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Is China's coastal engineered defences valuable for storm protection?

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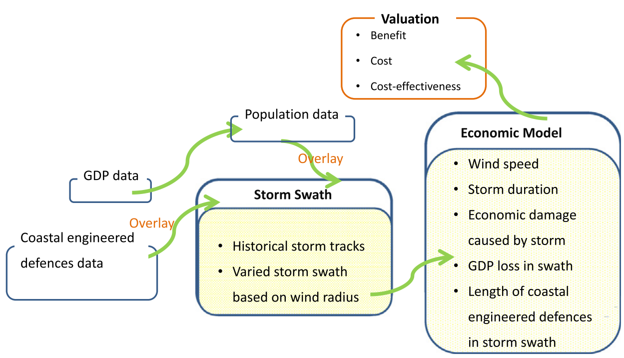
HIGHLIGHTS

- Coastal engineered structures play significant role to mitigate storms in China.
- Engineered structures are cost-effective for storm protection in China.
- Coastal wetlands rank over engineered structures economically to mitigate storms.

GRAPHICAL ABSTRACT



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ABSTRACT

China has a long history of building hard engineered coastal defences for storm protection, which enables us to examine the economic effects of the hard engineering to mitigate storm damage. Examining historical storm impacts between 1989 and 2016, a significant negative relationship exists between the relative economic damages (i.e., TD/GDP) by storm and the length of existing hard engineering within the storm swath. This indicates that hard engineered defences play a critical role in storm mitigation. We estimated that the storm protection value provided by hard engineered defences in China is CNY 3.18 million/km [US$0.50 million/km] on average, with a median of CNY 1.69 million/km [US $0.27 million]. They provide an annual economic value of CNY 6.04 billion on average. Despite their great contribution to reduce total economic damages from storms, hard engineered defences are not as efficient as coastal wetlands. Coastal wetlands are more cost effective based on comparison from China and USA. This study highlights the need for the Chinese government to transfer focus from prevailing hard engineered defences to ecosystem-based measure or the combination of both measures to prevent storm damage in the future.

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1. Introduction

The number of intense storms has increased over the past few decades due to climate change (Mendelsohn et al., 2012; Webster et al., 2005). Storm surges present deadly and destructive hazards for coastal areas worldwide (Needham et al., 2015). In response, many governments have built a series of hard infrastructures, such as man-made sea walls, to protect low-lying areas. One country with a wealth of experience in this area is China. China has relied mainly on seawalls for storm protection along its coasts for decades. During the period between 1980 and 2015, the length of Chinese coastal engineering increased from 5322 km to 13,316 km.

Since 1970, China has been hit by the most storms worldwide. China's coastline is 18,000 km long on the mainland and is approximately 34,000 km including numerous islands (Han et al., 1995). At present, 595 million residents live in the coastal area and roughly 57.4% of the country's gross domestic product (GDP) is generated in this region. A combination of frequent storm strikes, extensive coastline, growing population, and wealth accumulating in the coastal area will only add to the challenges faced by the aging structured defence system in China.

In addition, it is argued that many of these coastal engineered defences have been randomly built with little consideration of environmental impact at any stage of construction (Watham and Dafforn, 2018). For instance, conventional coastal engineering often exacerbates land subsidence (Temmerman et al., 2013; Syvitski, 2009), reduces natural coastal defences such as wetlands and coastal vegetation (Spalding et al., 2007; Murray et al., 2015) and facilitates harmful algal blooms (Ismael, 2014).

In recent year, a burgeoning pool of research has confirmed the effect of coastal wetlands on storm and flooding by using numerical simulations (Loder et al., 2009; Barbier et al., 2013; Wamsley et al., 2010; Narayan et al., 2017). Some studies have attempted to estimate the storm protection service of coastal wetlands in a money term and have argued that coastal wetlands can provide better defence against storms and at the same time, other ecosystem services (Martin and Watson, 2016; Costanza et al., 2008; Ouyang et al., 2018).

