https://doi.org/10.5194/hess-2024-391
Preprint. Discussion started: 17 January 2025

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Robust Adaptive Pathways for Long-Term Flood Control in Delta Cities: Addressing Pluvial Flood Risks under Future Deep Uncertainty

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Abstract:

Delta cities are increasingly vulnerable to flood risks due to the uncertainties surrounding climate change and socioeconomic development. Decision-makers face significant challenges in determining whether to invest in high-level flood defenses for long-term planning. Adaptation solutions should be given considerable attention not only to robustness but also to adaptiveness if the future unfolds not as expectation. To support decision-making and meet long-term multi-objective targets, we propose a synthesized framework that integrates robustness analysis, adaptiveness analysis, and pathway generation. This framework was applied to evaluate alternative solutions for

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managing pluvial flood risk in central Shanghai. The results show that using a single-objective decision-making approach (focused only on robustness) tends to yield biased options. By examining the valid period and flexibility of candidate solutions, we assessed whether alternative solutions could meet long-term flood control targets. The analysis reveals that a combined option—incorporating increased green areas, an improved drainage system, and a deep tunnel with a 30% runoff absorption capacity (D+G+Tun30)—is the most robust and adaptive pathway, based on multi-objective trade-off analysis. This study highlights the importance of considering valid period within predefined control targets and retaining flexibility to avoid path-dependency and minimize long-term regrets. The proposed framework can be applied to other delta cities to guide adaptive responses to future flood risks.

Keywords: decision-making under deep uncertainty; flood risk reduction; multi-objective trade-off, robust adaptive pathway, Shanghai

1 Introduction

Flood risk is increasing in low-lying delta cities due to rapid urbanization and climate change (Yang et al., 2023), hindering the capacity of urban development. Delta cities such as Shanghai (Yin et al., 2020), Ho Chi Minh City (Scussolini et al., 2017), and London (Dottori et al., 2023) are facing the combined challenges from extreme rainstorms, sea level rise and urbanization-induced land subsidence with regard to flooding risk reduction (Ward et al., 2017). It is anticipated that as a result of changing climate patterns, the frequency and severity of extreme flood events will increase in urban area, thereby increasing the flood risk, particularly in increasing developing delta

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cities (Sun et al., 2021).

Delta cities are urged to examine potential climate adaptation options (Han and Mozumder, 2021;) and test their cost-effectiveness in designed social and climate scenarios to address the rising flood risks (Lin et al. 2020). Dottori et al (2023) proposed ~~economically attractive~~ strategies for European cities to deal with increasing river flood risk ~~from cost-effective point of view~~. However, if these strategies or options will remain effective within a fixed timeframe under the uncertainties of climate change, land use change or political change is questionable; in addition, how ~~flexible~~ these strategies can be up-scaled to meet the future needs is ~~also~~ rarely discussed. This ~~comes to~~ a pressing concern for decision makers in long-term planning. In the field of Decision Making under Deep Uncertainty (DMDU), various approaches have ~~been~~ emerged, such as Robust Decision Making (RDM) (Lempert et al., 2013; Workman et al., 2021), Dynamic Adaptive Policy Pathway (DAPP) (Haasnoot et al., 2013; Dias et al., 2020) and Real Options Analysis (ROA) (Buurman and Babovic, 2016; Kim et al., 2018; Xu et al., 2023).

These DMDU approaches have been continuously improved and optimized, the boundaries between methods have become increasingly blurred, and fusion thinking is progressively adopted (Haasnoot et al., 2020). As pointed out by Lempert et al. (2003), RDM provides systematic procedures that emphasize the iterative analysis process of scenario exploration, which can help decision-makers discover situations where options may fail, and understand the trade-off among all the adaptation options (Lempert et al., 2013). Kasprzyk et al. (2013) proposed the Multi-Objective Robust Decision Making

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(MORDM) approach by the combination concept of both multi-objective evolutionary optimizations and RDM (Bartholomew and Kwakkel, 2020; Yang et al., 2021). Kwakkel et al. (2019) pointed out that the RDM approach usually pays less attention to the dynamic planning of pathways on long-term scales of climate change. On the other hand, DAPP, which consist of the strengths of both Adaptive Policymaking (Walker et al., 2001) and Adaptation pathway (Haasnoot et al., 2012; Ranger et al., 2010), focuses on generating alternative dynamic pathway to achieve flexibility and avoid lock-in effects while it lacks robustness metrics (i.e. satisficing and regret) and vulnerability analysis to quantify potential failures (Haasnoot et al., 2013).

