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# Current status and formational mechanisms of coastal erosion on typical islands in China

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A geological hazard survey of 82 islands in coastal China from 2010 to 2012, and subsequent periodic monitoring of coastal erosion on 10 representative islands from 2012 to 2014, found 138 coastal erosion points on 39 islands. Coastal erosion was a typical pattern of the coastal geological hazards, with the most serious impacts occurring on the southeastern coast of Chongming Island, the maximum erosion rate was 18.3 m/a under the conditions of sediment reduction and drastic hydrodynamic changes of the Yangtze river. The primary causes were changes in river dynamics, the marine hydrodynamic environment, and human activities, the specific factors included sea-level rise, river diversion, river-borne sediment reduction, wind-driven waves, storm tides, construction, coastal degradation, beach drainage, and sand mining. Natural and human factors accounted for 57 and 43 % of coastal erosion effects, respectively. Sea-level rise operated on a long-time scale, causing an annual mean shoreline retreat of 0.15 – 0.30 m, although such changes were not obvious over short time scales, they were significant at the decennial and centennial scale. Storm tides were among the most important factors operating over shorter time scales, although increasing human development of islands is rapidly becoming a significant cause of coastal erosion.

[**Keywords**: Coastal erosion, Human activities, Islands, Sea-level rise, Storm tide]

## Introduction

China's coastal zone is a primary region for national economic development, with extensive human activities[1,2]. Rapid development of the marine economy and increasing exploitation of the coastal zone has significantly altered this region, resulting in frequent coastal erosion events that endanger economic and social development as well as the property and safety of coastal residents. The global sandy coast will suffer devastating erosion by 2100[ref. 3], but this conclusion needs further research[4]. Coastal erosion represents a net loss of sediments through natural forces (*e.g.* wind-driven waves, currents, and tides), causing beach erosion and shoreline retreat. Island will be affected first by the ongoing rise in global sea level[5]. As these often have smaller areas and more fragile ecological environments, the impact of coastal erosion on island ecology and infrastructure is often significant and irreversible. Examples include destruction of coastal forests and defense works, flooding of salt pans and farmland by seawater, degradation of marine environments, damage to the spawning and feeding grounds of marine fishes, and the disappearance of civilization[6-10].

Coastline change under global climate change has become a frontier and hot issue in the study of coastal environmental evolution. Coastal erosion research has also received extensive attention from scientists all over the world, especially the relationship between coastal erosion and global climate change[3]. China's active focus on preserving and enhancing marine ecology has included detailed periodic monitoring of the mainland shoreline, obtaining comprehensive data on coastal erosion, and implementing a series of ecological remediation plans. Coastal erosion has affected ~70 % of sandy shorelines and almost all silt shorelines in China[11]. Of the 14 main types of island geological hazards defined in China[12], coastal erosion ranks second (just after landslides) in terms of abundance. However, monitoring of island coastal erosion lags far behind that of mainland coastal erosion[13], creating an urgent need to enhance the scope and depth of such research efforts[14,15] in order to determine the current status and casual mechanisms of island coastal erosion in China.

## Materials and Methods

### Study area

A geological hazard survey of 82 islands was conducted in coastal China from 2010 to 2012, finding different degrees of coastal erosion on 39 islands (Fig. 1). Thereafter, 10 islands representative of different types and located in different latitudinal zones were selected for further periodic monitoring. From north to south, these were Changxing Island, Dawanggang Island, Jijiapuzi Island, Daqin Island, Chongming Island, Xiushan Island, Liuheng Island, Dongshan Island, Donghai Island and Weizhou Island. All monitoring was conducted from 2012 to 2014, except for Weizhou Island from 2006 to 2014.

### Data sources

Given the different island types and coastal erosion characteristics, imagery captured by remote sensing and Unmanned Aerial Vehicles (UAVs) were used to

