal erosion and disaster prevention.

The aim of this paper is to present the primary analysis of the effects of climate change on coastal erosion in China and to propose prevention measures. However, many unknowns require further research.

2. Characteristics of coastal erosion

The continental coastline of China extends for about 18,000 km, from the Yalu River mouth in the north to the Beilun River mouth in the south, forming a southeastward convex arc. The total length of island coastline is about 14,000 km. Coastal erosion, which is widespread in China, is distributed over one-third of the coastline with a preliminary estimate suggesting that 46% of the Bohai Sea coastline, 49% of the Yellow Sea coastline, 44% of the East China Sea coastline (including the Taiwan Island coastline), and 21% of the South China Sea coastline (including the Hainan Island coastline) suffered erosion [12]. Coastal erosion along the shoreline in China is significantly affected by several factors that reflect complicated phenomena and processes. In this section, three aspects of coastal erosion are briefly discussed.

2.1. Large-scale regional variation in coastal erosion

The Meso-Cenozoic evolution formed a regional tectonic framework characterized by a landform higher in the west than in the east. China's coastline faces the world's largest marginal sea. In the coastal zone from northwest to southeast lie the Yanshan uplift belt, Xialiaohe-North China subsidence belt, Jiaoliao uplift belt, South Yellow Sea-North Jiangsu subsidence belt and Zhe Min Yue Gui uplift belt [13] (Fig. 1), and the climate varies obviously from north to south. The macro tectonic background not only determined the coastal evolution and features, but also influenced the sediment budgets and stability of the coastal zone. Thus, understanding the tectonic background would greatly help researchers studying large-scale regional variations in coastal erosion.

The wide distribution and various degrees of erosion exhibit different features in different tectonic belts.

(1) *Subsidence belts:* the change in the river watershed, reduction of the sediment budget and change in offshore submarine geomorphology due to natural processes and human activities result in large scale and widespread muddy coastal erosion. Erosion chiefly occurred on the abandoned sub-delta muddy coast of the modern Yellow River estuary, the abandoned Yellow River delta and Qionggang and Lusi muddy coast in North Jiangsu, and part of the muddy coast of the Yangtze River estuary.
(2) *Uplift belts:* hurricanes and storm surges, sand mining and reclamation form uplift belts with the erosion of sandy coast, typically on the east coast of Liaodong Bay near Xiongyue, the coast of Qinhuangdao, the coast of Penglai and southern Rizhao in Shandong Province, the east coast of Xiamen Island, the coast of Shuidong port in Guangdong Province, and the coast of the Nandu River estuary on Hainan Island.

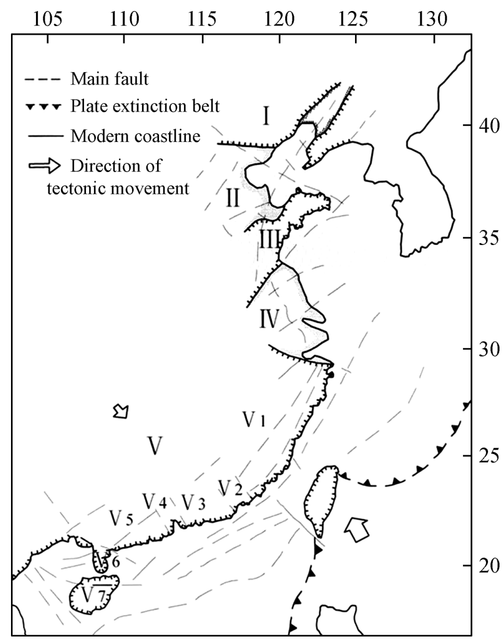

Fig. 1. A sketch showing the tectonic movement of Mesozonic–Neozonic eras along the coastal zone of China. I, Yanshan uplift belt; II, Xialiaohe-North China subsidence belt; III, Jiaoliao uplift belt; IV, South Yellow sea-Northern Jiangsu subsidence belt; V, Zhe Min Yue Gui uplift belt; V_1, Zhemin uplift belt; V_2, Hanjiang delta fault depression; V_3, East Guangdong fault uplift; V_4, Pearl River delta fault depression; V_5, West Guangdong-South Guangxi fault uplift; V_6, Leiqiong fault depression; V_7, Centre-South Qiong fault uplift.

Different climatic zones are distributed from north to south along China's coast, having different climate impacts, biological successions and human activities. Coastal erosion for different climatic zones is roughly described as follows:

(1) *Tropical and subtropical zones:* erosion occurring along southern China and the nearby islands has destroyed the coral reefs; e.g., over 80% of coral reefs have been destroyed on Hainan Island (The State Oceanic Administration, 1996). There has also been loss and degradation of wetland and the recession and disappearance of mangroves; e.g., the area of mangrove forest has been reduced by 65% since the 1950s [14].