While, there is a growing body of evidence that evaluate the storm protection service of coastal wetlands, less is known about its cost-effectiveness to mitigate storms, and how to compare the soft defences with the hard defences in an economic way. Furthermore, it is expected to facilitate a better integration of coastal engineering with natural ecosystem based on comparison of these two different storm protection systems. Our analysis fills the gap of the literature to provide an initial comparison of the cost-effectiveness related to the two coastal defence types for storm protection based on the long-term observations. We investigated the effectiveness of each type of coastal defence in reducing economic damages from storms. To our knowledge, this is first attempt to compare the value of storm protection by human-made coastal defences with coastal wetlands.

2. Methods and data

To determine the effect of hard engineered defence to mitigate the storm damage, we proposed an economic regression model (see Eq. (1)) based on a multiple of data. Graphical abstract can be referred for more details.

$$\ln(TD_i/GDP_i) = \alpha + \beta_1 \ln(wind_i) + \beta_2 \ln(duration_i) + \beta_3 * hard\_defence_i + \mu_i \quad (1)$$

where, the dependent variable was natural log of the relative economic damage (i.e., TD_i/GDP_i) caused by storm i, independent variables contained the length of hard engineered defences ($hard\_defence_i$) in the swath of storm i, storm duration ($duration_i$) in hour and wind speed at landfall ($wind_i$) of storm i. μ_i denotes to the random error. All data inputs can be seen in Supporting Information. Multiple regression analyses were conducted by Eviews 10.

The data used in this study were collected from pertinent websites and official government statistics as follows:

- Marine Disaster Bulletin (MDB);
- Unisys weather;
- U.S. Geological Survey.

Marine Disaster Bulletin (MDB, 2016) has been published annually by the State of Ocean Administration (SOA), China since 1989 to report the first hand information on economic damage caused by all types of marine disasters including cyclones. We collected 127 historical storms striking China with economic damage over the period from 1989 to 2016 (details with data can be seen in Supporting Information). The total economic loss (i.e., variable *TD* in Eq. (1)) caused by storm includes damages in lives, properties, roads, bridges, fishery ships, agriculture and mari-aquaculture. Track, storm duration (i.e., variable *duration* in Eq. (1)) and wind speed (i.e., variable *wind* in Eq. (1)) for each of 127 storms were extracted from Unisys Weather (http://weather.unisys.com/hurricane). This information was used to calculate the effect swath for each storm following Willoughby and Rahn (2004),

$$R_i = 51.5 \exp(-0.0223V_i + 0.0281\varphi_i) \quad (2)$$

where the wind radius, R_i, is a function of combining wind speed (V_i) and the latitude position (φ_i) at a specific time *i*. We proposed a varied storm swath, which is a belt area with a central line along the track of the cyclone approaching inland and a wind impact radius R_i.

A vast variety of Landsat data with 30 m or 60 m resolution for 1980, 1990, 2000, 2010 and 2015 covering the entire China's coast were downloaded from U.S. Geological Survey and were then used to retrieve the spatiotemporal distribution of hard engineered defence along the China's coast by utilizing remote sensing and GIS technologies. Storm swaths were overlaid on map of hard engineered defences to obtain the involved length of hard engineered defences in each storm swath (i.e., variable *hard_defence* in Eq. (1)).

Several additional datasets including population and Gross Domestic Product (GDP) were used to assist the analysis. Population data for 1990 and 2015 were found at SEDAC (Socioeconomic Data and Applications Center at Columbia University), while population data for 1995, 2000, 2005 and 2010 were obtained from RESDC (Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences). The study period covered 28 years from 1989 to 2016. Population data for other years were interpolated based on data at specific years available. Temporal statistical GDP data for Chinese coastal provinces were obtained from the National Bureau of Statistics of China. Both the population census data and GDP statistic data were used for calculating the spatially explicit gross domestic product (GDP) in each storm's swath (i.e., variable *GDP* in Eq. (1)). The ration of TD/GDP (i.e., dependent variable *TD/GDP* in Eq. (1)) represented the relative economic damage of each storm.