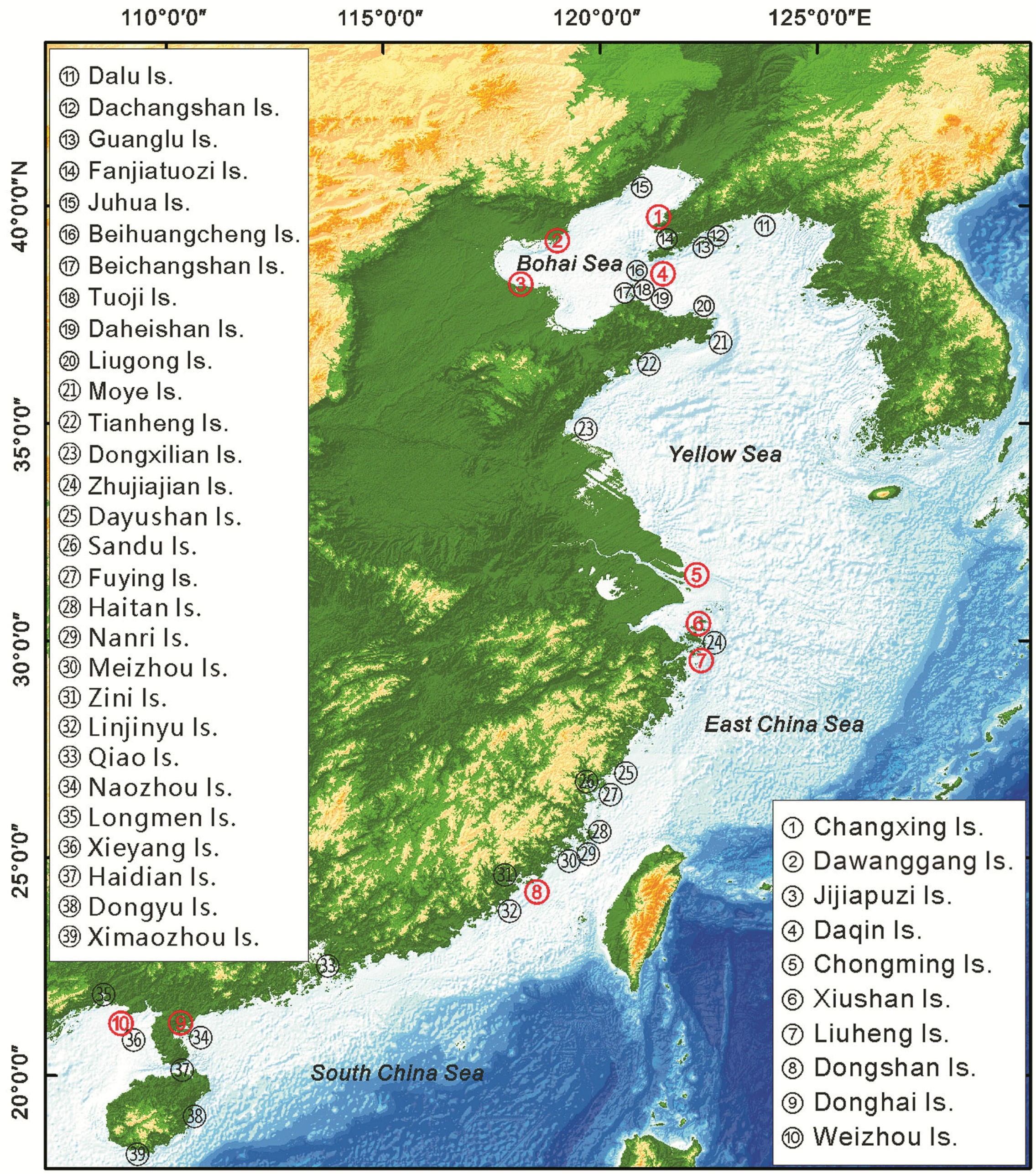


Fig. 1 — Study area and location of studied islands: (1–10) Islands selected for intensive monitoring of coastal erosion; (1–39) Islands where coastal erosion was documented

monitor shoreline changes. The RTK positioning was also used to monitor changes in coastal elevation and to document surface-sampling locations used to assess granularity and monitor changes in surface sediments. Monitoring was conducted twice a year during the study period.

**Remote sensing**

Satellite remote sensing data sources included Landsat8, Spot5, Worldview, and other satellite platforms. These data were processed by radiation correction, atmospheric correction, geometric correction, data fusion, mosaicking, and other processes. Island shoreline information was obtained by segmentation, classification, and visual interpretation at different times[16-18], and conducted on-site investigations to ensure the accuracy of this information. The accuracy of remote sensing interpretation is about 1 – 2 m.

**UAV monitoring**

MD4-1000 four-rotor UAV flown under autonomous navigation along a pre-designed route at 150 – 200 m altitude was used to obtain high-overlap photos that were processed by orthophoto, 3D point cloud, and topographic data extraction. The accuracy is about 0.2 – 0.5 m. The position and type of coastal erosion were interpreted from individual orthophotos, while shoreline change characteristics and coastal erosion patterns were analyzed using multi-date orthophotos.

**Coastal elevation monitoring**

Vertical profiles on the shoreline were arranged to monitor erosion, using high-precision real-time network differential technology based on the Chinese CORS system. Centimeter-level positioning accuracy was used to obtain the geodetic coordinates and elevation data of profile points, resulting in profile maps that reflected beach erosion patterns and depositional changes.

## Results

**Changxing Island**

Changxing Island, located in the northern Bohai Sea, is a bedrock island with its southern and eastern sides facing the mainland and a sandy shoreline on its northern and western sides facing the sea. Coastal erosion on this island mainly occurred along the capes and bays of the latter areas over a total length of ~500 m; widespread erosion scarps occurred along ~300 m of the coast. Erosion and retreat of a scarp in December 2013 resulted in the loss of 900 $m^2$ of land and 700 $m^3$ of material. During the monitoring period from June 2012 to September 2014, the shoreline retreated by an average 1 – 2 m (40 m maximum) (Fig. 2) and lost an average 0.1 m depth (0.6 m maximum) (Fig. 2). The surface sediments underwent continuous roughening, with mean coarsening in the northern high-tide zone of up to 0.369 Φ. In general, Changxing Island experienced continuous erosion and retreat along the northern shoreline, with significant erosion in some areas.

