Damage of extreme water levels and the adaptation cost of dikes in the Pearl River Delta

Lei He, Guosheng Li, Kuo Li, Yue Zhang and Tengjiao Guo

ABSTRACT

Many of the world's largest coastal cities are becoming increasingly vulnerable to extreme events due to their growing populations and infrastructure, the changing climate, and subsidence. This paper assessed the economic impacts of extreme climatic events including sea-level rise and storm surge risk and the benefits of the adaptation strategies in the Pearl River Delta, a lowing-lying area located in southern China. An economic benefit–cost model was established for the estimation of the impacts and benefits. The damage of the extreme events was calculated using the damage rate modeled from the historic disaster database, and then the difference between the damage and the cost of heightening dikes was investigated under different scenarios. The results showed that the damage rate and storm surge level were positively related. The adaptation strategies benefited when the dike was heightened by 1.43–12.67 m, with the optimum reached at 5.15 m, and the dike did not exceed 12.67 m. The maximum benefits were obtained when the dike was designed to defend a 20-year return period storm surge in 2100, and the minimum when the dike is heightened to defend a 100-year return period storm surge in 2100.

Key words | adaptation cost, extreme events, Pearl River Delta, sea-level rise, storm surge

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INTRODUCTION

Globally, coastal and low-lying areas are becoming 'key risk' areas owing to growing populations and infrastructure, subsidence, and extreme events, which may be caused by sea level rise, storm surges, or high tides (IPCC 2014; Kar *et al.* 2017). By 2050, the world's 136 largest coastal cities may lose US$1 trillion per year due to coastal floods, of which Guangzhou, part of the Pearl River Delta (PRD) in China, ranks first (Hallegatte *et al.* 2013). By 2100, more than half of the world's deltas will be flooded if global sea level continues to rise rapidly (Ericson *et al.* 2006; Syvitski *et al.* 2009). It is expected that 0.2–4.6% of the global population would be flooded annually in 2100 under 25–123 cm of global mean sea-level rise, with annual losses of 0.3–9.3% of global gross domestic product (GDP) (Hinkel *et al.* 2014). Under extreme sea levels, more than 37 million people in China are exposed to a 100-year flood, which is 3% of the country's population and 53% of the global exposure (Muis *et al.* 2016).

Extreme sea levels, mainly caused by storm surges and high tides, can have devastating economic impacts. Adapting to sea-level rise requires a comparison of different possible adaptation strategies, comparing the cost of different actions (including no action), and assessing where and at what point in time the chosen strategy should

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be implemented (Thorarinsdottir *et al.* 2017). Benefit–cost analysis is a powerful decision-making tool for assessing adaptation strategies to climate change; for example, assessing the defense infrastructure projects designed to prevent risk (Hallegatte *et al.* 2011b; Camille *et al.* 2016). The analysis results can be used to compare projects to determine which one will provide the greater net benefit (Chiabai *et al.* 2015).

Great efforts have been devoted to estimating the damage caused by extreme sea levels and the costs of adaptation (Anthoff *et al.* 2010; Ruckelshaus *et al.* 2016; Dupuits *et al.* 2017). Global models such as dynamic and interactive vulnerability assessment (DIVA) have been established to assess the damage caused by extreme weather events under different climatic and socio-economic scenarios and adaptation strategies on a global scale (Webster & Stiff 2008; Murdukhayeva *et al.* 2013). But further uncertainties might be added when downscaling the information from the global model to the local situation, taking into account regional and local spatial variations in sea levels due to meteo-oceanographic factors, gravitational effects related to ice melting, and local uplift or subsidence processes (Hinkel *et al.* 2015). According to the IPCC SREX concept, risk of sea-level rise can be estimated from the hazard, exposure, and vulnerability (IPCC 2012). At a regional scale, the economic impacts have been evaluated by estimating the areas affected by floods, and then calculating the corresponding unit costs of dikes for protection along the coastline, and finally interpolating to the whole vulnerable area (Titus *et al.* 1991; Hallegatte *et al.* 2011a). The economic impacts can also be estimated by the models from the historical data about extreme events characteristics and the socio-economic statistical data during those events. For instance, the future economic impacts can be deduced from the relationships between the damage probabilities of affected objects such as buildings, crops, and roads and the parameters of the extreme events such as the return period of storm surges, tide heights, and depth/duration of the flooding (Heberger *et al.* 2012; Rizzi *et al.* 2017). The statistical model based on large samples can estimate the impacts of extreme events accurately, especially for some special assessments such as those for industry, crops, or infrastructure (Lian *et al.* 2017). However, remarkable performance of the model is highly dependent on the long-term and detailed historical loss data for the affected objects, which limits the application of the model to the regions where such data was available. Therefore, an accurate and feasible disaster assessment method is needed urgently for the estimation of regional economic impacts of extreme events (Sutton-Grier *et al.* 2015).