3. Results

3.1. China's hard engineered defences

The major countermeasure for storm protection in China is hard engineered defences. These defences include seawalls, groynes, sheltered structures (i.e., harbour or port), and man-made bars (Fig. 1) for mari-aquaculture, agriculture, salt fields, transportation, and construction. From 1980 to 2015, hard engineered defences were extended extensively (Fig. 2). In 2015, nearly 74% of China's coastline is dominated by human-made structures.

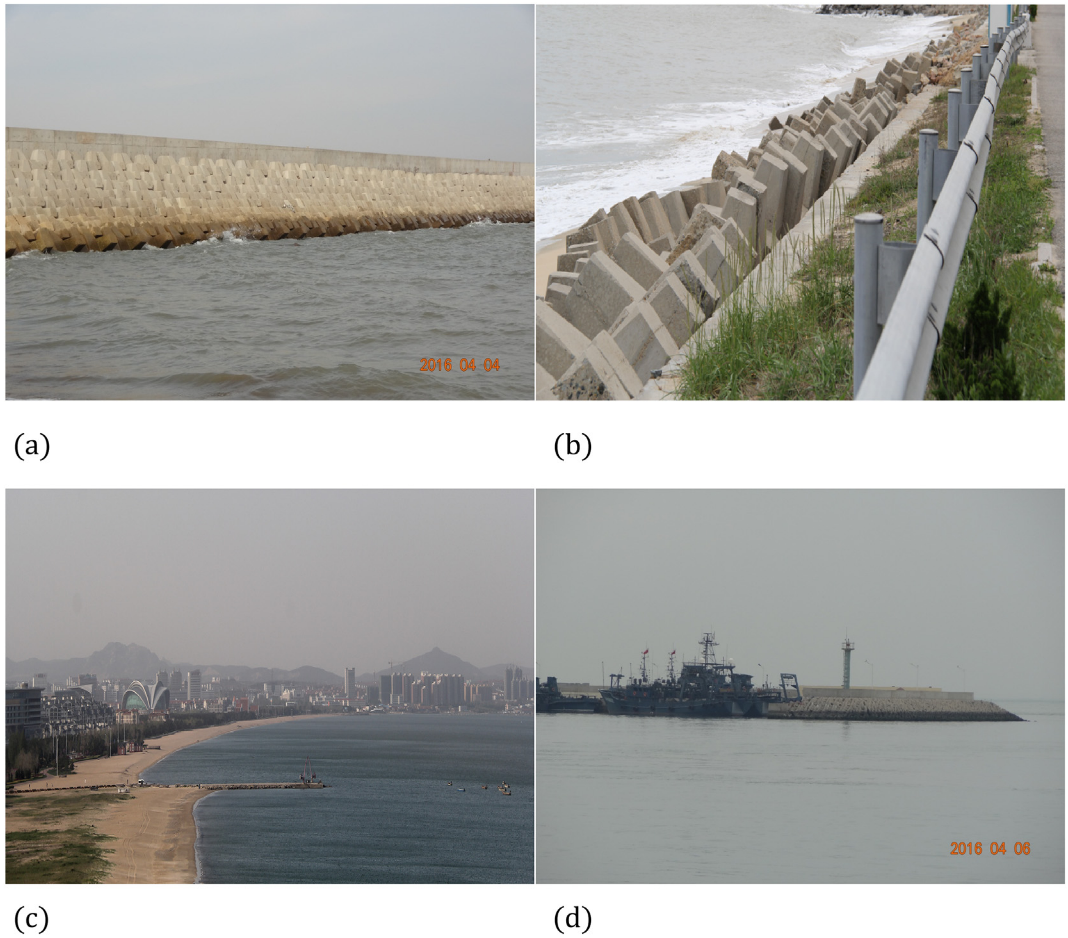

Fig. 1. Major hard engineered defences along China's mainland coast: (a) seawalls; (b) man-made bars for transportation; (c) groynes; (d) sheltered structures. Photos taken by M. Liu in 2016.