Both the RDM and DAPP approaches are arguably ~~in~~ most widely applied, and the concept of integrating two approaches has been proposed (Kwakkel et al., 2016) and practiced in cases (Tariq et al., 2017). However, as Ramm et al. (2018a) illustrated, integration of RDM and DAPP has not been thoroughly implemented, and future opportunities to engage with participants in a combined RDM and DAPP approach include defining adaptation objectives, metrics and risk tolerance (Ramm et al., 2018b) since all these factors are anticipated to largely influence the outcomes of alternative pathways Robustness emphasizes the ability of a strategy to perform in an effective way in many plausible scenarios. How to define robustness and assess whether options are insensitive to deep uncertainty to ensure certain performance across multiple plausible futures have sparked extensive discussions, especially when meeting multi-objective targets (Herman et al., 2015; McPhail et al., 2018).

The selection of indicators for robustness depends on the priorities and preferences

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by policymakers and it will substantially affect the outcomes of decisions (Giuliani and Castelletti, 2016). For example, the decision-makers who endorse risk aversion may under-estimate adaptation options' performance. To overcome the single objective problem framing, Quinn et al. (2017) optimized operations of the four largest reservoirs under several different multi-objective problem framings in Hanoi city (Vietnam), and highlighted the importance of formulating and evaluating alternative stakeholder objectives.

However, there is a need for a discussion on either the robustness evaluation of alternatives concerning policymakers' risk aversion can exclusively underpin rational decision-making or the multi-objective trade-off analysis can offer more comprehensive practical and theoretical support. For example, the cost of a climate adaptation option is normally proportional to its benefit (risk reduction rate). Options with high performance often mean higher cost input and potentially longer construction periods (Dottori et al., 2023). The single-objective in either performance assessment in reducing the risk or solely considering cost-benefit provided limited information for long-term planning, indicating a potential for lock-in or path dependency due to overinvestment or maladaptation over time.

Adaptiveness refers to the ability of a strategy to adapt to change (Haasnoot et al., 2013; Malekpour et al., 2020). In this sense, maintaining high level of robustness compromise high level of adaptiveness of a strategy as conditions change. For example, high cost of effective solution may cause path-dependency and fails to adapt to the changing circumstances due to its financial commitment and over-confidence on the

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safety from societies. Considered as the other side of coins against robustness, quantification of adaptiveness is yet clearly addressed (Kind et al., 2018). Tipping point analysis provided insight into when the options might falter, indicating potential failure point concerning the risk reduction target (Haasnoot et al., 2013), and Patient Rule Induction Method (PRIM) is proven to be illuminated to identify the use-by date of tipping points in a quantitative way (Ramm et al., 2018a; 2018b). Kirshen et al. (2015) raised that the option of selecting urban flood control options may differ if additional criteria of no-regret and flexibility were considered, when a critical threshold is reached under a climate change scenario. Instead of applying optimal here-and-now options, wait-and-see decisions allow for flexibility. Within ROA, flexibility is valued since it allows delaying commitment to large, costly, and irreversible decisions while either exercising different interventions or incrementally implementing interventions with long construction times until more information is available (Erfani et al., 2018). Therefore, incorporating both the tipping point (specify as valid period later in this paper) and flexibility reflect the key characteristics of adaptiveness and thus better assists in a long-term planning

In this study, we aim to propose a synthesized framework which incorporates both robustness and adaptiveness to formulate a robust adaptive pathway for long-term climate adaptation planning under deep uncertainties. This framework can be utilized to guide decision-making on the prioritization and sequencing of climate adaptation alternatives, which nowadays remains as a pressing question for urban practitioners on climate action planning. To demonstrate the novel synthesized framework, it was

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applied to examine various climate adaptation alternatives to address the increasing pluvial flood risk in a delta city – Shanghai, based on future (uncertain) scenarios of a combination of extreme rainstorm and the deteriorating drainage capacity by the time of 2050s, to support the decision-making.