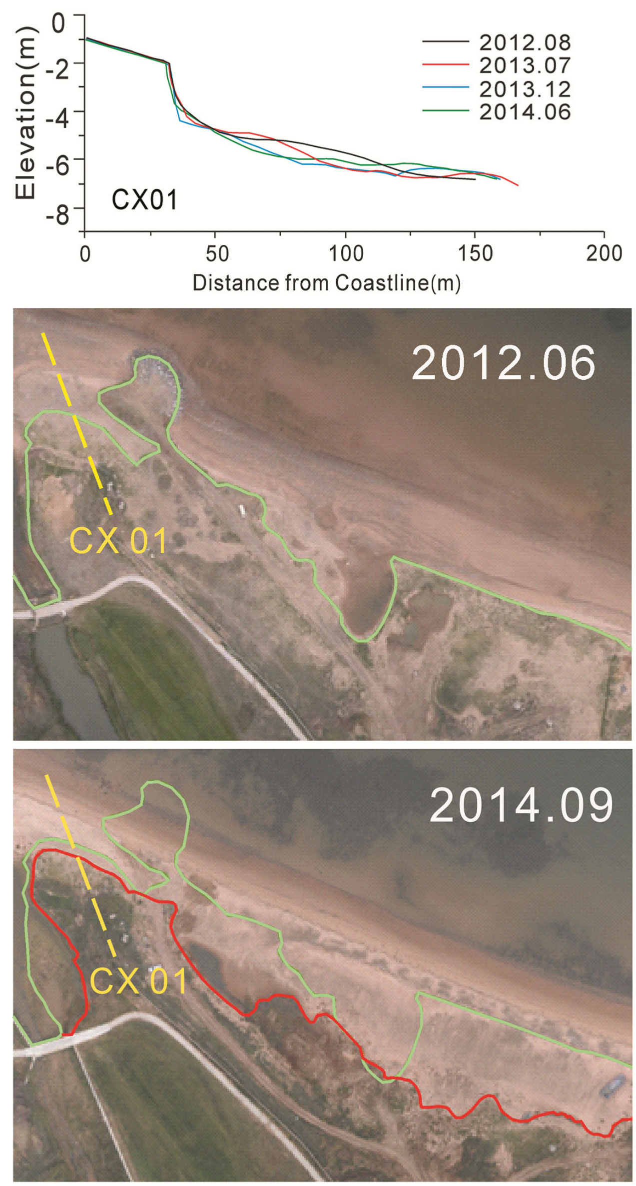


Fig. 2 — Coastal erosion of Changxing Island

**Dawanggang Island**

Dawanggang Island, located in the western Bohai Sea, is a sedimentary island with its southeast side facing the sea and its northwest side facing the land. Both have sandy shorelines, and revetments have been constructed along portions of the northeast side. Coastal erosion of this island mainly occurred along the sandy southeastern shoreline. Due to reduced sediment flux from the Luanhe River, which enters northern Xiangyun Bay along the northeast side of the island, this area was badly eroded and revetment foundations were hollowed out and collapsed. During the study period, the southern shoreline retreated by an average of 10 – 12 m/a (maximum total of almost 40 m) (Fig. 3), forming an erosion scarp of 0.5 – 1.0 m high. The shoreline of Qianshui Bay on the southeast side retreated by an average of 1 – 2 m/a, primarily due to a sand-slope scarp formed by sand-blowing sea reclamation. The beach experienced serious erosion (average 0.5 m depth) from August 2012 to August 2013, deposition in December 2013, and serious erosion in June 2014. Overall, serious erosion dominated, with an average loss of 0.2 m depth (maximum 1.1 m) (Fig. 3), related to continuous erosion of the high-tide zone. The beach sediments were mainly represented by fine sand generated continuously from the backshore dunes.

**Jijiapuzi Island**

Jijiapuzi Island, located in the southern Bohai Sea, is a shell ridge island with beaches mostly formed by sediment accumulation due to changing channels of the Huanghe (Yellow) River. Four surveys in October 2011, April 2012, October 2012, and May 2013 documented very little shoreline change overall. Seasonal changes in incoming water and sediment from the Huanghe (Yellow) River may result in changes along this island's coast, but these were not obvious due to the erosion of the whole shoreline.

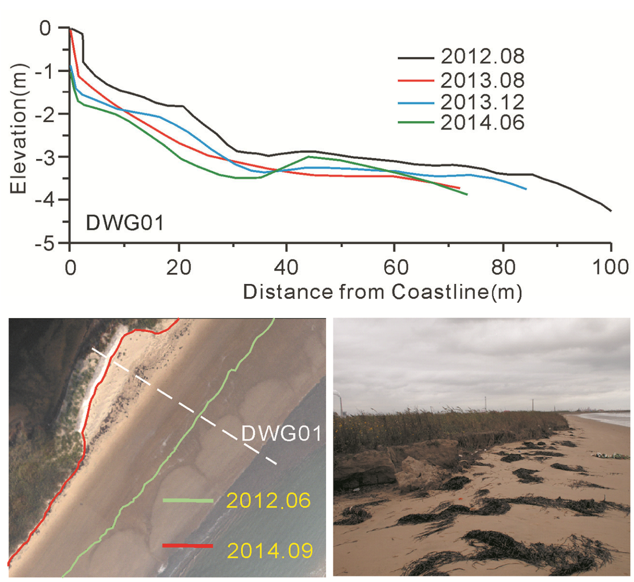


Fig. 3 — Coastal erosion of Dawanggang Island

**Daqin Island**

Daqin Island is located among the Miaodao Islands in the Bohai Strait, between the Yellow Sea to the east and the Bohai Sea to the west. This is a bedrock island whose shoreline varies between bedrock, sand, gravel, and artificial structures. Typical coastal erosion is occurred on the coast of Xikou Bay along the island's western shoreline. Monitoring data collected from 2012 to 2013 with the historic shoreline in 2006 was compared finding that most of the shoreline along Xikou Bay had eroded and retreated, especially in the south. The whole shoreline retreated by an average 3.2 m, (4.4 m in the middle-southern section), with a maximum retreat of 10.2 m. Meanwhile, continuous beach erosion since 2012 reduced depth by 0.25 m by May 2013 and 1.02 m by October 2013. The surface sediments underwent continuous roughening.

**Chongming Island**

Chongming Island, located in the Yangtze River estuary, faces the river on three sides and the East China Sea to the east. This is an alluvial island formed by the continuous deposition of sediments discharged by Yangtze River, and is the largest typical estuarine sandy island in China. The northern coast primarily experienced deposition, as it lies in a wave shadow with gentle tides and high suspended-sediment content from the river. In contrast, the effect of waves from the south and the strong erosional effect of flood currents led to constant erosion along the southern coast. From March 2013 to September 2014, the southeast coast retreated by an average of 19.1 m (Fig. 4), generally higher at the north end than at the south end (averages of 24.2 and 15.9 m, respectively). Additionally, ~2 m high erosion scarp is developed along this section of shoreline, which retreated by ~25 m from March to December 2013, then another 10 m by June 2014. The total retreat of this scarp was 36.5 m over the two-year study period (an erosion rate of 18.3 m/a) (Fig. 4). Overall, this coast experienced continuous and serious erosion.