(2) *Temperate zone:* erosion having occurred in the coastal plains, delta plains and estuarine river banks of this climatic zone can be described as shoreline retreat and downward cutting of the shore face. An investigation found that the most severe coastal erosion was along the northern coastline.

2.2. Main types of coastal erosion

Coastal erosion has different spatial and temporal forms (Fig. 2). There are three major spatial forms of coastal erosion: (1) coastline retreat, which occurs dominantly for soft coast (comprising quaternary sediment and eluvial sediments of red soil weathering crust and barrier-lagoons) without protection measures like seawall engineering, (2) landward movement of the zero meter depth contour, which is caused by beach surface incision, usually occurring on a coast with a seawall, and (3) downward erosion of the lower beach in the sub-tidal zone by tidal current with the upper flat maintaining its original shape. The former two cases are widespread, and the latter case, for instance, was found on the tidal flat of Jinshazui in the north of Hangzhou Bay.

Erosion can also be divided into two types in terms of time scale: (1) Long-term erosion (invisible) is the permanent change in the shoreline position due to events such as a sea level rise, river diversion or decrease in sediment discharge, which reduce the original sediment budget. Under the circumstances of new coastal dynamics and sediment budget, erosion takes a long time and moves slowly. For instance, with the eastward movement of the Luanhe River mouth since the Holocene, the original coast of the Luanhe Delta was reworked by waves and tidal currents and as a result, the coastal plain sank and turned into a lagoon, a number of sea dikes off the coast were eroded and destroyed, and the accretion of coast switched to erosion and retreat [15]. (2) Short-term erosion (visible) can be caused by storm tides and storm surges without causing a permanent change in the shoreline position, but it brings enormous destruction. Erosion due to hurricanes and storm surges in the summer and autumn on the south coast of China is an example.

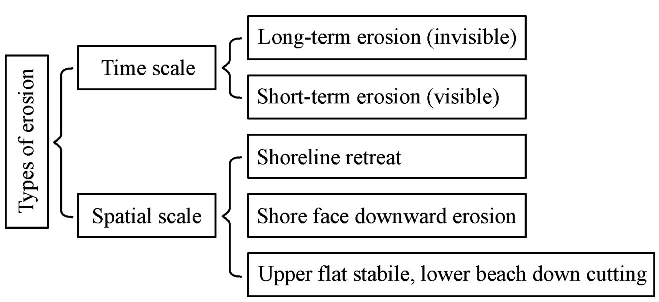

Fig. 2. Forms of coastal erosion.

2.3. Causes of erosion and challenges faced

The causes of erosion include natural processes and human activities (Fig. 3). Erosion intensity and development depend to a high degree on the equilibrium state of coastal dynamics and beach stability. Generally, several controlling factors influence a certain coast simultaneously. With economic development and coastal exploitation since the 1950s, the impact of human activities has increased day by day. In consideration of the global sea level rise in recent decades, China is currently facing three major challenges due to the developing trend of coastal erosion.

(1) Threats of global warming and rising sea level to coastal plains

Global warming increases the frequency and intensity of hurricanes, storm surges, and floods, while a sea level rise directly enhances ocean dynamics and causes coastline retreat. Both phenomena play important roles in coastal erosion [16]. They are mutually complementary and thus the threat is greater, especially for the coastal plains that are located in subsidence belts and fault depression basins of uplift belts, and have the most sensitive response to a sea level rise.

(2) Variation of sediment discharge

In recent decades, in the pursuit of enormous economic benefits, the main river watersheds have undergone increased exploitation, especially a series of large engineering projects such as that which returned cultivated land to forest in western China, the Three Gorges project, the Xiaolangdi project, and the south-to-north water transfer project. As a result, sediment discharge into the sea has decreased sharply. According to an updated estimate pre-

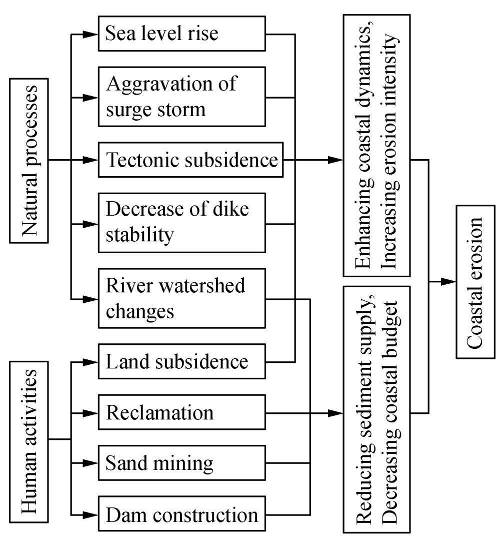

Fig. 3. Sketch map of the main causes of coastal erosion.

sented by Chen et al. [1], the amount of sediment discharge was almost 2000 million tons per year before the 1980s and it decreased to 1000 million tons, maybe only 500–700 million tons, by the end of the 20th Century. This resulted in notable changes in erosion or accretion evolution in estuary deltas and adjacent coasts under the new dynamic environment and sediment conditions, thus reducing the sediment budget of beaches and eventually driving severe coastal erosion.