The PRD, located in the southeast of Guangdong Province, China, inhabited by millions of people, with 13% of its surface area below mean sea level and limited coastal barrier protection, is highly vulnerable to storm surges (Syvitski *et al.* 2009). The direct economic loss caused by marine disasters in Guangdong Province during 2008–2016 is about US$64.25 million, of which $63.99 million is caused by storm surges, accounting for more than 99% of the total loss (State Oceanic Administration 2016). Storm surge is one of the critical factors that threatens regional economic and social sustainable development. The distributions and impacts of the storm surges in the PRD have attracted wide attention and much research (Loy *et al.* 2014; Peng & Li 2015). However, information on the related loss and adaptation is rare in the literature (Kang *et al.* 2016).

The dike, with a total length of more than 4,000 km, is the vital strategy that protects more than 15 million people and about 5,000 km^2 of cultivated land from the storm surges in the PRD (Chen 2005). Sea-level rise shortens the storm surge periods and downgrades the design protection levels of the defense infrastructure. Moreover, it erodes the dikes, and weakens their defensive capabilities. It is estimated that the sea level will rise by 30 cm in 2030 in the PRD, and under this scenario the period of storm surge will shorten by a half; for example, near Guangzhou station the storm surge return period of 50 years will become 25 years (Huang *et al.* 2001).

Therefore, as a highly developed and densely populated zone, the PRD is severely threatened by sea level change and storm surges, and establishing a method for accurately assessing the socio-economic impacts of storm surge in the context of sea-level rise is of great scientific and social value. The main objectives of this work are: (1) to investigate the economic impacts of storm surge and sea-level rise based on the historical disaster data in the PRD; (2) to establish a benefit–cost model from the impacts of the extreme events and the cost of heightening dikes; and (3) to evaluate the efficiency of adaptation strategies for different scenarios by applying the benefit–cost model.