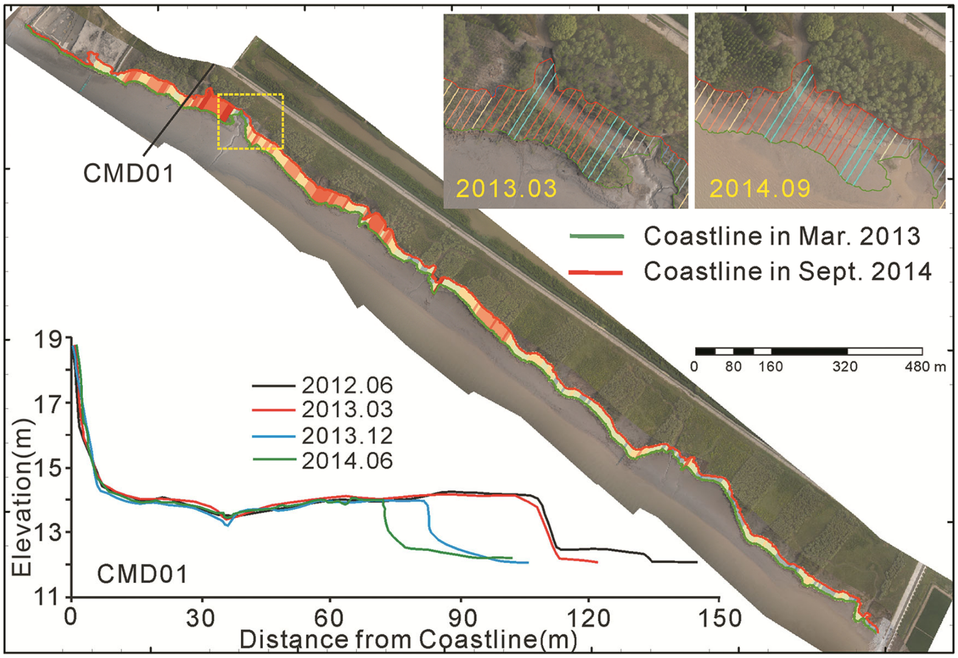


Fig. 4 — Coastal erosion of Chongming Island

**Xiushan Island**

Xiushan Island, located within the Zhoushan Islands in the East China Sea, is a bedrock island with many cape-bay sandy beaches along the eastern shoreline. Due to the wind-driven waves from the East China Sea, these beaches were eroded as a whole but changed seasonally. The whole profile was eroded in winter, with a mean depth loss of 0.5 m (maximum 1.0 m), while the berm moved upward in summer, resulting in backshore deposition and foreshore erosion (0.5 – 1.0 m). The surface sediments did not vary greatly over time and had a fine-coarse gradation from berm to backshore to foreshore.

**Liuheng Island**

Liuheng Island, located in the Southern Zhoushan Islands in the East China Sea, is a bedrock island with many cape-bay sandy beaches along the south shoreline. These beaches were naturally formed and experienced natural evolution; all backshore areas experienced coastal erosion and the eolian dunes retreated continuously by ~10 m. These beaches were sheltered and experienced only slight erosion without obvious annual changes. Seasonal changes were largely deposition in winter and erosion in summer, with usual changes of 0.5 – 1.0 m. The surface sediments did not vary greatly over time and had a fine-coarse gradation from berm to backshore to foreshore.

**Dongshan Island**

Dongshan Island, located in the western Taiwan Strait, is a bedrock island with many sandy beaches along the eastern shoreline. Coastal erosion along Wujiao Bay was typical, with an erosion scarp of 1 – 2 m high along much of the coastline. From October 2013 to July 2014, the entire shoreline along Wujiao Bay experienced no obvious changes, but the scarp on the partial coast retreated consistently by 2 – 3 m. The beaches along Wujiao Bay tended to experience erosion in winter and deposition in summer (Fig. 5); the latter did not exceed 0.5 m while the former mainly occurred in and along drainage gullies, with erosional depth losses of up to 0.5 – 1.0 m (Fig. 5). This was the main factor affecting shoreline retreat and beach change along Wujiao Bay[19].

**Donghai Island**

Donghai Island, located in the Northern South China Sea east of the Leizhou Peninsula, is a volcanic island and coastal erosion mainly occurs on the sandy beach. Continuous shoreline retreats and beach erosion is combined with continuous aeolian dune collapse, which supplies new beach materials[20]. During the study period, the shoreline retreated by ~0.4 m/a (maximum 4.0 m/a) and erosion removed an average of 0.1–0.3 m/a depth (maximum 0.66 m/a). The collapse of backshore dunes may have resulted in local deposition on the middle beach. In addition,