(3) Impacts of improper coastal exploitation

With the rapid development of the economy over the past two decades, the hazard of coastal erosion has become more and more serious in China because of the dominant driving force of negative environmental impacts resulting from human activities. Sand mining has been the direct cause of sandy beach erosion in uplift belts in recent years. Over-exploitation of groundwater under a coastal plain resulted in land subsidence and triggered immediate saltwater erosion. Reclamation, reservoir and other unreasonable coastal engineering projects effectively reduced the coastal sediment discharge. All the above human activities, which have severe negative impacts on the environment and arrest the increasing attention of coastal researchers, are indirect causes of coastline retreat. In addition, river rebuilding has also aggravated erosion in abandoned estuaries.

3. Impact of global climate change on coastal erosion

China has been experiencing accelerating coastline erosion, as have other countries. Many studies have indicated that the global climate change has a complex and extensive impact on the coastal zones [17–21]. Fig. 4 roughly shows the links between the effects of global climate change and coastal erosion. In this section, the effects of a rising sea level and storm surges are emphasized.

3.1. Sea level change and coastal erosion

The first model relating shoreline retreat to a rise in the regional sea level was proposed by Bruun [22]. The analysis by Bruun assumes that with a rise in sea level, the equilibrium beach profile moves upward and landward with its original shape. The upper beach is eroded owing to the landward translation of the profile, and the material eroded from the upper beach is transported immediately offshore and deposited on a nearshore bottom. The model was widely used by many researchers, and was named the Bruun Rule. Despite its simplicity and numerous assumptions, which have been criticized by some scholars [23–31], the Bruun Rule has been continually developed and has worked well in many settings. The rule has wide applications: from a simple concave-downward beach profile to an underwater barrier and barrier island; from two dimensions to three dimensions, which refers to the impact of longshore sediment transport on the beach profile; from theoretical models to physical models or field demonstrations; and from sandy coast to muddy coast [32–41]. In addition, it also helps in designing protective measures against a sea level rise. However, the Bruun Rule cannot be applied as a common model to predict the erosion state in various coastal environments so far, and further research is needed for it to have general acceptance.

A sea level rise can be either a global sea level rise or a regional sea level rise. A global sea level rise is attributed to the thermal expansion of the upper ocean layers and melting of polar ice sheets and mountain glaciers and even to the movement of celestial bodies and sunspot activity. A regional relative sea level rise is caused not only by a global rise but also by a regional groundwater level change resulting from a monsoon, ocean current, delta accretion or engineering project, or local land subsidence, which consists of the vertical movement of the Earth's crust caused by tectogenesis and rheomorphism, sediment compaction, overexploitation of groundwater, or overloading by large buildings.

Because of the effects of local tectonic movements and human activities, the rate of the relative sea level rise varies in different areas [42]. According to a previous study [43], the rate of the regional relative sea level rise can be ten times or even a hundred times that of the global sea level rise, and as a result, research interest has switched to regional relative sea level rises since the 1990s.

There have been great achievements in the study of a sea level rise since the beginning of the new century, involving an increase in the number of monitoring stations, basic forecasting and impact assessments on the progression of sea level change, and establishment of a professional and specialized monitoring system. The China Sea Level Bulletin (Fig. 5) edited by the State Oceanic Administration makes the following remarks [44,45].

(1) The rate of the relative sea level rise in China varied between 1.0 and 3.0 mm/year over the last 50 years, and has an accelerating trend in the last few years.
(2) The rate of sea level change over the last 30 years has a general pattern of a fluctuating increase, which varies remarkably from place to place. The rate in the south is higher than that in the north, but in the past few years, a few areas (e.g., Tianjin) in the north have also seen a continual increase.
(3) The rate of sea level rise was 2.5 mm/year in 2006, and this was above the estimated mean global value of 1.8 mm/year. The value varied in different regions; the Yellow Sea had a rate of 2.5 mm/year, whereas the East China Sea had a higher rate and the Bohai Sea and South China Sea had lower rates. The China Sea Level Bulletin 2006 forecasts that the mean sea level will rise by 9–31 mm in 3–10 years.