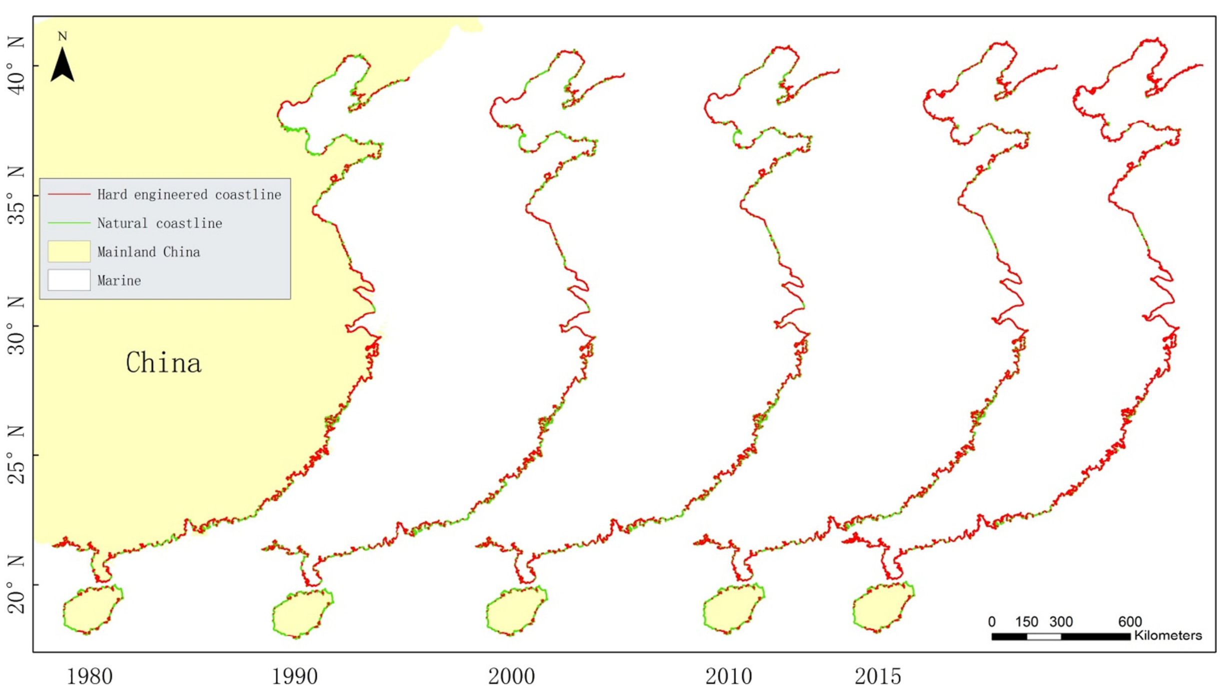

Fig. 2. Spatial-temporal changes of hard engineered defence along the mainland China's coast. The total length of hard engineered coastline in 1980 (5322 km), 1990 (7842 km), 2000 (9073 km), 2010 (11,407 km), and 2015 (13,316 km).

3.2. Valuing the hard engineered defences for storm protection

We analysed the relationship between the total economic damage caused by 127 storms that hit China from 1989 to 2016 and the presence of hard engineered defences. In this regression, the dependent variable is the log-transformed total economic damage for each storm (TD) per unit gross domestic product (GDP) (i.e., ln(TD/GDP)) in the storm swath. The independent variables included the length of existing hard defences in the swath of the storm and the log-transformed wind speed at landfall and the storm duration. There does exist a significantly positive effect of hard engineered defence in mitigating storms damages in China over the 28 years based on regression results. The regression results for the parameter of hard engineered defences were listed in the Table 1 ($\beta_3 = -0.0017$, $p = 0.0018 < 0.01$, $R^2 = 0.55$). The negative sign of the hard defence suggests that the longer the hard defence in the storm swath the lower the storm damage. The coefficient is negative and significant implying that in areas where hard defence were present, coastal community suffered less economic damage. On average, the expected reduction in the log count of relative economic damage (TD/GDP) with a kilometre increase in hard defence cover is 0.0017. Aside from the hard defence, the other significant determinants of economic damage by storm include wind speed at landfall and storm duration. As expected, both wind speed and storm duration significantly affected the relative economic damage caused by storm. The relative economic damage increases as the 3.114 power of the wind speed at landfall during storm and the 1.118 power of the storm duration.