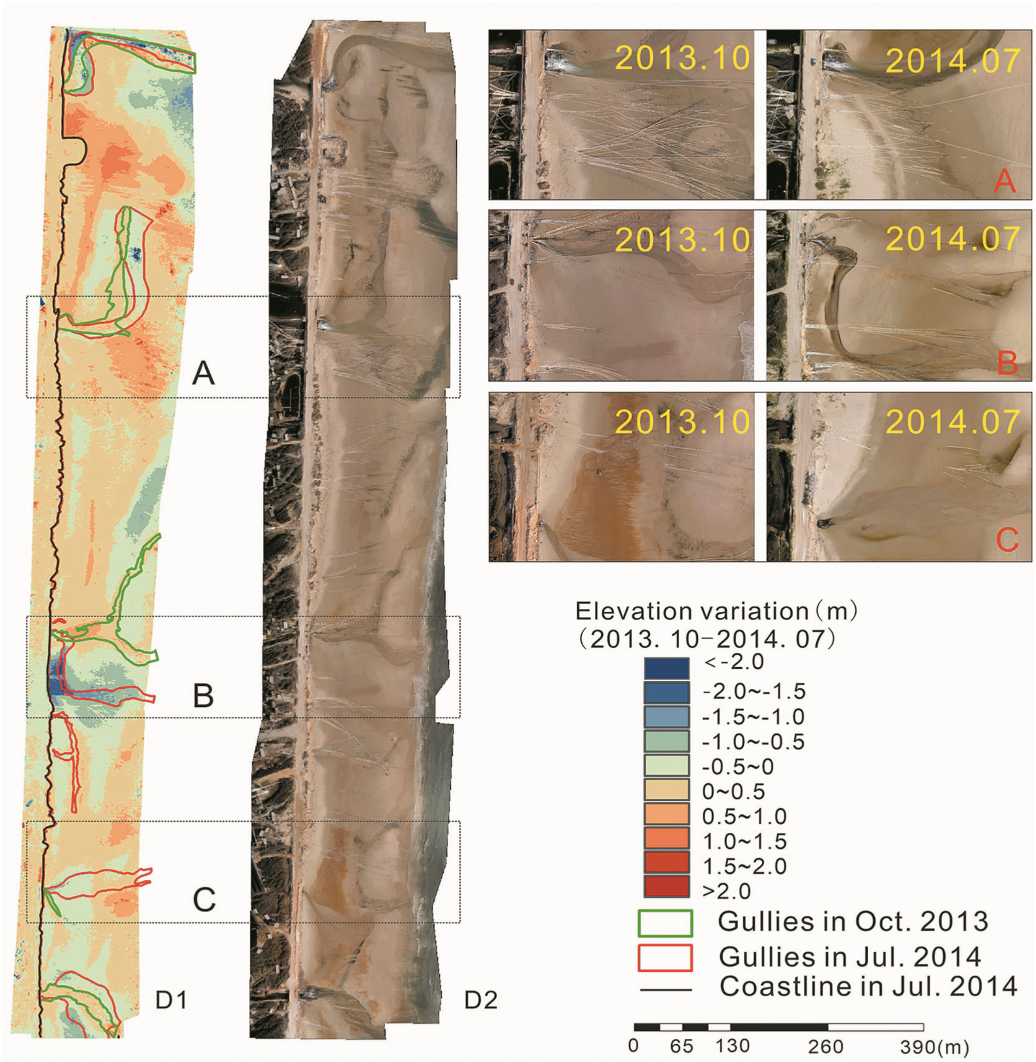


Fig. 5 — Coastal erosion of Dongshan Island

extreme weather conditions may have reshaped the beach over short periods. For example, Typhoon Rammasun (2014) caused 18.9 m of shoreline retreat (Fig. 6) and eroded 0.7 m depth (Fig. 6) while roughening all surface materials[21-24]. However, the continuous collapse of backshore dunes resulted in deposition of fine sediments on the beach, the most important material source maintaining the beach.

#### Weizhou Island

Weizhou Island, located in the Northern South China Sea and west of the Leizhou Peninsula, is a typical volcanic island with a sandy shoreline except for its western bedrock shoreline. From May 2006 to June 2014, the western beach was seriously eroded, erosion of the northern and eastern shorelines was relatively slight, and the southern coast tended to be stable[25]. The western shoreline eroded by an average of 0.12 m/a (maximum 1.0 m/a) and the erosion rate of the lower beach averaged 0.06 m/a. The northern and eastern shorelines experienced both deposition and erosion; the latter mainly occurred within the lower beach (mean erosion rate of 0.05 m/a), though this was slight. Overall, the shoreline of the southern bay changed very little (Fig. 7).

## Discussion

The geological hazard survey found 575 hazard points on 82 islands, of which 138 coastal erosion points were found on 39 islands, representing 24 % of all points and 48 % of all islands. Coastal erosion ranked second among all hazards and could be further classified by island and shoreline type (*i.e.* muddy coast erosion of muddy islands, sandy coast erosion of