From an analysis of regional differences of the main coastal plains and sea level changes in recent decades, Yang et al. [18,46] made a prediction of the possible sea

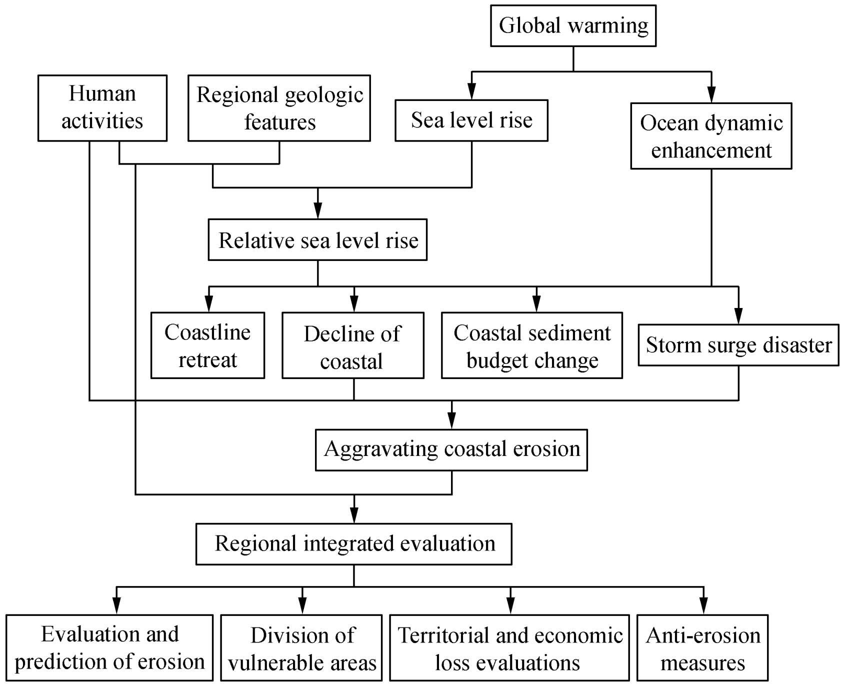

Fig. 4. Effects of global changes on coastal erosion and its evaluation and prevention.

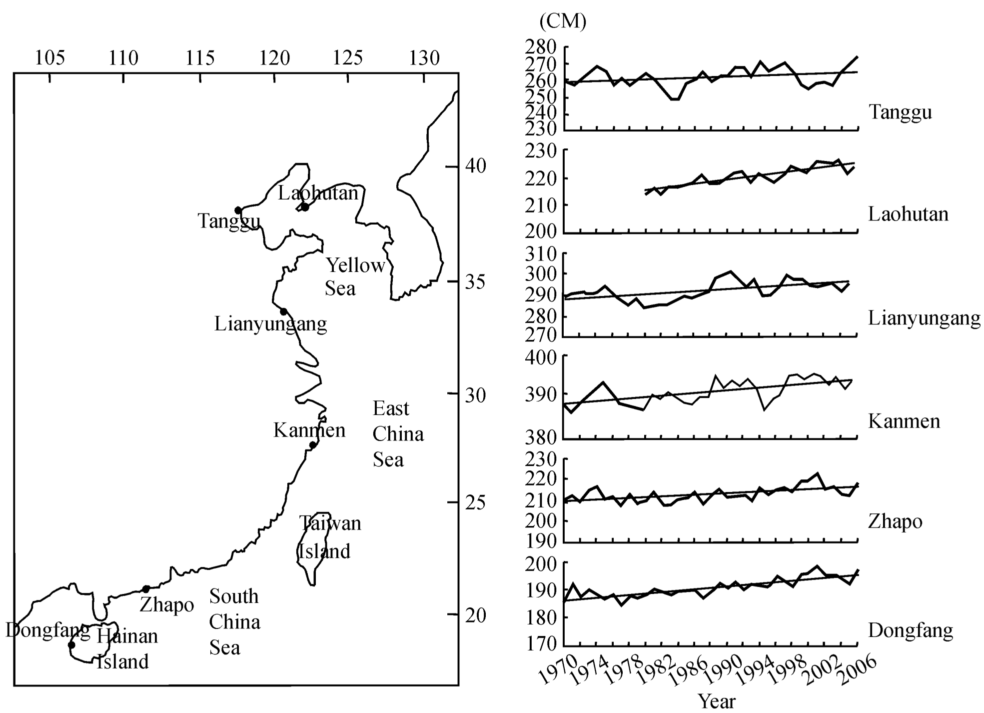

Fig. 5. Sea level changes from 1970 to 2006 from observation stations along the coast of China.

level rise and inundated areas for the main coastal plains (Table 1).