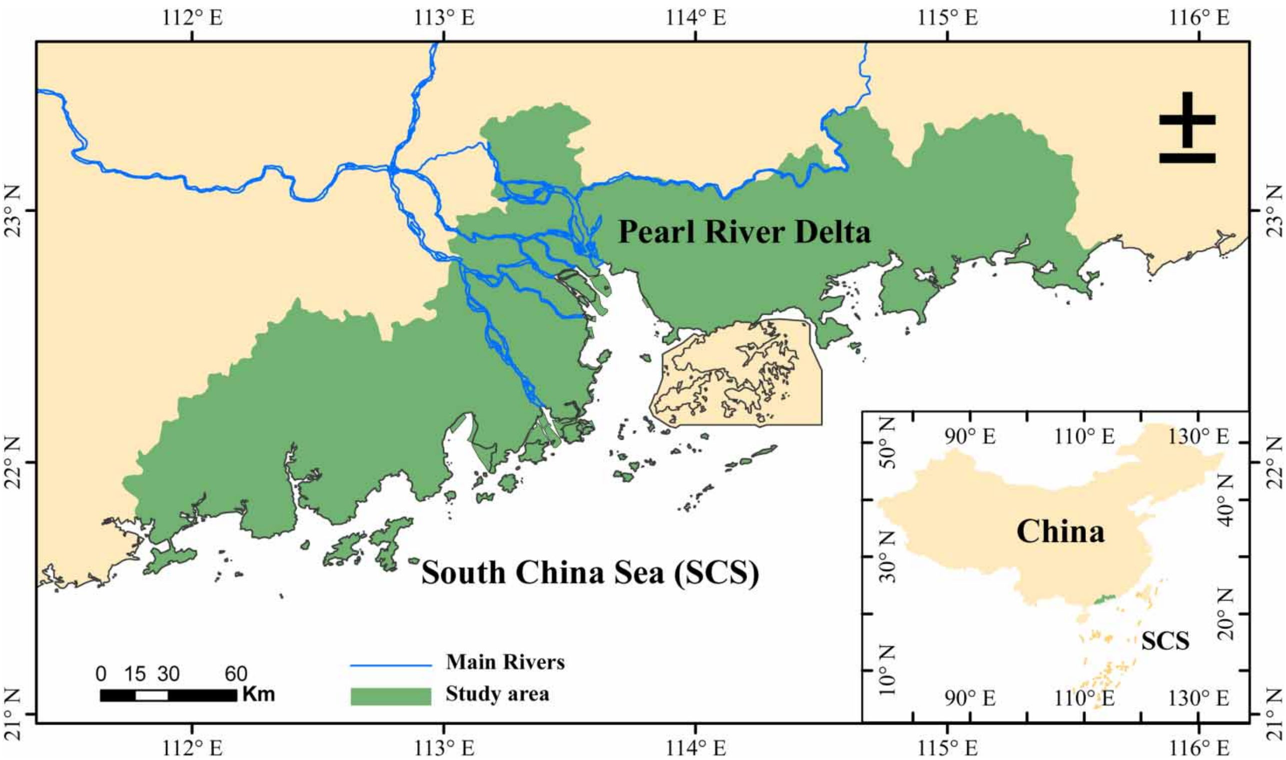

Figure 1 | Location of the study area.

MATERIALS AND METHODS

Study area

The current study focuses on the PRD, which is located in southern China and abuts the northern coast of the Pacific; it is a low-lying area through which the Pearl River flows into the South China Sea (Figure 1). The PRD is dominated by a sub-tropical monsoon climate and the topography has mixed features of a crisscross river-network, channels, shoals, and river mouths. The PRD has been the fastest developing region in China since the 'open door and reform' policy was introduced in the late 1970s. On less than 0.5% of the country's territory, the PRD region produces about 20% of the national GDP, attracts about 30% of foreign direct investment, and contributes about 40% of exports (Yang *et al.* 2010). Rapid property accumulation and population growth puts enormous pressures on the local environment, and makes the PRD one of the most vulnerable zones in the world to sea-level rise and storm surges (Hallegatte *et al.* 2013; Yang *et al.* 2015). The dike is the vital adaptation strategy against this risk.

Data sources

This study collected data on dike construction, socio-economic data for the PRD, and the direct economic losses during the storm surge events. Data for 75 dikes (the total length is 1,631 km) in the study area were collected from the report 'Planning for key dike construction in the south China coastal area', and includes the dike lengths, heights, design levels, protection standards, the protected population and cultivated land, and protected industrial and agricultural output value. The direct economic loss data were obtained from the 'disaster census' of the Pearl River Commission and historical data from Yu (2015), including the times the storm surges happened, the areas (administrative city, county) affected, the water level, and direct economic loss caused by each disaster. Social and economic data were obtained from the *Statistic Almanac* (Guangdong

Statistic Almanac Committee 1986–2016), including the national economic income, the population, and the average elevation of the affected area. The protection level of the dike and the direct economic loss caused by the storm surges were adjusted to the current level according to the national retail price index (National Bureau of Statistics of China 2018).

Methods

Storm surges are *force majeure* events, and the prediction, impacts assessment, and mitigation measures are made to mitigate the impacts or limit the effect of the disasters, which cannot completely eliminate the occurrence.