The remainder of this article is organized as follows: Section 2 presents the proposed comprehensive framework and methodology. Section 3 introduces the background of the case study area and the preprocessing procedures. Section 4 presents the results, where a multi-objective trade-off is applied to evaluate the potential pathways for generating a robust adaptive pathway. This analysis combines metrics such as the average risk reduction rate (ARRR), benefit-cost ratio (BCR), valid period, and flexibility of all options. Section 5 discusses the key findings related to pluvial flood risk management in coastal cities, the implications of multi-objective trade-off considering both robustness and adaptiveness, how the synthesized framework can inform long-term adaptive policy formulation, and provides recommendations for future work. Finally, Section 6 concludes with a summary.

2 Methodologies

2.1 Framework development

Having established the challenges of pluvial flood risks posed by future deep uncertainties, this study now presents a robust adaptive pathway framework designed to support long-term planning. To build robust adaptive pathway framework, we extended the taxonomy proposed by Kwakkel et al. (2019), which categorizes existing DMDU approaches into five dimensions, akin to the taxonomy in the robustness framework (Herman et al., 2015). Building on recent advancements in DMDU approaches, we further refined the framework into the following procedures:

1) **Research framing.** In contrast to the short-term implementation of baseline standards, the policy structure proposed in this work is designed to be dynamic and adaptive. It provides a continuous pathway toward achieving long-term flood control goals while maintaining the flexibility to adjust to an uncertain future. As a result, the 'adaptive' options enhance the robustness of the solutions and reduce the risk of over-investment.

2) Scenario generation. The process of scenario generation applies multiple (uncertain) ~~factors of~~ meteorological, hydrological, or social-economic. The range of uncertain factors may ~~either~~ according to expert's opinion, policy guideline or climate projections (Lempert et al., 2013). Plausible futures can be generated via scenario sampling algorithms as of Latin Hyper Cube Sampling **(**Workman et al., 2021**).**

3) Alternative generation. Climate adaptation alternatives were developed through focus-group discussions during a workshop and an analysis of policy documents. The workshop included key stakeholders such as flood experts, policymakers, and residents. As a result, the existing flood options serve as the baseline scenario, compared to the generated climate adaptation alternatives which are set to be evaluated using flood modelling.

4) Model simulation. Flood inundation models such as SOBEK1D2D, Mike1D2D (Wang et al., 2018) and Info Works can be used to simulate flood routing process and produce maximum inundation maps, which further can be used for flood risk assessment when incorporating the geospatial statistics.

5) Robustness analysis. To evaluate the robustness of all options that have the highest utility under a certain threshold, robustness metrics (e.g. Laplace's principle of insufficient reason) were used as the decision-making criterion. The calculation of indicators such as the average risk reduction rate (ARRR) and benefit-cost ratio (BCR) for each alternative option was performed for each scenario, with an assumption of equal probability for their occurrence. Subsequently, the performance of each option and its combination was evaluated by quantitative comparison and ranking stability (McPhail et al., 2018).

6) Adaptiveness analysis. Valid periods of the alternative options were determined based on the conditions of the successful scenarios under each (individual or combined) option, in conjunction with a specific flood control objective. Optimizing the value of coverage and density of subspace in the PRIM (Patient Rule Induction Method) algorithm help to identify signposts in the adaptation pathway which is in line with the idea of the tipping point in DAPP. Flexibility is evaluated by the ability of convertibility.

7) Multi-objective trade-off. Multi-objective trade-off was implemented using robustness and adaptiveness metrics to evaluate the candidate alternatives. All the metrics are given equal weight and are compared based on their normalized values. The alternative options with highest score to satisfy all the objectives are regarded most promising.

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8) Robust adaptive pathway. In light of the adaptability of the valid period (tipping point) and flexibility of transitions in each alternative portfolio, potential pathways were identified, and generated a roadmap based on transient scenarios. A robust adaptive pathway was selected in multi-objective to satisfy the flood control criteria for long-term planning. The signposts can be monitored to support future decisions.

