Using Multidisciplinary Analysis to Develop Adaptation Options against Extreme Coastal Floods

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Abstract Long-term flood risk adaptation and decision making are complex because the future is full of deep uncertainties. Flexibility and robustness can be used to deal with future uncertainty. This study developed an integrated modeling framework that extends previous studies to the spatial domain to assess the future flood risks and the cost and benefit of three adaptation measures for four types of buildings in Shanghai. Real options analysis (ROA) and dynamic adaptive policy pathways (DAPP) were integrated to develop a dynamic adaptation pathway and identify robust adaptation options. The results show that: (1) Sea level rise and land subsidence will significantly exacerbate the flood risks in Shanghai; (2) Among the three flood control measures, wet-floodproofing has the best economic performance in terms of both the net present value and the benefit/cost ratio, followed by dry-floodproofing, and elevation; (3) Dry-floodproofing can be used at the beginning of the future period (2030–2100), and it can be replaced by wet-floodproofing in 2035–2042; the elevation measure also shows good performance at the beginning of implementation, but its performance will decline after 2041–2045; (4) The combined strategy of dry- and wet-floodproofing in 2044–2046 and a hybrid strategy combining the three measures should be the optimal solution for reducing the flood risks in 2047–2051. The methodology developed in this study can provide insights for coastal cities to formulate cost-effective and feasible adaptation strategies in a deeply uncertain future.

Keywords Adaptation options · Building-level measures · Climate change · Coastal floods · Cost-benefit analysis · Shanghai

1 Introduction

The Intergovernmental Panel on Climate Change’s Sixth Assessment Report shows that global sea level will continue to rise throughout the twenty-first century, leading to more frequent and severe floods in coastal areas (IPCC 2021). The combined risk of extreme floods due to the sea level rise, land subsidence, and climate change is threatening coastal cities (Abadie et al. 2020; Catalao et al. 2020; Strauss et al. 2021). Under Representative Concentration Pathway (RCP) 2.6 and RCP8.5 carbon emission scenarios, the global comprehensive risk will increase two- and fourfold, respectively (Magnan et al. 2021). Risk analysis of extreme storm floods is crucial for coastal cities to develop strategic plans and adaptation measures (Scussolini et al. 2017; Du et al. 2020; Wang et al. 2020). In particular, extreme floods with low probability and high magnitude have become the focus of recent studies because of their catastrophic consequences and losses (Shan et al. 2021; Tang et al. 2021). Many studies have assessed flood risks in coastal cities in the context of
sea level rise, land subsidence, and climate change (Lin et al. 2016; Hinkel et al. 2018; Shan et al. 2019; Ngo et al. 2020; Nguyen et al. 2021). Due to sea level rise the 1/500-year flood in New York City before the Industrial Revolution, for example, has become the current 1/25-year flood (Reed et al. 2015; Garner et al. 2017). Hence, how coastal cities adapt to the increasing risk of extreme storm flooding needs extensive and insightful discussions (Barnett et al. 2014; Haasnoot et al. 2021).

Flood adaptation refers to the implementation of a series of measures to reduce the occurrence and potential impact of flood events (Tanoue et al. 2021). Cost-benefit analysis (CBA) is commonly used to evaluate the effectiveness of flood adaptation measures, and is an effective tool to support making adaptation decisions (Ward et al. 2017; de Ruig et al. 2019). Many studies have examined the cost and benefit of flood adaptation measures in coastal cities. Studies for Ho Chi Minh City (Scussolini et al. 2017), Jakarta (Ward et al. 2011), New York (Aerts et al. 2014), Los Angeles (de Ruig et al. 2020), London (Hall et al. 2019), and Osaka Bay (Ha et al. 2021) have focused on the impact of coastal flooding on people and assets, and the cost effectiveness of adaptation measures under different sea level rise scenarios. In addition, some studies have focused on the cost-benefit analysis of flood adaptation measures at the household level (Wang et al. 2015; Qin and Stewart 2020; Shan et al. 2021). For example, Shan et al. (2021) evaluated the cost-effectiveness of two flood adaptation measures—dry flood-proofing and wet flood-proofing—for flood adaptation of residential buildings in Shanghai. Qin and Stewart (2020) assessed the cost-effectiveness of four adaptation measures for reducing the risk of residential buildings. However, in the research of extreme flood risk adaptation, uncertainty exists not only in disaster risk assessment, but also in cost-benefit analysis of adaptation measures, as well as in the decision-making process. Therefore, extreme flood risk adaptation carries deep uncertainty.