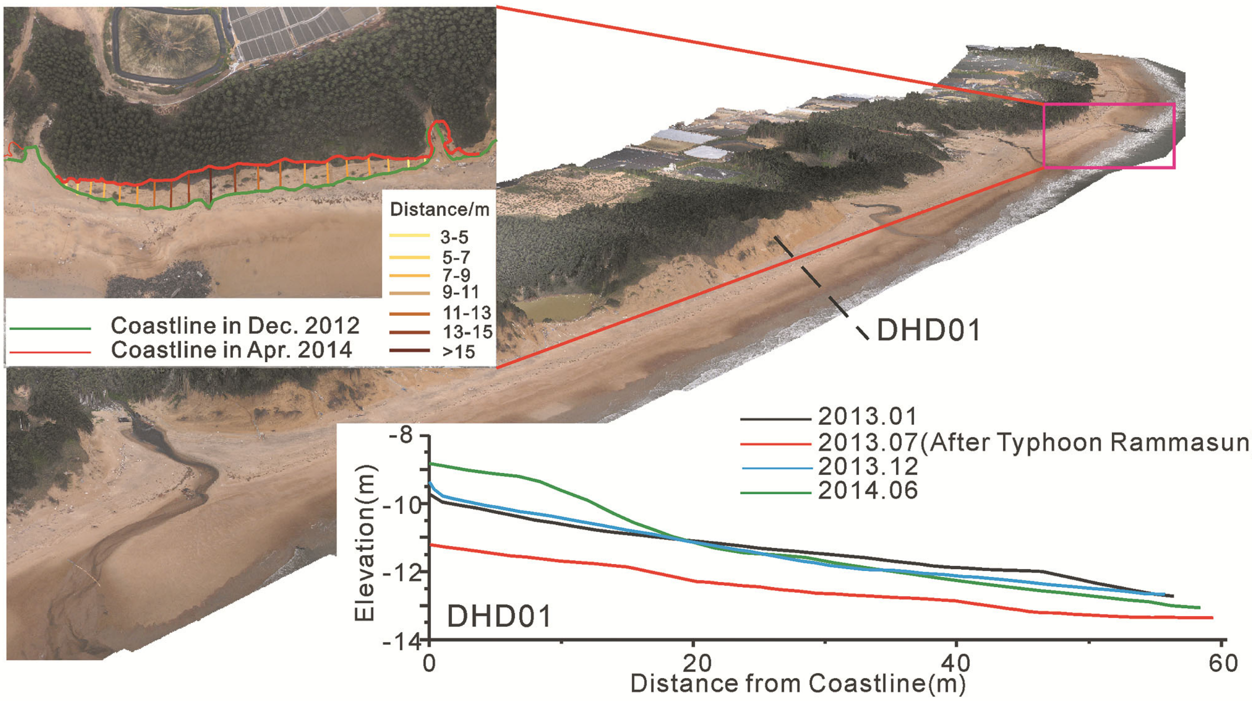


Fig. 6 — Coastal erosion of Donghai Island

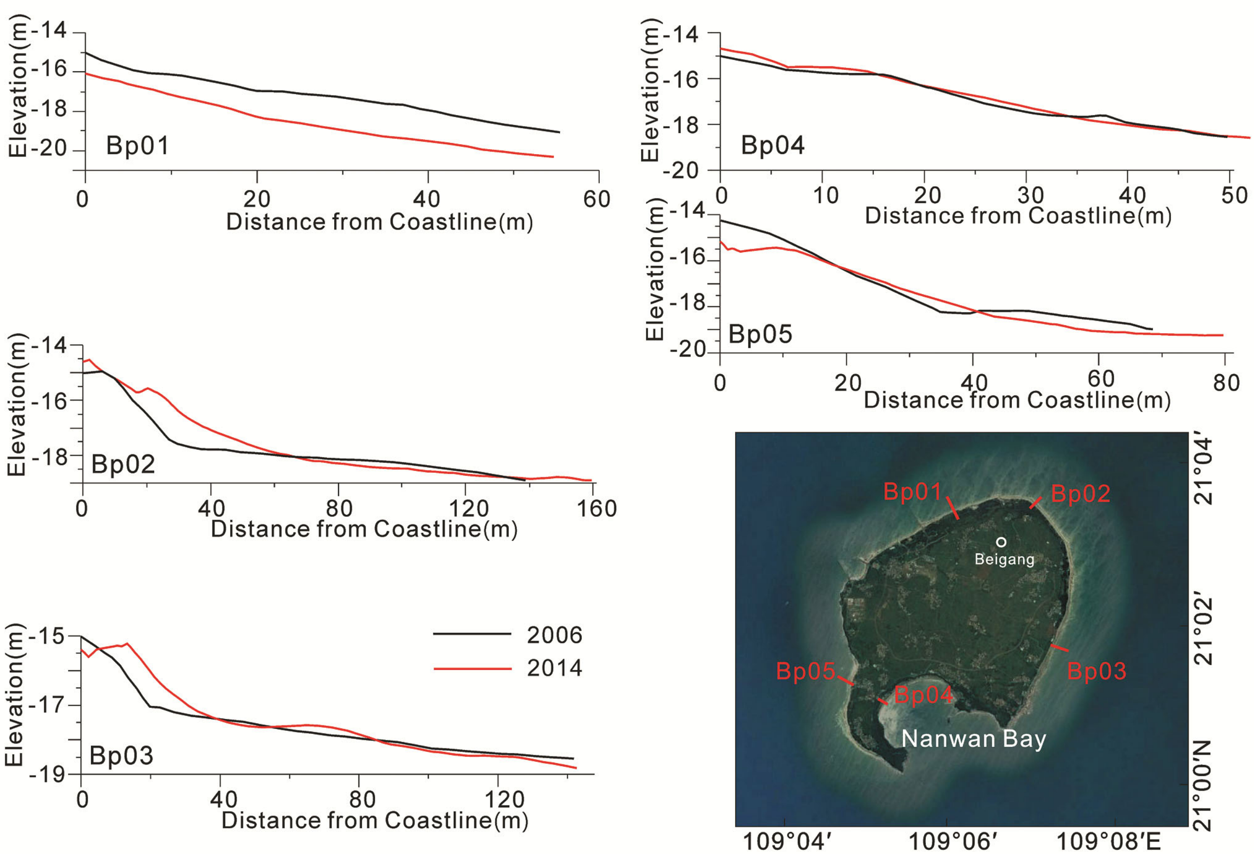


Fig. 7 — Monitoring results and location of the monitoring section on Weizhou Island

bedrock islands, loess coast erosion of bedrock islands, red soil coast erosion of bedrock islands, and bedrock coast erosion of bedrock islands). Increasing erosion intensity means that the proportion of seriously eroded coast increases annually. Erosion on the southeast coast of Chongming Island, the east coast of Donghai Island, and the Xikou Bay coast of Daqin Island was most serious. Island coastal erosion was also seriously affected by island type and changes in hydrological and climatic conditions. Based on the initial results, eight main influence factors were identified and analyzed resulting in island coastal erosion.

## Main influencing factors for coastal erosion

### *Sea-level change*

Ongoing sea-level rise has been recognized throughout the world. It's most direct and obvious result is shoreline retreat[26-27]. Islands are the first barrier meeting sea-level rise, and the response of sandy island coasts to sea level is very sensitive. Shoreline retreat can be calculated by the Bruun rule (1962):

$$R = \frac{L}{B+h} S$$

Where, $R$ indicates the retreat distance upon sea-level rise; $h$ indicates the closure depth; $L$ indicates the distance from shoreline to closure depth $h$; $B$ indicates dune height; and $S$ indicates sea-level rise. In addition, tan $\theta$ = (B+h)/L; where, $\theta$ indicates the beach slope.

Although most sandy coasts in China are located in an uplift structure belt and the applicability of this rule to coastal China is still under discussion. The impact of sea-level change on island coastal erosion can be determined by the relative sea-level change along the island's coast[28]. The rate of coastal sea-level rise in China has fluctuated over time. From 1980 to 2017, this was 3.3 mm/a (Fig. 8), higher than the global mean for that period. The slope of sandy beaches in China is

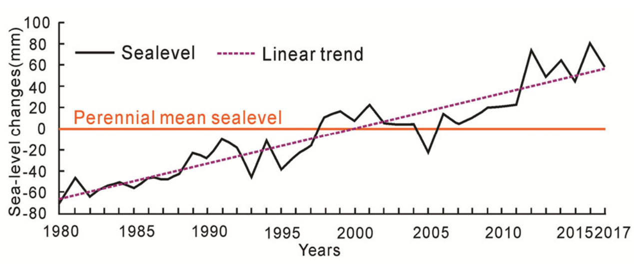


Fig. 8 — Trends of sea level change in China (from China Sea Level Bulletin 2017)

tanθ = 0.01 – 0.02[ref. 19], so the annual mean retreat distance is 0.15 – 0.30 m. Although this value is small compared with short-term retreat caused by storm tides (see below), the impact remains very serious over longer time scales. For example, beach retreat since 1980 may reach 5.6 – 11.0 m.