This study was conducted with an assumption that the damage could only occur due to the overtopping of the defenses (Jonkman *et al.* 2009). Then each dike height corresponded to a certain probability of storm surge (the higher the dike, the smaller the damage probability). Dike heightening led to a reduction of the expected damage. However, the investment cost increases with dike heightening, while the probability of storm surge at a higher water level becomes lower. Therefore, balancing the construction of dikes according to the protection level and damage due to storm surges to formulate an optimal strategy is the vital component in the study of adaptation to extreme events.

Based on the characteristics of storm surge disasters and the availability of data, the benefit–cost model was selected to quantitatively analyze the losses due to extreme events and effects of heightening dikes under different scenarios (Chow *et al.* 2017). From the perspective of the benefit–cost model, taking adaptation measures is the process of resource reallocation, and the construction of dikes needs social resources investment, which can be seen as costs. On the other hand, under present conditions or without any adaptation, the population and infrastructure are highly exposed to storm surges. If full protection is adopted there may be little vulnerability, so these exposures or losses can be seen as the benefits of the adaptation. Whether it is beneficial or not depends on the difference between the cost of heightening the dikes and the losses when no adaptation is adopted.

In this study, the net benefit of building dikes can be calculated from the difference between the damage caused by storm surges under present conditions and the cost of heightening the dike to the lowest level to protect the coastal area from the storm surges. That is:

$$B = D - C \quad (1)$$

Here, B is the net benefit of building the dike, D is the damage caused by storm surges under present conditions, and C is the cost of heightening the dike.

The cost is the investment to heighten one unit length (e.g. 1 km) of the dike. The estimation of the damage (D) caused by storm surge is the focus and difficulty of this study. The damage changes along the inundation height; so does the damage rate. In this study, the damage rate is the ratio of the direct economic damage to the GDP in the affected area protected by dikes, which can be calculated by evaluating the direct loss due to each storm surge and the protection level of the dikes. And then the relationship between the damage rate and the height was identified from a database of historical extreme events. Then, the damage along the height was calculated from the relationship. By comparing the damage and the cost, the benefit of heightening the dike was obtained as a function of height. As a consequence, a point was determined where the benefit was maximal. Finally, losses in the absence of adaptation and benefits with full protection were analyzed for different scenarios and a comprehensive analysis of optimal adaptation strategy against the extreme events was presented.

RESULTS AND DISCUSSION

Scenarios

Extreme events are usually caused by long-term sea-level change and storm surges; that is the extreme water level is the sum of sea-level rise and storm surges under different scenarios. Studies have shown that the rate of sea-level rise in the PRD is about 3.72 mm/year over the past 50 years, with a sea level rise of 70.68 mm, 145.08 mm, and 331.08 mm, respectively, by 2030, 2050, and 2100 (He *et al.* 2014).

Table 1 | Extreme levels corresponding to various storm surge return periods, with sea-level rise in 2030, 2050, and 2100

	Storm surge level (mm)		
Return period	**2030**	**2050**	**2100**
10-year	4,050.68	4,125.08	4,311.08
20-year	4,790.68	4,865.08	5,051.08
50-year	5,740.68	5,815.08	6,001.08
100-year	6,450.68	6,525.08	6,711.08

Pearson III and Gumbel methods were applied to calculate the return periods of storm surges in the PRD (Li & Li 2013); the results showed that water levels of storm surges with 10-year, 20-year, 50-year and 100-year return periods are 3,980 mm, 4,720 mm, 5,670 mm, and 6,380 mm, respectively.

Moreover, the extreme level of storm surges with different return periods in 2030, 2050, and 2100 can be obtained, as shown in Table 1.

Impacts of extreme events

Given the unified calibration, the protected industrial and agricultural output value was converted to GDP by establishing the regression relationship between industrial and agricultural output value and GDP in the study area. The lowest height of the dikes is 2 m, the highest is 8.8 m and the total length is 1,631 km. The protection level of the dike is shown in Figure 2, and a good logarithmic relationship can be found between the height of the dike and the protected wealth. The aggregated protected wealth presents logarithmic growth as the height of dikes (x) increases. That is:

$$GDP = 7667 \times \ln(x) - 5233.60 \quad (2)$$

Here, GDP is the protected GDP by dike and x is the height of the dike.