Due to the deep uncertainty of the changes, decisions need to be formulated as flexible and adaptable. Robust decision-making methods such as real options analysis (ROA) and dynamic adaptive policy pathways (DAPP) provide solutions to decision making that involve deep uncertainty and can be applied to research on decision making and planning to deal with climate change.

Real options analysis is a method to deal with the uncertainty of investment timing by considering management flexibility and volatility (Erfani et al. 2018; Kim et al. 2019). Decision makers can decide when to invest and maintain the possibility of greater investment in the future using ROA. In recent years, the concept of ROA has been used in flood risk management to help decision makers formulate robust decisions to enhance flood adaptation in the context of climate change. Adaptation can be achieved because ROA provides an optimal sequence of future investment decisions to cope with uncertainty in flood hazards over time (Kind et al. 2018). Flexible options can give more time to manage areas where investments may be overwhelmed or future risks are more severe than expected (Wreford et al. 2020; Ginbo et al. 2021). Kim et al. (2019) evaluated the adaptive investment timing of Lymington, a flood-prone coastal town in the UK, under the scenario of sea level rise based on the ROA method. Liu et al. (2018) used ROA to assess adaptation options for flood risks under climate change scenarios in London, and pointed out that this method was more flexible than fixed adaptation (that is, maintaining the current adaptation measures). Hino and Hall (2017) showed that a flexible adaptation plan can better deal with deep uncertainty than implementing a single plan at present. Similarly, postponing the timing of decision making under uncertain conditions allows for learning more from the change and making better decisions in the future (Woodward et al. 2014).

The dynamic adaptive policy pathways (DAPP) approach is a method that explores alternative sequences of investment decisions to achieve goals over time in the context of uncertain future development and environmental changes (Haasnoot et al. 2013a; Haasnoot et al. 2013b). Haasnoot et al. (2020) proposed an economic evaluation framework to explore adaptation pathways or a series of strategic investment options and took flood risk management in the Netherlands as a case study. Monitoring and reevaluation of the adaptation strategies should be an ongoing process, and investment tipping points should be identified in time to transit or make changes to the adaptation strategies accordingly.

The DAPP and ROA approaches have commonalities in adjusting options or strategies depending on the realization in the future. At present, these approaches are increasingly used to design or plan long-term adaptation options over multiple decades and longer terms (Woodward et al. 2014; Kim et al. 2019). Gersonius et al. (2015) compared ROA (Gersonius et al. 2013) with the tipping point analysis (the core idea of DAPP) (Kwadijk et al. 2010) and showed that the two methods could be combined. Buurman and Babovic (2016) developed a conceptual framework to deal with deep uncertainty in climate change adaptation policy making based on ROA and DAPP, and demonstrated the framework to policy making for pluvial flood protection in Singapore. The combination of ROA and DAPP can be used to investigate the optimal timing of flood adaptation measures under deep uncertainty, and develop effective adaptation pathways for both the short term and the long term.

A wide range of economic and robust decision-making methods is available to support decision making on coastal flood protection options under changing flood risks for effective adaptation, such as CBA (Aerts et al. 2014), ROA (Kim et al. 2019), and DAPP (Haasnoot et al. 2020). However, few studies have demonstrated how to combine
several types of such methods to generate complementary cost-effectiveness information to support coastal flood control decisions. Concerning the research gaps, based on a case study in Shanghai, this study aimed to develop a multidisciplinary analysis framework that encompasses risk analysis, cost-benefit analysis of adaptation measures, and adaptation pathways study using ROA and DAPP. The specific scientific questions to be examined with the data analyses are:

1. Will there be a significant increase in the future flood risk of buildings in the case study area?
2. What adaptation measures should be taken to reduce storm flood risks and how can the costs and benefits of measures be quantified?
3. How can dynamic optimal pathways for the short, medium, and long terms under deep uncertainty be formulated to help decision makers make robust decisions? The methodology to be developed should also provide insights into flood risk assessment and management in other coastal cities.