We derived an average marginal value of CNY 3.18 million/km and a median marginal value of CNY 1.69 million/km provided by hard engineered defences for storm protection. That means that a gain of 1 km of hard engineered defences corresponds to an average of CNY 3.18 million (US $ 0.50 million/km) decrease in economic damage loss per storm. The marginal value per unit length of hard engineered defences ranged from a minimum of CNY 7699/km (US $1216/km) for Typhoon Lekima (2007) to a maximum of CNY 26.58 million/km (US $4.2 million/km) for Typhoon Linfa (2015). Taking the annual frequency of storms hitting China into account, the annual storm mitigation value of hard engineered defences is estimated to be CNY 6.04 billion for all of China (Table 2).

3.3. Comparison of the hard engineered defences with wetlands

Generally, seawalls have an average life span of approximately 50 years. Construction expenditure of seawalls is estimated to cost up to CNY 6,397,500/km with an annual maintenance bill ranging from CNY 15,622/km to CNY 74,216/km in China (MWR, 2004). Existing coastal wetlands are free, self-maintaining gifts of nature. For a conservative comparison, we considered constructed wetlands in this paper. If we had to construct the wetlands, the average cost of one acre of constructed wetlands is USD $1036/yr when the wetlands were analysed over 40-years (Iowa Learning Farm, 2015). Costanza et al. (2008) assess the annual economic value of coastal wetlands for storm protect at USD $1.05 million/km^2 (converted to 2016 USD) on average. The benefit/cost ratio of hard engineered defences for storm protection was estimated conservatively to be between 2.6 and 4.0, indicating such defences are cost-effective measure for storm protection (Table 3). While, wetlands (e.g., the benefit-cost ratio = 4.1) was higher than hard engineered defences in terms of cost-effectiveness for storm protection. Regarding the cost-effective solution to mitigate storm damage, we concluded that even constructed wetlands fully outweigh hard engineered defences. Furthermore, unlike hard engineered defences, coastal wetlands naturally adapt to changes in wave storminess (Duarte et al., 2013). Besides the storm protection, coastal wetlands provide other added benefits including water purification, fishery, recreation, and other ecosystem services (Aburto-Oropeza et al., 2008; Gosselink et al., 1974; Jaworski and Raphael, 1979; Costanza et al., 1989).

Table 1
Regression results for hard engineered defences and coastal wetlands, respectively.

Variables	ln(TD/GDP) = α + β1 ∗ ln(wind) + β2 ∗ ln(duration) + β3 ∗ (hard defence)	
	Coefficient	Prob.
Constant	−20.949***	0.0000
Wind speed at landfall (m/s)	3.114***	0.0000
Storm duration (hour)	1.118***	0.0000
Hard defence in length (km) within storm swath	−0.0017***	0.0018
Regression fit (R)	0.55	
Sample size (N)	127	

Note: TD: total economic loss of storm; GDP: gross domestic product in storm swath.
*** Statistically significant at 1% level.

Table 2
An estimation of the total annual storm mitigation value derived by hard engineered defence in China.

Steps in calculation	Result
A. Predicted mean value of hard engineered defence per km for storm protection (from regression model)	CNY 3.18 million km^{-1}
B. Estimated mean length of hard engineered defence in storm swath	418.8 km
C. Estimated average annual frequency of storms hitting China	4.536 storms yr^{-1}
D. Annual protection value of hard engineered defence (A ∗ B ∗ C)	CNY 6.04 billion yr^{-1}
E. Total length of existing hard engineered defence in China, 2016	13,316 km
F. Estimated storm protection value of hard engineered per km per year (A ∗ B ∗ C/E)	CNY 453,663 km^{-2} yr^{-1}