A sea level rise has been identified as the principal forcing function in large-scale shoreline retreat [47]. There are two main aspects to the response of coastal erosion to sea level change:

(1) A sea level rise has direct and indirect impacts in terms of the form of erosion it promotes. Direct impacts include coastline retreat, inundation and swamping of low land on coastal plains, seawater intrusion and destruction of the seawall and drainage system. Indirect impacts are mainly caused by

Table 1
Prediction of the possible sea level rise and inundated area for the main coastal plains in 2050.

Region	Rate of relative sea level rise in the past few decades (mm/year)	Relative sea level rise in 2050		Expected area of inundation (hm^2)
		Rate (mm/year)	Height (cm)	
Yellow River delta	4.8	6.4–6.9	35–40	39,000
Western coastal plain of Bohai sea	2.1	11.0–11.5	65–70	21,000
North Jiangsu coastal plain	2.2	6.8–7.3	40–45	38,000–89,000
Yangtze River delta	6.6	7.9–8.4	45–50	7000–11,000
West Taiwan coastal plain*	2.0	7.0–9.5	28–38	—
Pearl River delta	2.5	4.1–4.6	25–30	2000
Hainan coastal plain	1.8	3.4–3.9	20–25	7000
Guangxi coastal plain	1.8	3.4–3.9	20–25	17,000
Hanjiang River delta	1.5	3.1–3.6	15–20	2000
Minjiang River delta	1.8	3.4–3.9	20–25	6000–15,000
Xialiaohe River delta	1.7	3.3–3.8	20–25	4000–9000

* From W.J. Chen, C.T. Kuo.

dynamics changes and sediment budget reductions, which induce accelerating coastal erosion. Generally, indirect impacts are more complicated.

(2) Different regions have different physical geographies and levels of social–economic development, which influence the intensity and form of erosion due to a sea level rise. Therefore, different regions should be studied separately.

According to the analysis of these factors of altitude, relative sea level change (ground subsidence), coastal erosion, storm surges and coastal protection work, Ren plotted out the eight regions that were most vulnerable to coastal hazards. These regions comprised the ancient Yellow River delta, modern Yellow River delta, coastal plain in Laizhou Bay, abandoned Yellow River delta, coastal plain in North Jiangsu, Yangtse River delta, coastal plain in western Taiwan, and the Pearl River delta. It is estimated that the disaster-affected area is about 35,000 km^2.

According to the previous studies [48–61], we present the characteristics of erosion for the main coastal plains in Table 2. It can be concluded that a sea level rise and the environmental effects it induces are the major factors contributing to the coastal erosion.

3.2. Storm surge and coastal erosion

Global warming can cause a catastrophic rise in the sea level, and a warming climate is expected to raise the intensity and frequency of storm surges (tides). *The China Marine Disaster Bulletin* edited by the State Oceanic Administration reported that from 1995 to 2006, the numbers of yearly storm surges were 10, 6, 4, 7, 5, 8, 6, 8, 10, 10, 11, and 9, respectively, giving an average occurrence of 7.8 times per year. It can be seen that the frequency has increased in recent years. The relationship between climate change and the frequency of storm surges is complicated. A numerical simulation [62], case analysis [16] and the interannual variation in atmospheric circulation [63,64] show that a tropical cyclone intensity has a remarkable positive correlation with the sea surface temperature, and global climate changes have obvious effects on tropical cyclone activity.

A storm surge is a regional paroxysmal hazard that brings about the heaviest loss of life and property; for instance, storm surges caused a direct economic loss of 3.298 billion yuan (RMB) and 137 deaths in 2005 in China [65]. A surge also strongly changes the seafloor terrain, marine sediments and coastal geography; in particular, it violently swashes the shore and upper tidal flat. A strong hurricane usually induces more significant erosion than that occurring in a normal dynamic condition, and the prominent consequences from large events can remain for many years. Such destruction was reported for typhoon No. 9914 on the east coast of Xiamen Island and for typhoon No. 0307 (Imbudo) on the west coast of Guangdong Province [66,67].

From a study of hazards caused by storm surges in recent years, it has been noted that hurricane frequency and intensities have risen gradually. *The China Sea Level Bulletin 2006* has stated that from 2004 to 2006, more frequent and higher intensity storm surges have been responsible for the greatest property losses in the coastal areas of Zhejiang and Fujian provinces, and the losses were more serious than those in the historical records. The enormous losses were certainly related to the rapid socio-economic development of the coastal areas, but the global climate change and a sea level rise play more important roles.