### *Wind- driven waves*

The shaping of beaches by waves generally varies seasonally[29]. From north to south, Chinese islands are located in the temperate monsoon, subtropical monsoon, and tropical monsoon climate zones, respectively, within which wave patterns vary greatly with season and climate. Normally, northwest waves prevail in winter, but southeast storm waves prevail in summer. Island beaches facing the open sea are more affected by wind-driven waves. For example, at Changxing Island (located at the northern end of the Bohai Gulf), waves become stronger under southerly winds but waves driven by northwesterly winds are weaker in winter due to sheltering by the mainland, so this island's beaches experience erosion in summer but deposition in winter. Daqin Island, at the center of the Bohai Gulf, is exposed to southward-moving cold air and northerly winds in summer, such that its coastline is exposed to waves generated by strong winds throughout the year, causing erosion. This is especially true in winter, when > 65 % of days experience waves. The beaches near Tuanjie Shoal (Chongming Island) are clearly affected by wind-driven waves. The island's southeast side faces the sea, where beaches are eroded by waves driven by southeasterly winds. Along with the strong effect of tides, sediments eroded by such waves are removed rapidly, causing serious erosion. Weizhou Island, located in the southwestern monsoon zone, experiences north-northeasterly winds in winter and south-southwesterly winds in summer, such that waves cause serious erosion on the island's northeastern and southwestern coasts.

### *Storm tides*

Storm tides are the abnormal rise (surge) of sea level caused by a violent atmospheric disturbance (strong wind and rapid pressure change). Weaker storm tides may last for hours, but stronger events may last for days, resulting in surges over the normal tide level with heavy winds and high waves, leading to large-scale rapid coastal erosion over short timer periods[30-33]. Northern areas are mainly affected by temperate-zone storm tides. In the Bohai Sea, these have an annual mean frequency of 12.6 (surges > 1 m).

Southern areas are mainly affected by typhoon storm tides; on average seven typhoons or tropical cyclones make landfall in coastal provinces every year. China is one of only a few countries suffering the serious impacts of both types of storm tides[34], which has severe impacts on island coastal erosion. Storm tides have much stronger effects than ordinary waves on coastlines, due to the scouring of beaches and destruction of coastal protections such as forests or human infrastructure. These events increase the sediment-carrying capacity of waves and roughen beach materials. For example, at Donghai Island, Typhoon Rammasun (2014) resulted in a dune retreat of 18.9 m and depth erosion of 0.7 m. Storm tides can reshape beaches by moving sediments along the coast, and strong storm tides often result in serious imbalances between beach sediment input and output, resulting in permanent coastal erosion.

***Sediment reduction***

Reductions in river-borne sediments are the most fundamental internal factor resulting in alluvial island and coastal erosion near estuaries[35]. From the 1950s to 1960s, many reservoirs were constructed in China, which greatly reduced sediment quantities reaching the sea and caused annual increases in coastal erosion. For example, a reduction in sediments carried by the Fuzhou River resulted in a major decrease in the sediment supply at Changxing Island. Beach materials on Dawanggang Island mainly come from the Luanhe River, but construction of water conservation works in the upper and middle reaches resulted in the river's sediment load declining from $2700\times10^4$ t/a (before the 1960s) to just 48,600 t/a from 2000 to 2009[ref. 36]. Chongming Island is located near the Yangtze River estuary[37]; interception of river-borne sediments by upriver water and soil conservation projects has reduced the mean annual sediment load at Datong station from 433 million t (1954 to 2000) to 163 million t (2001 to 2013)[38]. Such reductions have reduced the supply of new beach materials, rendering coastal erosion unavoidable.

***Sand mining***

While reductions in sediment supply reduce input in the beach material balance, sand mining increases output. The increasing economic development of Chinese coastal islands has created a rising demand for sand (used in construction); due to limited transport conditions, sand mining from coasts has become the simplest source[39]. For example, the sand on the coast of Xiushan Island is well-sorted and makes a high-quality building material, so large quantities are excavated locally to construct beach houses. Sand mining and illegal collection of coral reefs are more common on Weizhou Island, where sand mining destroys beach structure and damages the forests protecting the backshore. After such mining, the sand at the front edge of the backshore is carried to the sea, resulting in the loss of sand at the base of the forest and finally the collapse of its protective role and further worsening of coastal erosion[40]. Massive coastal silica mining operations on Dongshan Island have resulted in worsening coastal erosion within Wujiao Bay.

***Coastal engineering***

Coastal engineering is another main factor resulting in changes to island coasts, commonly including structures such as ports, piers, spur dikes, and revetments[41,42]. Generally, structures protruding into the sea (such as spur dikes) change the direction of coastal currents, while coastal revetments alter natural beach erosion patterns by waves. The resulting changes in hydrodynamic conditions alter sediment transportation and deposition patterns[43]. The scope of influence varies, but all coastal engineering projects affect coastal erosion and deposition.

For example, a sand dike constructed at Jingtang Port extended into water 8 – 9 m deep, resulting in further reductions in sediments carried by the Luanhe River toward Dawanggang Island. Huanghua Port (constructed in 1984) and Binzhou Port (constructed in 2010) partially block sediment transport toward Jijiapuzi Island. On Changxing, Xiushan, Liuheng, Donghai, and Weizhou Islands, dike construction creates insufficient space between the backshore and high-tide zone, resulting in the erosion of the dike foot by waves such that the beach at the dike foot experiences continuous erosion. Overall, coastal engineering alters the natural sand-transportation regime and hydrodynamic conditions, changing the input-output balance of coastal materials. Especially in environments with a single sediment source, deposition on some coasts must cause erosion of other coasts.

***Coastal destruction***

Coastal destruction on islands mainly represents unauthorized construction within breeding zones and damage to the vegetation of protective forests. For example, coastal destruction on Daqin Island is being caused by the excavation and destruction of partial coasts by local residents for kelp drying. In addition, gravel roads built on coastlines around Xikou Bay block the supply of coastal sediments, worsening coastal erosion. Vegetation in the protective forests of both Donghai and Weizhou Islands has been destroyed, resulting in worsening coastal erosion.

***Beach drainage erosion***

Beach drainage erosion relates to the development of gullies and other channels caused by the direct discharge of wastewater, sewage, or rainwater onto beaches, which often occurs in areas with developed marine aquaculture or industry[44,45]. Island beach erosion is mainly caused by drainage from breeding operations, and the extent depends on scale, type, and economic benefit of the operation. Our field surveys showed that drainage outlets from most breeding operations were not supervised or planned, and reached beaches directly by a rough method, seriously affecting beach resources and seawater quality. Beach erosion caused by such drainage tends to form linear slot-like gullies and other temporary erosive landforms caused by running water. The dissected channels have obvious edges, with scarps of 1 – 2 m deep formed at their mouths[46]. These also have obvious scarps at their heads, which often collapse and/or slides along the edges, resulting in constant widening. These may be tens of meters wide and hundreds of meters long. Beach erosion on Dongshang and Donghai Islands was typical; assuming a breeding pond with a water area of 2.5 mu (~1700 $m^2$), a 2 m water depth, and three breeding cycles per year. The annual drainage from one pond would be up to 10,000 t. This large amount of wastewater results in serious beach erosion. For example, 15 large gullies (1 – 1.5 m deep and 20 m wide) were found within a single 4 km stretch of beach on northeastern Donghai Island.