2 Data and Methods

This study used a set of multidisciplinary and comprehensive methods—flood risk analysis, cost-benefit analysis of adaptation measures, and adaptation pathways—to assess the flood risk dynamics, the effect of adaptation measures on reducing risks, and the formulation of dynamic adaptive policy pathways for buildings in 2010, 2030, 2050, and 2100 (Fig. 1).

First, hydrodynamic modeling was conducted to produce flood hazard maps associated with the storm surges in the baseline year of 2010 and future years of 2030, 2050, and 2100. The asset value of buildings was estimated and mapped according to the area, number of floors, and cost of each building type. The baseline year and future extreme storm flood...
simulation results were overlaid respectively with the asset values of buildings in 2010, 2030, 2050, and 2100 to evaluate the exposed assets. Building losses were obtained by combining exposed assets and vulnerability curves. The risk was quantified as estimated expected annual damage (EAD) (see more details in Sect. 2.1.1).

Second, cost-benefit analysis of adaptation measures was performed through net present value and benefit/cost ratio. This study evaluated the cost and benefit of the building-code strategies for individual buildings, including dry-floodproofing, wet-floodproofing, and elevation in Shanghai under the current and two representative concentration pathways (RCP2.6 and RCP8.5) scenarios. Dry-floodproofing measures mean that the flood-prone parts of a building are waterproofed, so that floodwater is prevented from entering inside. Wet-floodproofing measures allow floodwater to enter a building and its contents through adjusting the interior and material of the building. Elevation measures refer to the use of materials such as concrete to raise the height of the steps of the building.

Third, on the basis of evaluating the performance of flood adaptation measures, by integrating the ROA of the continuation value and termination value of flood adaptation measures and the tipping point analysis of DAPP, the flood dynamic adaptation pathways of short, medium, and long terms were developed.

2.1 Methods

This section outlines the methodology employed in the study. The methods specifically include flood risk analysis, cost-benefit analysis, real options analysis (ROA), and dynamic adaptive policy pathways (DAPP).

2.1.1 Flood Risk Analysis

The risk analysis mainly includes four parts: (1) The total value of the elements at risk can be calculated from the total asset value; (2) Exposure is measured by overlaying flood simulation results with the total assets; (3) The depth-damage functions for Shanghai were developed by Ke (2014)—they represent the relationship between flood characteristics and damage rate, and reflect the relationship between inundation depth below 0.5 m to above 3.0 m at an interval of 50 cm and the damage rates of residential, commercial, public, and industrial buildings (Fig. 2). The losses can be evaluated by Eq. (1); (4) Risk can be represented by a curve, which combines the losses under all return periods to obtain the expected annual loss (EAD), and EAD can be calculated using Eq. (2).

\[ L = \sum_{i=1}^{n} (E \times V) \]  
\[ EAD = \int x f(x) \, dx \]  

where \( L \) is the losses of the elements at risk; \( E \) is the exposed asset (Eq. 1); and \( V \) is the loss rate of the elements at risk under different inundation depths.

2.1.2 Cost-Benefit Analysis

The adaptation measures are economically evaluated through a cost-benefit analysis (Aerts et al. 2014; Scussolini et al. 2017). The building-code strategies that were used in this study include wet-floodproofing, dry-floodproofing, and building elevation. The costs include both initial investments and maintenance costs (Du et al. 2020; Shan et al. 2021). The benefits are expressed as the reduction in EAD from the current level. For each strategy, the net present value, the payoff period, and the benefit/cost ratio are estimated.

Net Present Values: Net present value provides the amount of net economic benefits that an adaptation strategy generates. The discount rate is a key indicator of cost-benefit evaluation, with great uncertainty and time dynamics (van den Bergh and Botzen 2014). This study used three discount rates: the Chinese official discount rate of 8% as a higher bound, a lower-bound discount rate of 4% to reflect the long-term benefits of investments, and an in-between rate of 6%, all of which have been applied in relevant studies (Du et al. 2020; Shan et al. 2021). It can be calculated using Eq. (3) (Aerts et al. 2014):
Real option analysis (ROA) is a probabilistic decision-making process. When irreversibility and uncertainty are the key characteristics of decision-making problems, ROA can assess the flexibility and adaptability of future decisions. Real option analysis evaluates the value of two options: (1) the continuation value, which is an option value when the option is deferred; and (2) the termination value, which is an option value when the option is implemented (Kim et al. 2019). The real option value in any given year \( t \) can be defined by Eq. (5):