Beach erosion derived from storm surges in many coastal states and areas has attracted great attention. A field survey of damage by storm surges on the coastlines and beaches in China has been undertaken in recent years, and the preliminary effects of storms on beaches in China have also been studied [66,68]. In future, more attention should be paid to the characteristics of beach erosion and accretion during a storm, mechanism of coastal erosion, post-disaster construction, and in particular, tendency forecasting for climate change and coastal socio-economic development.

Table 2
Characteristic erosion on the main coastal plains.

Region	Yangtze River delta	Yellow River delta	Pearl River delta	Taiwan coastal plain
Causes	Reduction of sediment supply; coastal dynamic change; mainstream swinging; flood tidal rush; tectonic subsidence; sea level rise	Reduction of sediment supply; adjustment of sedimentary dynamics; river diversion; sea level rise	Land subsidence; storm surge aggravating; weakening in defense capability of dikes; sea level rise	Reduction of sediment supply from rivers; construction of improper engineering structures; land subsidence; sand mining; sea level rise
Performance	Channel siltation, shoreline retreat, and lowland inundation	Shoreline retreat; downward erosion of beach; submerging of drilling platform; fracture of oil pipeline; destruction of seawall	Destruction of mudflat, marsh, mangrove, coral reef; devastation of seawall	Beach erosion, lowland inundation, salinization of freshwater
Examples	Over 390 km of the coast are eroded; average rate of shoreline retreat in the recent three decades in Hangzhou Bay is up to 30 cm/a	The maximum shoreline retreat reached 11 km between 1976 and 2000, with an annual loss of 420 m; the largest downward erosion depth was 10.5 m, with an annual erosion exceeding 40 cm	Several meters of shoreline retreat occurred in Shekou District between 1966 and 1979; Since 2000, the largest retreat in bridgehead of north Tangjia is 70–80 m	The coastline in Taipei retreated about 500 m between 1980 and 2003
Characteristics	Shoreline erosion is mainly located in the south margin of delta and the north part of Hangzhou Bay	With regional and unbalanced characteristics, the overall erosion trend is difficult to stop	86.7% of this delta is protected by dikes, other parts of it are mainly eroded	Relative sea level rise in the west is higher than elsewhere and make obvious coastal erosion, while some areas remain stable

There are several aspects to an evaluation of the impacts of climate change on coastal erosion, including the natural environment, socio-economic factors, and coastal engineering projects, which make up an integrated system. Sea level changes also play an important role in the system; however, they have temporal and spatial variations and an accurate evaluation of their contribution to coastal erosion requires further widespread ocean monitoring, data collection, and intensive study. It is concluded that different areas have great regional variations in the natural environment, ocean condition and coastal stability [69], human activities also have enormous impacts on the coastal zones, and the adaptive capacity of economically developed regions allows a more flexible response to climate change. In summary, the impacts of climate change on coastal erosion have a distinct regional variability.

4. Coastal protection measures

Global warming has accelerated the continuous development of coastal erosion, and raised the challenges in coastal zone management, exploitation and research in China, and the government and scientists have paid increasing attention to this problem. A basic theoretical study of coastal processes has been running for several decades, and has had a great deal of success in improving the integrated coastal zone management and monitoring. On the basis of recent studies, a summary of the main protection measures is presented in Fig. 6. Both long-term planning and updated protection measures are required to eliminate the adverse impacts of the hazard and guarantee sustained and harmonious development of the coastal economy.

4.1. Basic research of coastal erosion and assessment of its impacts

According to studies since the early 1980s, the characteristics, processes and mechanisms of coastal erosion in different areas are basically understood and much valuable data have been obtained [70–78]. A rapid change in the coastal environment has induced irreversible long-term erosion. To protect coastal property and reduce losses, a forward-looking analysis method of the erosion trend was constructed to provide a useful theoretical foundation for nationwide investigation and assessment [1,79–86]. In recent years, the Chinese government has implemented the strategy of “Ocean Exploitation” and the policy of the “Development of National Ocean Economy”. To meet the requirements of economic development and ocean management and comprehensively investigate marine resources and environmental conditions, in 2004, the state organized a large-scale marine survey called the “908 Special Project”. Great progress in the basic theoretical study of coastal erosion is expected from the success of the “908 Special Project”. For instance, a general understanding of the mechanisms, processes, and causes of nationwide current erosion, and knowledge of characteristics of seasonal and annual variations of typical coasts will provide fundamental data for disaster reduction, the rational use of coastal resources and assessment of the impacts of global climate change on coastal erosion. Scientific evaluation of the carrying capacity (including the carrying capacity of coastal resources), the coastal environment and the coastal ecological system that is affected by the coastal erosion will provide a scientific basis for changes to marine industries and the distribution of productivity, help plan the exploitation and economic development of coastal areas, promote the establishment of a "digital coast" and building of a fundamental database for coastal protection.