**Factor analysis for island coastal erosion**

The coastal zone has a mutual relationship of check and balance mechanism between the hydrodynamic conditions and the sediment supply. When the balance is broken, the process of establishing a new equilibrium point is manifested as the advance or retreat of the exchange area in space. Under the dual stress of global climate change[47] (especially sea-level rise) and human activities, the pattern or elements of the coastal zone system will change significantly, which lead to the more intense exchange process of hydrodynamic conditions and sediment supply and increase the risk of coastal zone erosion.

The rise of sea level determines the long-term development trend of coastal erosion. The century's continuous rise of sea level has increased the depth of the underwater slope and gradually reduced the disturbance of waves on the drowning ancient coast, which reduced the transverse sediment supply but strengthened the scouring of the upper beach by the strong waves. China's sea level rise rate is relatively fast, which means that the serious coastal erosion problem in the 20th century will further worsen in the 21st century. It is a slow process, but long-term accumulation will play a decisive role in coastal erosion.

Human activities have changed the material supply system in the coastal zone. With the development of economy, coastal migration and the expansion of the scope of human activities, sand mining, coastal engineering and various water conservancy engineering facilities are very common. Human activities have completely changed the shoreline types, sediment sources and hydrodynamic conditions of local coasts, which have a very profound impact on coastal erosion. At present, almost all coastal environmental evolution has the influence of human participation, but the proportion of human activities in the influencing factors is still in the qualitative stage. Compared with the rise of sea level, the impact of human activities on coastal erosion is local in space and rapid in time. When the change of human activities on the environment is stable, coastal erosion can reach equilibrium in a certain time. Therefore, human activities will have an important impact on local coastal erosion in a short period, but with the extension of human activities, the local impact will develop into a global threat.

Coastal evolution depends on the input-output balance of materials and energy over short and long time periods. Coastal changes are the combined result of more than one factor, and so defining the final state is more complex than simply summing the results of every influence factor. Instead, the main control factors for coastal erosion on different islands using the proportion of influence factors were determined in present study. Compared with other studies, the main influence factors on each island coastal erosion were identified in the present study especially small islands and there is very lack of relevant studies now. As mentioned above, almost all kinds of influencing factors are affected by human activities. However, the factors that are obviously affected by human activities in the coastal erosion of each island are calculated

Table 1 — Factor analysis statistics of typical island coastal erosion

| Factors | River sediments | | Marine hydrodynamic environment | | | Human factors | | | |
|---|---|---|---|---|---|---|---|---|---|
| | River diversion | Sediment reduction | Sea-level rise | Wind-driven waves | Storm tides | Coastal engineering | Coastal destruction | Beach drainage | Sand mining |
| Changxing Island | | ★ | ☆ | ★ | | ★ | | | |
| Dawanggang Island | | ★ | ☆ | ☆ | ★ | ★ | | | |
| Jijiapuzi Island | ★ | ★ | | | | ★ | | | |
| Daqin Island | | | ☆ | ★ | ★ | | ★ | | |
| Chongming Island | ★ | ★ | | ★ | | | | | |
| Xiushan Island | | | ☆ | | ★ | ★ | | | ★ |
| Dongshan Island | | | ☆ | | ★ | | ★ | ★ | ★ |
| Liuheng Island | | | ☆ | ☆ | ★ | ★ | ☆ | | |
| Donghai Island | | | | | ★ | ☆ | | ★ | ☆ |
| Weizhou Island | | | ☆ | ★ | ★ | ★ | | | ★ |

★ indicates a main influence factor, ☆ indicates a secondary influence factor.

here. Natural and human factors accounted for 57 and 43 % (Table 1) of Chinese island coastal erosion, respectively. Sea-level rise is a long-term factor; although its short-term effects are not obvious, they become so at decennial and centennial time scales. In contrast, storm tides are among the most important short-term factors. With the increasing development and exploitation of coastal islands, the proportion of human activities such as unreasonable construction and sand excavation is becoming a more influential cause of coastal erosion and may become a major influence factor.

## Conclusions

Coastal erosion of Chinese islands is worsening every year. Of the 575 geological hazard points identified in current survey of 82 islands, 138 coastal erosion points were found on 39 islands, representing 24 % of all points and 48 % of all islands, respectively. Coastal erosion ranked second among all geological hazards identified, and sandy coast erosion was most common and typical.

The different geographical locations of these islands resulted in various formational mechanisms of coastal erosion. Of the ten islands monitored more closely, nine experienced serious erosion. Erosion was the most serious on the southeastern coast of Chongming Island, the eastern coast of Donghai Island, and along Xikou Bay on Daqin Island, with a maximum erosion rate on Chongming Island of 18.3 m/a. The main factors affecting the coastal erosion of these islands included rivers, the marine hydrodynamic environment, and human activities; specific factors included river diversion, river-borne sediment reduction, sea-level rise, wind-driven waves, storm tides, construction and development, coastal destruction, beach drainage, and sand mining.

Natural and human factors accounted for 57 and 43 % of island coastal erosion, respectively. Sea-level rise was the most important long-term influence factor, causing an annual mean shoreline retreat of 0.15 – 0.30 m with significant effects on decennial and centennial time scales. Storm tides were among the most important factors at shorter time scales. However, the increasing development and human use of islands means that human activities are likely to become a significant factor.

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## Conflict of Interest

The authors declare no commercial or associative interest that represents a conflict of interest in connection with the work submitted.

## Author Contributions

WG & PL designed experiments; JL & YQX carried out experiments; LJL analyzed data and charted the illustrations; and WG & PL wrote the manuscript.

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