\[
R_t = \max \left[ R_{\text{con},t}, R_{\text{ter},t} \right]
\]

where \( R_t \) is an option value in the year \( t \), which is the higher of the two values; \( R_{\text{con},t} \) is a continuation value in year \( t \); and \( R_{\text{ter},t} \) is a termination value in year \( t \).

The termination value \( R_{\text{ter},t} \) at any year \( t \) is the net present value of the investment made in year \( t \). It can be calculated using Eq. (6):

\[
R_{\text{ter},t} = \sum_{i=t+1}^{T} \frac{EAB_i}{(1 + r)^i} - \frac{I}{(1 + r)^t}
\]

where \( EAB_t \) is the expected annual benefit of the project at year \( i \); \( r \) is a discount rate; \( I \) is investment cost; and \( L \) is the service life of adaptation measures.

A continuation value \( R_{\text{con},t+1} \) and a termination value \( R_{\text{ter},t+1} \) are values that the option holder can expect in year \( t+1 \); the continuation value at year \( t \) is the higher one of these two values discounted from year \( t+1 \) to year \( t \). It can be calculated using Eq. (7):

\[
R_{\text{con},t} = \frac{1}{(1 + r)} \times \max \left[ R_{\text{ter},t+1}, R_{\text{con},t+1} \right]
\]

The calculation of the continuation value and the termination value starts from the end of the waiting period \( T \), using a backward induction method (Kim et al. 2019). The backward induction method requires a boundary value at the end of the time horizon for option evaluation. This study set the end year at 2100.

### 2.1.3 Real Options Analysis

2.2 Study Area

Shanghai had a permanent population of 24.88 million in 2020, making it one of the most populous estuary megacities in the world. Shanghai is located on the coast of the Northwest Pacific, with the East China Sea to the east and Hangzhou Bay to the south. The terrain is low and flat, and the city is extremely sensitive to sea level rise and typhoon storm surges. One of the deadliest storm surge events that killed more than 29,000 people in Shanghai occurred in 1905; Typhoon Winnie killed seven people and flooded more than 5000 households in 1997. In August 2005, Typhoon Maisha hit the urban area of Shanghai and thousands of houses were flooded, followed by Typhoon Fitow in 2013, Typhoon Lekima in 2019, and Typhoon In-fa in 2021. These events exhibited large uncertainty in timing, magnitudes, and damages to Shanghai. The rainstorms brought by the typhoons may cause a rapid increase in river network flow, and land subsidence and insufficient drainage capacity in Shanghai have also exacerbated the rainstorm and waterlogging disasters in low-lying areas. In the future, climate change, sea level rise, land subsidence, and rapid urbanization will increase the risks of extreme storm floods in Shanghai (Wang et al. 2018). The study area consists of 16 districts, among which Putuo (PT), Hongkou (HK), Yangpu (YP), Changning (CN), Xuhui (XH), Jingan (JA), and...
Huangpu (HP) Districts are located inside the Outer Ring, constituting the city center of Shanghai (Fig. 4).

2.3 Data

The data used in this study mainly include extreme storm floods in Shanghai, land use data, Shanghai’s building data, and building cost data.

2.3.1 Extreme Storm Floods

A simplified 2D flood inundation model (FloodMap Inertial) was used to simulate dike failure-induced flooding and to derive inundation maps. For the risk decision of sea level rise, the upper limit scenario is usually considered (Hinkel et al. 2015). The representative concentration pathways RCP8.5 and RCP2.6 (the lower limit scenario of sea level rise) were used to estimate the multiple climate change scenarios and probability of future sea level rise. All relative sea level projections by 2100 are given with the baseline year of 2010 (Yin et al. 2020). Then, according to the height and structure of the river embankments along the Shanghai coast, the overwhelming and breaching discharges of storm surges in 1/10, 100, and 1000-years are calculated. A 2-day (48 h) tidal cycle including four rising phases and four falling limbs is applied in the flood simulations. The two-dimensional hydrodynamic model (FloodMap-Inertial) was used to simulate the baseline year (2010) and future (2030, 2050, and 2100) flood inundation depths of extreme storm floods under the RCP8.5 and RCP2.6 scenarios, with a spatial resolution of 50 m by 50 m. Figure 5 shows the most extreme storm flood inundation map in Shanghai under the RCP8.5 scenario. The simulation results have been verified and used in previous research (Yin et al. 2020; Shan et al. 2022).