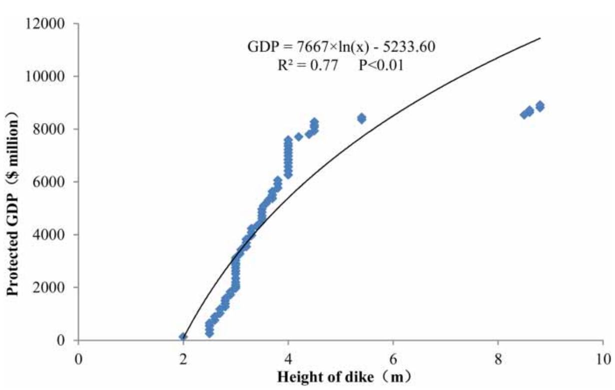

Figure 2 | Relationship between the height of the dikes and the cumulative protected GDP in the PRD.

Selecting the appropriate factors to establish the disaster loss model is the key point of the study on the economic impact of storm surges. The damage caused by storm surges is mainly affected by the storm surge intensity, inundation area, inundation depth, and the duration time, and the damage rate (Cooper & Chen 2013; Hinkel *et al.* 2015). Previous studies on natural disasters and socio-economic development have found that disaster losses are largely related to factors such as GDP, population, and age composition (Dinan 2017). In this study, 119 storm surge disasters and the natural and socio-economic factors were collected to analyze the relationships among them, including the water level during the storm surge, the affected area and population, GDP in the affected area, and the damage rate.

There is no significant correlation between the direct economic loss due to storm surges and the water level of the tide gauge, the GDP, population or administrative area in the affected area (Table 2), while the damage rate is positively correlated with the surge height, with a correlation coefficient of 0.26 ($\alpha = 0.01$). This indicated that the economic losses of the disaster have no direct relationship with the surge height or the regional GDP. However, the damage rate is significantly related to the surge height. Therefore, storm surge height was chosen as the independent variable for the damage rate modeling (Figure 3).

$$Rate = 0.11 \times \ln(x) + 0.13 \quad (3)$$

Here, $Rate$ is the damage rate and x represents the water level of the storm surge.

Combining Equations (2) and (3), the direct economic losses under present conditions can be calculated according to the protected GDP and the damage rate. In terms of benefit–cost, the loss incurred when protective measures are not adopted will become a gain under the protection strategy in response to the extreme events, and then the

Table 2 | Correlation coefficients between the losses/damage rate and the main factors

	Losses	Surge height	GDP	Population	Area	Damage rate
Losses	1	0.053	−0.017	0.066	−0.049	0.493[a]
Damage rate	0.493[a]	0.255[a]	−0.157	−0.062	0.005	1

[a]at the confidence level of 99% ($\alpha = 0.01$).

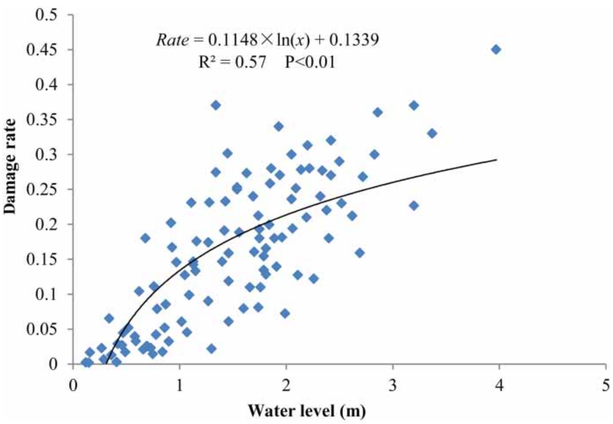

Figure 3 | Relationship between the damage rate and the water level of storm surge.

relationship between storm surge and direct economic loss can be obtained:

$$L = 3266 \times \ln(x) - 259.85 \quad (4)$$

Here, L is the direct economic loss and x is the water level of the storm surge.