Monitoring the coast and beach erosion in different regions, determining its causes, mechanism, and trend, evaluating the impacts, and presenting protection measures are all necessary for the management and development of development projects. Coastal erosion is the main coastal geologic hazard, and like other hazards it has two types of attributes: natural and social attributes. From a comprehensive and correlative analysis of all attributes, further research will be conducted to promote quantitative and qualitative evaluations of the risks, erosion intensity, and financial losses during a coastal disaster, and to improve the forecasting of future erosion. In addition, new erosion type and intensity classifications, evaluation index systems and assessment models for the impacts of coastal erosion on the regional economy of surrounding areas, and erosion management and monitoring networks will be required.

In summary, the basic research mentioned above would provide a theoretical and scientific foundation for important decision making relating to the significant projects during exploitation, coastal zone management and environmental protection, and changes to the national economy development strategy.

4.2. Intensifying research on coastal protection measures and proper protection of typically eroded coast

Not many seawalls in China can stand the risk of being damaged by 1 in 100 year storm tides. A sea level rise caused by global warming will reduce a seawall's protective capability. Thus, determining how to reconstruct or reinforce seawalls and dikes is an urgent task.

There are two kinds of protective measures for controlling coastal erosion: structural measures and non-structural measures. Structures can be divided into hard and soft structures. Hard structures include seawalls, breakwaters, jetties, groins, and offshore dikes, whereas soft structures include beach nourishment, man-made dunes, planting of mangroves and rise grass, and coastal shelter belts. Non-structural measures include land-use controls, setting warning lines such as the coastal baseline and coastal construction control line to protect the coast from improper construction, and prohibition of unreasonable sand mining and reclamation.

Research and practices indicate the measures mentioned above have different scopes and prospects of application and economic and eco-environmental impacts (negative and positive) when put into practice. Therefore, according to the levels of economic development and coastal features in different regions, how to create proper protection measures against coastal erosion and determine an updated engineering standard are the major works for geomorphologists and coastal engineering scholars in China.

Principal protection measures before the 1960s were passive coastal defenses such as seawalls, breakwaters, and coastal shelter belts. Although they did reinforce the coast, they also caused much inconvenience during construction. Therefore, a new strategy of positive coastal protection has since then been put forward. In the new strategy, beach protection was put before coast protection and new kinds of groins, offshore dikes and their combinations were built in different regions. The aims of the strategy were to dissipate waves and tidal energy in front of the foreshore before they cause erosion, transform the previous integral protection into segment protection, reduce financial costs, and beautify the coastal environment. Over the past 10 years, a soft structural approach (such as beach nourishment and biological protection by mangrove planting), which is more natural and beautiful than building hard structures, has been greatly pursued [87–90].

With the development of tourism, the recreational function of beaches has attracted increasing attention. Thus, governments of many countries have put more effort into sandy beach protection. Beach nourishment, and mangrove and seaweed planting, which provide pro-

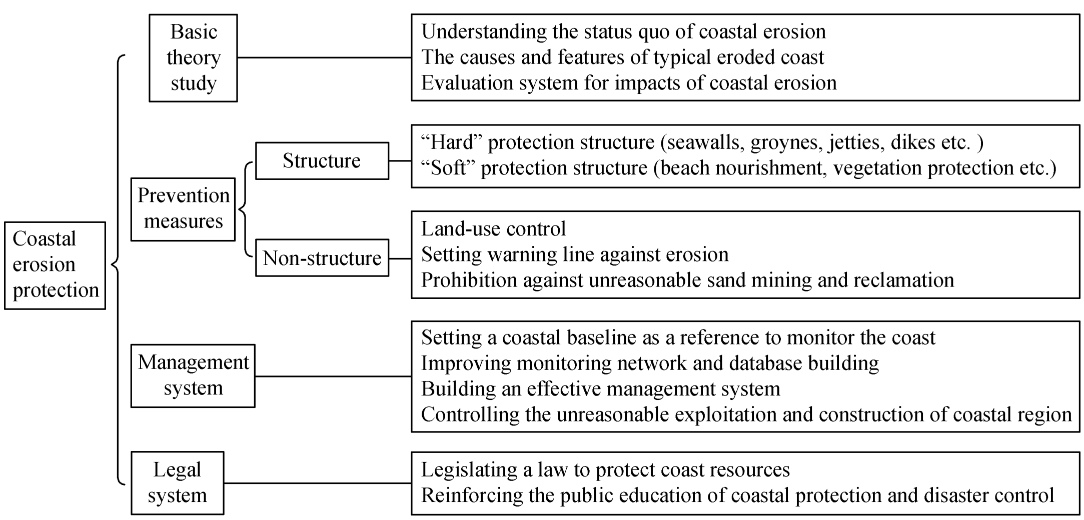

Fig. 6. Sketch map of the prevention measures against the coastal erosion in China.