2.3.2 Land Use Type

The land use data of Shanghai in 2010 were provided by the Shanghai Institute of Surveying and Mapping. Shanghai’s land use data in 2030, 2050, and 2100 are based on the 2010 land use data and were simulated using the FLUS model.
with a spatial resolution of 50 m by 50 m. The Kappa coefficient and figure of merit index were used to quantitatively assess the simulation results, which show that the simulated land use has high accuracy and meets the research needs (Shan et al. 2022).

2.3.3 Building Data

The building data of Shanghai in 2017 included the buildings’ footprint and height information, which were obtained from Baidu Map using a python-based web crawler and then processed by a GIS software. The resulting total buildings’ area is 1238.2 km². Shan et al. (2019) selected one of the Shanghai building types—residential buildings—and used Google Earth high-precision remote sensing images to evaluate the accuracy of residential building data, which proved that the accuracy is high. Based on the spatial distribution of buildings in 2017 and according to the residential, commercial, public, and industrial land areas in 2030, 2050, and 2100, the area of residential, commercial, public, and industrial buildings in Shanghai in 2030, 2050, and 2100 can be obtained according to a certain proportion coefficient. The results show that the total buildings’ area of Shanghai in 2030, 2050, and 2100 is 1518.1 km², 1739.4 km², and 1879.4 km², respectively.

2.3.4 Building Cost Data

The completed construction floor area and cost of construction by building use type were obtained from the Shanghai Statistical Yearbooks (1995–2019). The construction cost per square meter was calculated by dividing the cost of construction of buildings completed by the building floor area completed, which was applied in the study by Wu et al. (2019). For the prediction of the construction cost of residential buildings, commercial buildings, and public buildings, a polynomial curve was fitted on the future construction cost trend, by assuming that this trend will continue until 2050. Industrial building construction cost was based on the construction cost report of China’s mainland and Hong Kong released by the construction engineering consulting company ARCADIS, which published the construction cost of different building types in Shanghai. According to a certain average annual growth rate, the cost of industrial construction in 2050 is predicted. Due to the uncertainty of future building costs on a long-term scale, this study assumed that the building cost in 2100 will remain the same as in 2050.

1 https://map.baidu.com.

2 http://tjj.sh.gov.cn/tjni/index.html.

3 https://www.arcadis.com/en.
3 Results

This section presents the results of this study, which include dynamic changes of flood risk; performance of adaptation measures; and robust decision making of adaptation strategies under deep uncertainties.

3.1 Dynamic Change Analysis of Flood Risks

Under the RCP2.6 and RCP8.5 scenarios, the exposed area of the four types of buildings in Shanghai in 2100 will be 905.9 km² and 1010.9 km² respectively—that is 4.6 times and 6.4 times the 1/10-year flood, respectively—and the exposed assets will be 5–9 times larger in value. Of the 16 districts, the exposed building assets are mainly concentrated in the waterfront districts of Pudong and Baoshan and the city center under the two emission scenarios. Pudong has the largest proportion of exposed assets, accounting for about 30–33% of the total exposed assets. For the 1/1,000-year floods, the exposed assets of Shanghai city center amount to 33.3% in 2100.

The spatial pattern of building losses changed from a scattered distribution at the 10-year return period to a contiguous distribution at the 1000-year return period, with a total of USD 15.93 billion for the 1000-year floods under the RCP8.5 scenario, which is 10.6–17.9 times the 10-year flood losses (Fig. 6). Of the 16 districts, the loss of buildings is mainly concentrated in Pudong and Baoshan Districts and the city center. For different building types, residential building losses in 2100 are the largest at USD 6.52 billion, followed by commercial buildings with USD 3.81 billion in losses and public buildings with USD 3.66 billion in losses; industrial buildings have the smallest losses at USD 1.94 billion.