4. Discussion

China has responded to storm strikes by establishing hard engineered defences, such as seawalls, since 1970. The role of seawalls in mitigating economic loss caused by storms has been addressed by the Chinese State of Ocean Administration (SOA). However, there is a lack of quantitative studies that measure the value of storm protection function. Ouyang et al. (2018) conducted an analysis of cyclone mitigation provided by coastal wetlands and criticized that seawalls in China play an insignificant role in cyclone mitigation. However, this study had multiple problems. Firstly, they evaluated the effect of seawalls on the total economic damage (TD) from cyclones in China by comparing the actual and estimated relative damage derived from the regression model involving wetlands rather than seawalls as an independent variable. Secondly, the fitness of their regression model for the coastal wetlands is quite poor ($R^2 = 0.09$), which indicated that only 9% of variations in the relative damage was explained by the model. In contrast, we examined 127 storms hitting China with economic damage from 1989 to 2016 and selected the human-made defences as one of the major independent variable in the regression model. We found there is significant relationship between the ratio of total economic damage

Table 3
The benefit-cost analysis of storm protection function provided by the hard engineered defences and the constructed wetlands, respectively.

Indices	Indices value (references)	
	Hard engineered defences	Constructed wetlands
Benefit of storm protection on average	CNY 453,663/km/year (derived from this paper, see Table 2)	USD $1.05 million/km^2/year (converted to 2016 USD; Costanza et al., 2008)
Cost of construction and maintenance	CNY 113,300–173,000/km/year (MWR, 2004)	USD 2559/ha/year (Iowa Learning Farm, 2015)
Benefit/cost	2.6–4.0	4.1

to gross domestic production (TD/GDP) in natural log and the length of human-made defences within storm swath in China. Hence, we argued that the existing hard engineered defences critically provided protection against storms in China.

Hard engineered defences have been recently challenged as unsustainable due to their high maintenance costs as well as, their inability to keep up with storms of increasing intensity (Temmerman et al., 2013). Many urge that wetlands can provide a more sustainable and cost-effective alternative for storm protection (Deng et al., 2010; Hu et al., 2015; Marsooli et al., 2016; Zhang et al., 2012). Nonetheless, no empirical studies have quantitatively compared the effectiveness of coastal wetlands over hard engineered defence from the perspective of storm protection (Das et al., 2009). Our analysis presented in Table 3 contributes to compare the cost effectiveness of both storm protection systems in a quantitative way.

There are sources of error and limitations in our estimates. Firstly, R^2 is 0.55 for the regression model, which indicate 55% of variation in the dependent variable (ln(TD/GDP)) can be explained by the proposed model. The weak R^2 may be due to a large variance of ln(TD/GDP). The variance of ln(TD/GDP) in the sample was 4.05, which is relatively high for log-transformed variable. Secondly, the temporal-spatial distribution information on hard engineered defences were retrieved from satellite images obtained from US Geological Survey (USGS), which is limited to specific years including 1980, 1990, 2000, 2010, and 2015. Future studies can be improved by obtaining spatial distribution data of hard engineered defences in each year of the storm strike. Thirdly, aggregating individual cases to a national total introduces error. In general, we derived marginal unit length value of hard engineered defence for each of 127 storms. This resulted in statistical estimates such as average (and median) values of hard engineered defence mitigating cyclone (in CNY/km), which was then multiplied by two major factors: average (and median) length of hard engineered defence in the cyclone swath and the annual frequency of tropical cyclones hitting China. Such a national total can only be considered a crude first approximation and can introduce errors depending on the spatial heterogeneity for both storms and hard engineered defences. To control for such error, it is suggested to aggregate data on both storm hitting frequency and the exiting length of hard engineered defence at the provincial level. Finally, comparing hard engineered defences and coastal wetlands in their efficiency for storm mitigation is limited to two cases: one is from China and the other is from USA. More cases are expected to improve the precision of evaluation.

5. Conclusion

To our knowledge, this is first attempt to estimate the storm protection value provided by coastal engineering and further to compare its value with that of constructed coastal wetlands. Based on our estimation, the hard engineered defences in China provide CNY 3.18 million/km on average for storm protection. However, coastal wetlands outweigh the hard engineered defences in terms of cost effectiveness. To establish effective storm protection, China needs to shift away hard engineered defences to ecosystem-based measure, or a combination of the two. Often a combination of both measures produces the best results (Luo et al., 2015; Temmerman et al., 2013).

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.409.

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