2.2 Methods of robust adaptive pathway procedures

Robustness analysis

The choice of robustness option is the meta-problem of how to decide (Herman et al., 2015). The performance of a system is frequently described by robustness option when dealing with a decision-making process, including significant uncertainty. Various robustness metrics, including Maximax, Maximin, Mean-variance, Starr's domain criterion, Laplace's principle of insufficient reason, etc., are used to evaluate a system's performance in various scenarios (state of the worlds). Different robustness metrics represent distinctive risk preferences, and the selection of robustness indicators influences the choice of alternative options (Giuliani and Castelletti, 2016). For the risk aversion metric, the Laplace principle of insufficient reason is widely documented to help identify the solution that performs best in neutral risk aversion. Furthermore, it suggests that in the absents of knowledge of the probabilities associated with the different scenarios, the decision could be taken by assigning equal probability to all scenarios. The performance of option i is depicted as Equation (1).

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$$a_p = arg\max_{a}\left(\frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n} f\left(a_i, w_j\right)\right) \quad (1)$$

Where a_i is option i of alternative options set (a) (listed in table 2), and w_j is in the scenario set w. $f\left(a_i, w_j\right)$ represents the option performance value of scenario j, a_p is the selection of option p with best performance.

Satisfaction and regret are frequent indications of robustness options in RDM decision-making procedures (Herman et al., 2015). Broadly, regret quantifies the cost (not necessarily monetary) of choosing incorrectly. It can be defined as the cost of a single solution, associated with the deviation from its baseline performance. On the other hand, satisfaction can be defined as the amalgamation of effectiveness and efficiency. In this situation, the evaluation of candidate options' performance is presented as the deviation from the baseline performance. see Equation (2).

$$P_i = \frac{1}{n}\sum_{i=1}^{m}\sum_{j}^{n}\frac{\left|f(a_i,w_j)-f(a_0,w_j)\right|}{f(a_0,w_j)} \quad (2)$$

Where P_i is the average performance of alternative options, $f\left(a_i, w_j\right)$ represents the performance value of scenario j, and $f\left(a_0, w_j\right)$ is the performance of the baseline option of scenario w_j.

Decision-makers care that whether the scenario sets of alternative options contain an unacceptable possibility. The threshold for vulnerable scenarios defines whether there is an intolerable risk control level. The domain criterion quantifies the volume of the uncertain factor space in which a solution meets the decision-makers' performance requirements. Indicators of risk control policy are frequently included in the research, such as local environmental protection legislation, urban drainage planning, and other documents. They can also provide appropriate reference opinions determined by local

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governments or relevant decision makers and experts. Based on the elicitation of local requirements, we define the P_i^* as the average performance of risk reduction which satisfies the minimum threshold of the given flood control target (F_0, F_0=0.7 in this case), as depicted in Equation (3).

$$P_i^* = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n} f\left(a_i, w_j\right) \geq F_0 \quad (3)$$

Where P_i^* represents the average performance value of the option a_i in all plausible scenario that meets the given flood control target F_0.

Internationally, the net present value of benefits (PVB) and the net present value of costs (PVC) are commonly used to represent benefits and costs, respectively (Liao et al., 2014). In this study, PVB is selected as the pluvial flood risk reduction rate (RRR) before and after the implementation of the options, rather than as the pluvial flood risk reduction value. It is important to note that the goal of this study is not to calculate the direct risk of extreme pluvial flooding in the future, as the absolute value of the risk would be too large for meaningful comparison. Therefore, the benefit-cost ratio (BCR) is presented simply as the ratio of PVB to PVC.

Adaptiveness analysis

PRIM is an interactive statistical clustering algorithm that generates a series of subspaces by peeling away layers of the uncertainty space, where the coverage and density of points of interest in each box are greater than in the surrounding space (Matrosov, 2013). As a visualized tool for exploratory analysis, PRIM is widely used in many works to investigate either key factors causing system failure or vulnerable scenarios that might cause alternative options' failure. Parameters of coverage, density, and interpretability characterize the subspaces. These three metrics are usually correlated, with increasing density resulting in decreasing coverage and interpretability. It turns out that an analyst needs to trade-off in selecting the potential coverage, density, and interpretability to achieve the best combination. The subspaces describe the conditions beyond which coastal inundation impacts are unacceptable signifying adaptation tipping points are reached (Ramm et al., 2018a). Key factors along with the tipping point of options are evaluated in associated timeframes which need not be exact. Identifying an indicative period at which conditions describing adaptation tipping points indicate a valid period (or use-by year) (Haasnoot et al., 2013). The results of PRIM can assist decision-makers in identifying sensitive ranges of uncertain factors or combinations, and factors with little influence can be safely disregarded.