The annual exceedance probability (AEP)-loss curves of extreme flooding for Shanghai’s buildings under the RCP8.5 and RCP2.6 scenarios are based on the losses under three flood return periods. The expected annual damage (EAD) was calculated by Eq. (2). In the current scenario, the EAD of Shanghai’s buildings in 2010 was USD 22.35 million/year. Under the RCP2.6 scenario, the EAD of the buildings is 2–10 times that of the current scenario. Under the RCP8.5 scenario, the EAD of the buildings in 2030, 2050, and 2100.
Fig. 6 Distribution of extreme storm flood losses for residential, commercial, public, and industrial buildings in Shanghai under the current and RCP8.5 scenarios.

is USD 40.01 million/year, USD 79.71 million/year, and USD 259.30 million/year, respectively—that is 2–15 times that of the current scenario. Pudong, Baoshan, and Xuhui Districts have the highest EAD. The EAD of the city center in 2010, 2030, 2050, and 2100 accounts for 27.7%, 29.6%, 32.7%, and 40% of the total, respectively.

3.2 Performance of Adaptation Measures

Using Eqs. (3) and (4), the net present value and benefit/cost ratio of dry-floodproofing, wet-floodproofing, and elevation are obtained under different discount rates (4%, 6%, 8%) (Fig. 7). Under the RCP2.6 scenario, the implementation of the three flood adaptation measures will effectively reduce the risks of Shanghai’s buildings in 2030, 2050, and 2100. If we implement wet-floodproofing in Shanghai in 2030, the net present value is USD 0.59–0.88 billion and the benefit/cost ratio is 6.87–7.54. The net present value and benefit/cost ratio in 2100 are 10.8–14.0 times and 0.8–1.1 times of 2030, respectively. Combining the dry and wet-floodproofing measures to form a “combined” strategy leads to a net present value of USD 0.41–0.64 billion and a benefit/cost ratio of 2.23–2.46 in 2030. It can be concluded that the “combined” strategy cannot generate good benefits in the near future (2030); however, the net present value and benefit/cost ratio in 2100 are 18.6–29.5 times and 3.3–4.3 times the 2030 values, respectively. We also formulated a “hybrid” strategy by combining dry-floodproofing, wet-floodproofing, and elevation, which has a better performance in terms of low residual risk and high benefit/cost ratio. The net present value and benefit/cost ratio in 2100 are USD 6.95–17.81 billion and 4.37–6.36, respectively. Under the RCP8.5 scenario, the net present value and benefit/cost ratio of wet-floodproofing implemented in 2100 will be 9.0–15.0 times and 1.3–1.4 times the 2030 values, respectively. Comparing the net present value and benefit/cost ratio of the three flood adaptation measures, wet-floodproofing measures have the best flood control outcome, followed by dry-floodproofing, and elevation. The net present values of the combined strategy (dry- and wet-floodproofings) and the hybrid strategy (dry- and wet-floodproofings and elevation) in 2100 are USD 7.21–14.20 billion and USD 6.44–13.29 billion, respectively. Correspondingly, the benefit/cost ratios are 4.79–6.19 and 3.08–3.99, respectively. The net present value and benefit/cost ratio of the hybrid strategy are significantly higher than those of the individual measures as well as the combined strategy. However, its cost is higher in the shorter term.
Therefore, the hybrid strategy is suitable for long-term planning.

Under the RCP2.6 and RCP8.5 scenarios, through the implementation of flood adaptation measures, the changes in Shanghai’s building EAD before and after the implementation of the measures were evaluated and compared (Fig. 8). Under the RCP8.5 scenario, after the implementation of dry-floodproofing, the annual benefits (that is, the reduction in EAD) of the four types of buildings can reach USD 37.04 million to USD 169.74 million. In addition, after the implementation of wet-floodproofing, the annual benefit is USD 38.61 million to USD 202.88 million; after the implementation of elevation, the annual benefit is USD 26.73–136.45 million. The annual benefits of implementing dry-floodproofing, wet-floodproofing, and elevation measures in 2030 is USD 37.04 million, USD 38.61 million, and USD 26.73 million, respectively. After the implementation of all three measures, the annual benefits of the four types of buildings in 2100 is USD 169.74 million, USD 202.88 million, and USD 136.45 million, respectively. These results show that the adaptations tend to generate better benefits in the long term, indicating that other coastal cities should begin their adaptation plans as early as possible.