tection to backshore property and increase the recreational space along the shore, are popular in many developed countries [91–96]. In addition, the economic activity created by beach tourism has local benefits. To aid the coastal defense scheme, further scientific and technical research and benefit assessment are needed. It is suggested that beach nourishment should be a part of integrated coastal zone management.

4.3. Improvement of the integrated coastal zone management

Integrated coastal zone management (ICZM) is a dynamic, multidisciplinary and iterative process to promote sustainable management of the coastal zones. It covers the full cycle of information collection, planning (in its broadest sense), decision making, management and monitoring of implementation. ICZM uses the informed participation and cooperation of all stakeholders to assess the societal goals in a given coastal area, and to take actions towards meeting these objectives. ICZM seeks, over the long-term, to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics. "Integrated" in ICZM refers to the integration of objectives and also to the integration of the many instruments needed to meet these objectives. It means integration of all relevant policy areas, sectors, and levels of administration, and integration of the terrestrial and marine components of the target territory, in both time and space (The Europe Commission).

The concept of ICZM was born in the mid-1980s, and its specific target was determined at the International Conference on Coastal Zone Management held in Noordwijk, The Netherlands, in 1993 [97]. China has implemented a new coastal zone management policy since the early 1990s to manage coastal resources and control environmental pollution.

Over the past 10 years, the State Oceanic Administration has conducted extensive studies including those on marine functional zoning, ocean space utilization and management, the promotion of legislation for marine regions delimiting, monitoring and evaluating aqueous environments, and established a series of coastal wetland reserves in regions where conditions permit, as well as presented research on a coastal zone management information system and a "digital ocean". Recently, technology integrating remote sensing, geographic information systems, global positioning systems and multiple sources of information has been applied in monitoring the temporal and spatial variations in coastal resources and environment [98–103]. Such technology would make a great contribution to ICZM and the sustainable exploitation and utilization of coastal resources. However, the ICZM project does not provide technical solutions to problems. In this section, pressing issues relating to the coastal protection in the new situation of climate change are presented.

(1) China's coastal baseline should be indicated on large-scale charts to improve coastal monitoring and management. The baseline is a relatively fixed reference line determined by the changes in the long-term shoreline position, the regional coastal physical geography, and socio-economic development trends. It can be used as a technical reference for coastline monitoring and dynamic assessment, coastline management and implementation of coastal protection policy.
(2) More efforts are needed in improving the nationwide dynamic monitoring network and database establishment program for coastal erosion, setting immovable monitoring profiles in eroded hotspots, and regular monitoring of the shoreline position, coastal topography and sediments. Aforementioned monitoring results are kept in a dynamic database so as to analyze the erosion trends promptly and provide fundamental data for coastal investigation, research and management.
(3) Establishment of a nationwide shoreline management system requires the cooperation and coordination of different departments, support of research and monitoring results, public participation in decision making, and implementation of local government. Presently, governments of coastal provinces, cities, and autonomous regions have their own institutions for ocean (aquatic) management with defective functions and regulations. There have been conflicts among various departments involved in shoreline and ocean management resulting in a waste of management resources. In summary, an unambiguous shoreline management plan is required.
(4) It is necessary to stop excessive resource exploitation and unreasonable coastal construction. Unwise human activities are one of the most important factors causing coastal erosion, with human influences overwhelming natural influences. Shore sand mining is considered to have been the major cause of numerous cases of erosion, and unreasonable coastal engineering (e.g., tide gates, reclamation, and docks) also have negative effects on the environment. Thus, government should pay more attention to these problems.

4.4. New development of coastal protection measures and a management system

Coastal protection is an important part of territorial management. Facing serious coastal erosion aggravated by global warming, the following precautions should be taken. First, public awareness of coastal resources and environmental protection should be increased, and a new consciousness for disaster control planning needs to be popularized. Second, the health of the coastal environment and ecosystems needs to be maintained to guarantee the stability and security of the coast. In the future, based on countermeasure research and the integrated planning and supervision of sustainable coastal development, the government should draft an exploitation and utilization plan, make feasible policy for scientific management, and especially promote legislation to enhance coastal erosion control. Finally, administrative law enforcement should be strengthened for coastal protection.

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