Adaptation to extreme events

Dikes would be seriously damaged by the high frequency and strong intensity tides from sea-level rise and storm surges, and the protection level would be degraded. While the return periods of storm surges are shortening, the fortification standard needs to be improved. Moreover, most of the dikes in the PRD were designed to resist storm surges with return periods of 20 years or 10 years. As the sea level rises, the protection levels are low and do not form an efficient defense system. Therefore, with adaptation, the dike along the coastline needs to be enhanced and heightened to upgrade the defense.

Cost estimates for dikes vary widely due to the local economy and natural environment (Aerts *et al.* 2013; Jonkman *et al.* 2013; Lenk *et al.* 2017). Ward *et al.* (2017) presented structural flood protection measures in urban areas around the world and, combined with the estimation in the PRD (Du 1997), a value of US\$0.39 million km m^{-1} heightening was adopted in this study. This estimate pertains to all investment costs, including groundwork, construction, and engineering costs, property or land acquisition, environmental compensation, and project management. A recent study based on empirical investment cost data from the Netherlands and Canada found that investment costs per metre heightening were well described by a linear function without intercept. And then the cost of heightening a kilometre of dike by x can be expressed as:

$$Y = 0.39x \quad (5)$$

where Y (US\$ million km m^{-1}) is the cost of heightening one kilometre of dike by 1 m height, and x is the increased height (m).

Optimal benefit strategies

Under present conditions, that is, no adaptation is adopted and dike heights are maintained but not raised, the risk and damage increases with time as relative sea level rises. The benefit–cost model for beneficial analysis on dike construction can be established from Equations (1), (4), and (5), as shown in Figure 4. Two intersection points (respectively, points A and B), when the increased height (x) is 1.43 m and 12.67 m, respectively, were found on the damage curve and the cost curve. When $x < 1.43$, the cost curve is above the damage curve; when $x = 1.43$, the two curves intersect; and when $x > 1.43$, the damage curve is above the cost curve until $x = 12.67$; after that the cost curve is always above the damage curve. That is, when the elevation of the dike is less than 1.43 m, although there is coastal protection, the frequency of storm surges around this height is so high that the dike fails to meet the

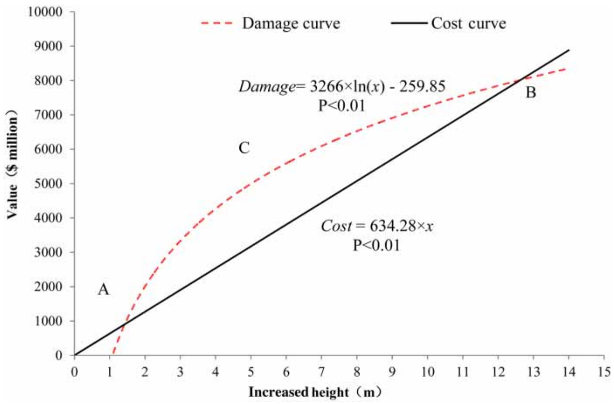

Figure 4 | The benefit–cost model for dike heightening (the benefit of dike construction is the difference between the damage curve of extreme events (dotted line) and the cost curve of dike heightening (solid line)).

protection needs, and the damage still happens. At this stage, the cost of the dike construction is higher than the damage, and additional investment should be made to heighten the dikes. While the dikes were heightened beyond 1.43 m, the cost and the damage reversed. The property the dike protects is of a higher value than the cost of construction. According to Equation (1), at this stage, the net benefit of heightening the dike is positive. When the dike elevation reaches 5.15 m, the net benefits reach the maximum (i.e., point C in Figure 4), after which the net benefits diminish. The height at point C is the optimal level for the dike heightening under present conditions. When the height is higher than 12.67 m, the cost and damage reach a balance again. As the height of the dike continues to increase, the probabilities of storm surge at this water level would be smaller, and the investment will be much larger than the losses that may be incurred if no protection is adopted. Then the economic effects of heightening the dike will be negative. In summary, under present conditions, the construction of the dike had two balance points. When the increased height ranges from 1.43 m to 12.67 m, the net benefit is positive, and the maximum occurred when it reaches 5.15 m. The height of the dike should not be more than 12.67 m.

Impacts under future scenario

The direct economic loss with no protection, the cost and the benefit of dike construction with protection under future scenarios can be calculated from the benefit–cost model (Table 3).