### 3.3 Robust Decision Making of Adaptation Strategies Under Deep Uncertainties

We used Eqs. (5)–(7), the continuation value, and the termination value of the three flood adaptation measures to determine the best time for investment. The optimal investment time was determined by checking whether expected
The annual benefit (EAB) reaches the critical threshold value (Table 1). We found that the critical threshold of the optimal investment time highly depends on the investment cost and discount rate. The more extreme the sea level rise scenario is (that is, RCP8.5), the earlier the optimal investment time appears. Therefore, a rapid sea level rise requires an immediate investment to obtain the maximum benefit value.

Under the RCP2.6 and RCP8.5 scenarios, the dry-floodproofing measure can be used in the initial period of 2033 and 2036. With time lapses, the performance of the dry-floodproofing may drop, and wet-floodproofing implemented in 2035 and 2042 will obtain better economic benefits. The elevation measures also show good performance at the beginning of implementation, but the performance will decline after 2041–2045. Dry-floodproofing and wet-floodproofing measures can be transformed into the combined strategy in 2044–2046. The combined strategy can be upgraded to the hybrid strategy in 2047–2051.

Figure 9 shows the optimal investment time for the three adaptation measures. Under the RCP2.6 and RCP8.5 scenarios, the dry-floodproofing measure is implemented first. Under the RCP2.6 scenario, after the wet-floodproofing
measure is implemented for 6 years the elevation measure is implemented, while under the RCP8.5 scenario, after the implementation of the wet-floodproofing measure for 3 years the elevation measure is implemented immediately.

Meanwhile, in order to enable decision makers to make robust decisions, three considerations were integrated: (1) economic benefits of measures; (2) the continuation value and the termination value; and (3) tipping points. The dynamic pathways for Shanghai’s future buildings to adapt to flood risks were formulated for both the short and long terms and are presented in Fig. 10. The figure shows a variety of adaptation pathways, and the tipping point of adaptation can be evaluated from the effectiveness of adaptation measures. A tipping point is the time period during which a given measure no longer meets its goal. These tipping points can be expressed in terms of the progression of the analyzed climate variable (that is, sea level rise) on a temporal scale. Through this map, the decision maker will know when to implement the investment in order to generate the largest net benefit (that is, the overall benefits minus the overall costs). It is necessary to point out that the timely switch between adaptation measures critically depends on periodic monitoring of the sea level rise and revising the estimations of its impacts and the effectiveness of existing measures.
4 Discussion

Future uncertainties in climate change and sea level rise pose a major challenge to flood risk management and adaptation in coastal megacities. This study applied an integrated modeling framework to assess the flood risk, provide a cost-benefit analysis of adaptation measures used to reduce risks, and coupled a ROA analysis with the concept of DAPP. Taking Shanghai as a case study, we developed a multidisciplinary approach to understand impacts and adaptation of coastal cities to sea level rise. We have found that sea level rise and land subsidence will significantly exacerbate the flood risks in Shanghai. Under RCP2.6 and RCP8.5, we identified that buildings with high risks are located in the city center and along the banks of the Huangpu River. We also found that with the rise of the sea level caused by climate warming, under the RCP8.5 scenario, the loss of Shanghai’s buildings in the future (2030, 2050, and 2100) accounts for 4.6%, 5.2% and 8.8% of the exposed assets, respectively. Climate change and sea level rise further increase the risk of flood, which are also a signal for other coastal megacities to plan for early adaptation in highly exposed and economically important areas.

The formulation of climate change adaptation measures needs to fully consider the uncertainty of future climate change in order to find a reliable solution for planning and design of flood control infrastructures. According to Yin et al. (2020), if no adaptation measures are taken, the risk faced by Shanghai is expected to increase by 3–160 times by 2100, which may repeat the tragedy of New Orleans. The results of this study show that the EAD of Shanghai’s buildings will increase by approximately 15 times in 2100 under the RCP8.5 scenario. Under the current, RCP2.6, and RCP8.5 scenarios, the three flood adaptation measures advocated in this study—through the use of building codes to reduce the exposure and vulnerability of the elements at risk—can effectively reduce the risks faced by Shanghai’s buildings in the future. Compared to the adaptation effects of dry- or wet-floodproofing, the effect of the elevation measure is smaller. Wang et al. (2015) showed that raising the elevation of old buildings may not bring substantive benefits at all, because the moderate long-term benefits may be offset by a large amount of social costs and high building renovation costs. Lifting new buildings separately is more cost-effective, easier to accept by society, and an easier policy to implement. Therefore, in the future risk adaptation in Shanghai, if the elevation measure is adopted, it should consider new buildings, where the maximum benefit will be obtained. In addition to adopting the three measures proposed in this study, for newly built low-lying communities, floor elevation of the lowest floor must exceed the local flood warning line.

From the perspective of decision support, the future challenge is not only the improvement of technical means, but also the application of risk assessment models to practical decision making, which is reflected in how to deal with uncertainty in the decision making process and quantify adaptation measures, and how to promote communication with decision makers and stakeholders. The combination of ROA and DAPP methods can help decision makers distinguish the advantages and disadvantages of the implementation results of their plans, and formulate the optimal combination of adaptation strategies and flexible adaptation pathways. The ROA and DAPP methods have been increasingly used to design or plan urban development for decades (Woodward et al. 2014; Buurman and Babovic 2016). Although Shanghai has established a system of policies and measures to adapt to climate change, there is a lack of a dynamic adaptation pathways map of measures for decision makers and stakeholders. The comprehensive analysis of ROA and DAPP can guide decision makers to make robust decisions, and provide a reference for flood risk adaptation in other coastal cities and delta areas.

There are some limitations to our study. First, the vulnerability curve established by Ke (2014) was used to evaluate the loss of buildings in Shanghai in 2030, 2050, and 2100. With the acceleration of urbanization and the renewal of the city, the flood vulnerability of buildings may change dynamically and need an updated vulnerability curve. Second, due to the current rapid urbanization process and many uncertain factors, there are inevitably limitations in the prediction of the spatial distribution of buildings and costs in the long term, especially for 2050 and 2100. In future research, Internet big data and machine learning methods can be adopted to map the building footprint, height, cost, and economic values, providing higher resolution spatial and economic information of elements at risk.

5 Conclusion

This study integrated risk analysis, cost-benefit analysis, real options analysis (ROA), and dynamic adaptive policy pathways (DAPP) methods to analyze the flood risk, adaptation measures, and adaptation decision making of coastal cities. With the case study in Shanghai, we quantified the future risks of buildings under extreme storm flooding scenarios for 2030, 2050, and 2100, analyzed the cost and benefit of three flood adaptation measures to reduce flood risk, and formulated the adaptation dynamic pathways for decision making. The main conclusions are:

(1) Sea level rise, land subsidence, and socioeconomic development will cause a sharp increase in the potential future flood risk. Under the RCP8.5 scenario, the EAD of the buildings in 2030, 2050, and 2100 will be 2–15 times that of the current scenario.
(2) Three adaptation measures based on building codes can effectively reduce the risks of Shanghai’s buildings in 2030, 2050, and 2100. Wet-floodproofing has the best flood control effect, followed by dry-floodproofing and building elevation.

(3) In terms of the adaptation pathways, we found that the flexible transformation of adaptation measures can achieve the highest economic benefits. Dry-floodproofing can be used in the initial period of 2033 and 2036, and should be replaced by wet-floodproofing in 2035 and 2042 under the RCP2.6 and RCP8.5 scenarios. The elevation measures also showed good performance at the beginning of implementation, but the gain in benefit will decline after 2041–2045. Dry-floodproofing and wet-floodproofing measures can be used together to form a combined strategy in 2044–2046. A hybrid strategy of dry- and wet-floodproofing and elevation measures can be adopted in 2047–2051.

However, future changes in storminess were not considered in the extreme storm flood simulation, and the cost effectiveness of adaptation strategies should be higher if their benefit of reducing indirect flood risk were considered. Moreover, the performance of adaptation strategies should be explained in terms of residual flood risks. Future studies can be improved through incorporating these aspects.

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