As can be inferred from Table 3, the costs for constructing dikes to resist the extreme events are much lower than the losses due to not taking measures in all scenarios, suggesting that remarkable benefits can be obtained as the result of constructing dikes. Therefore, in view of the current status, the protection strategy of heightening the dikes should be adopted in response to future sea level changes and storm surge events. The largest loss happens in 2100 in a 100-year return period storm surge if no adaptation is adopted. As the height of dikes increases, the defensive capability strengthens, but the cost increases, too. In terms of the economic impacts, the optimal strategy is to heighten the dikes to meet the needs against surges with a return period of 20 years in 2100, and the minimum net benefit occurs when heightening the dikes for protection against the 100-year return period storm surge in 2100. Taking into account the depreciation expense, and large investment of human and material resources for the maintenance of the dike, it is not sensible to heighten the dike to a relatively high level, such as for protection against low probability storm surge events in 2100. The loss data used in this study is direct economic loss, and if the indirect economic losses during the disaster were considered, the net benefit from heightening the dike should be higher than in Table 3.

Table 3 | Losses without adaptation and cost and net benefit with adaptations for different scenarios (US$ million)

	2030			2050			2100		
Return period	**Losses**	**Cost**	**Net benefit**	**Losses**	**Cost**	**Net benefit**	**Losses**	**Cost**	**Net benefit**
10-year	4,308.91	2,569.27	1,739.64	4,368.35	2,616.46	1,751.90	4,512.39	2,734.43	1,777.96
20-year	4,856.90	3,038.63	1,818.27	4,907.23	3,085.82	1,821.41	5,029.77	3,203.80	1,825.97
50-year	5,447.74	3,641.20	1,806.54	5,489.79	3,688.39	1,801.41	5,592.62	3,806.37	1,786.26
100-year	5,828.58	4,091.54	1,737.04	5,866.03	4,138.73	1,727.31	5,957.83	4,256.70	1,701.13

Sources of uncertainty

There are three main sources of uncertainty in this study. First, due to the complexity and difficult acquisition of the indirect losses caused by the storm surge, the direct economics losses from departmental statistics were used as the losses. Second, we focused on the extreme climatic events in this study, and the risk of non-climatic events such as tsunamis was not considered. These may result in the assessment of the impacts of the extreme events being small, which means the net benefit of the dike heightening might be underestimated. Finally, the benefit of the strategies in 2030, 2050, and 2100 was estimated based on the current protection level of the dike. As the economy develops and property accumulates in the future, according to Equations (2)–(4), even in the case of constant disaster rate, the economic losses caused by extreme events would increase, and the benefits of dike heightening would increase accordingly.

CONCLUSIONS

In this study, the benefit–cost model of storm surges was constructed based on the historical disaster data to investigate the economic impacts of sea-level rise and storm surges, and the adaptation strategy of heightening the dike in future scenarios in the PRD. The results showed that no significant correlation was found between the direct economic loss due to the storm surge and the water level, GDP, population or administrative area in the affected areas. However, the damage rate was positively correlated with the water level of the storm surge.

According to the benefit–cost model, the net benefit of dike construction is positive when the increased height ranges from 1.43 m to 12.67 m under present conditions in the PRD. And the optimal height is 5.15 m. The height of the dike should be no more than 12.67 m.

Under the scenarios of sea-level rise in the future, the present standard of dike defense in the PRD is relatively lower. In all scenarios, the protection strategies are beneficial. The heightening of the dike in the PRD is necessary in response to future sea-level rise and storm surge events. The maximum benefit occurs when the dike is heightened for defense against the 1:20 year storm surge in 2100, and the minimum happens when the height is increased for defense against the 100-year return period storm surge in 2100.

A storm surge disaster involves many industries and sectors, and the estimation includes complex types of disaster-bearing bodies, while usually little historical and economic loss data is available. The benefit–cost model established by using the damage rate and the storm surge level is scientific and feasible and would provide comprehensive analysis for storm surge estimation. It can provide a reference for research on extreme events study in other similar regions.

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