Following a decision initially, flexibility in decision theory is related to the remaining choices available in the following period. The larger this set, the more flexibility the decision maker retains. This idea can be generalized to staged choices over multiple periods. For example, Erfani et al. (2018) proved that flexibility is valuable in providing decision nodes in multistage scenarios (planning periods in every 5 years) for least-cost water supply intervention scheduling. One way of deriving the value of flexibility is thus by comparing costs and benefits of a flexible investment strategy with those of a less flexible, that is, a more robust strategy (Kind et al., 2018). However, flexibility is not treated as delayed option value as other ROA work calculated, instead, we consider the convertibility of options that is still in line with the

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idea of wait-and-see yet is more straight-forward.

Multi-objective trade-off

The cost and benefit of investment in adaption options may lead to a static decision-making perspective. Therefore, an important question was raised for robust decision-making of how to avoid failure scenarios regarding factors including risk reduction rates over time, cost of option, and economic benefit ratio. On this basis, making robust decisions needs to include other factors beyond cost and benefit, such as valid period and flexibility, for a comprehensive evaluation in the long-term (Erfani et al. 2018)

The optimization of options' combinations can be identified via the trade-off process by Equation (4).

$$Maximize\ F(l_{p,r}) = (y_{flexibility}, y_{valid\ period}, y_{cost-benefit}, y_{performance},) \quad (4)$$

$$\text{Where } l_{p,r} = [p_i, r_i]\ \forall p \in P;\ \forall r \in R$$

Where lp,r represents the pathway scheme, r_i is any of the robustness metric set R. $y_{flexibility}$ $y_{valid\ period}$, $y_{cost-benefit}$ and $y_{performance}$ are the values of indicators from different dimensional objects.

Robust adaptive pathway

Adaption tipping points (valid periods) are central to adaptation pathways, the conditions under which an action no longer meets the specified objectives. The timing of the adaptation points for a given action, its valid period, is scenario dependent. The DAPP, manually drawn based on model results or expert judgment, presents an overview of relevant pathways (Haasnoot et al., 2020). In this study, we first examined

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the valid period of alternative options by PRIM analysis to identify acceptably robust adaptation pathway for future flood control. We then identified the combination of candidate pathways in consideration of both valid period and flexibility, ensuring the adaptive solutions in incremental stages allow for maintaining flood control levels before committing to larger schemes. Roadmap of candidate's pathways are generated during this procedure. Lastly, the preferred robust pathway is determined by a trade-off analysis of all the criteria.

3 Case study

3.1 Background

Shanghai, with a domain of 6,340 km^2, provides residences to 24.9 million population with a built-up area of 1237.9km^2 in 2021. Shanghai has been perhaps the most important economic and financial center in China, and it now aspires to be one of the world's most important economic, financial, shipping, and trade centers (Shanghai Statistic Yearbook, 2021). Shanghai is surrounded by water on three sides: the East China Sea to the east, the Yangtze River Estuary to the north, and Hangzhou Bay to the south. In addition, the Huangpu River, a Yangtze River tributary, flows through the heart of Shanghai. The average yearly precipitation is approximately 1400mm in recent 10 years, with 63% concentrated during the flooding season from May to September (Shanghai Climate Change Research Center, 2022). As a result, the most catastrophic hazard in Shanghai has been floods produced by torrential rainfall, which annually disrupts transportation and other social activities, causes substantial economic losses, and threatens urban safety.

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Shanghai has the lowest elevation (with averagely 4m above m.s.l.) and large numbers of old-lane residential buildings in central city, which have fewer floors compared to other districts that is vulnerable to the extreme pluvial flood events see Figure 1). The spatial distribution of rainfall will continue to concentrate in urban areas, and the increasing likelihood of extreme precipitation (Liang and Ding, 2017), combined with the trends of relative sea-level, will cause stakeholders, includes residents, policymakers, and scientists etc., to be concerned about the rising flooding risk in delta cities of Shanghai (Du et al., 2020).

Figure 1 Case area, administrative, and solution district (blue shade) in center Shanghai, including spatial distribution of building footprints indicating the number of stories (gray shades), the base map was provided by Esri, using ArcGIS Online Services.

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3.2 Research Framing

Based on the proposed framework, the dimensions, components, and metrics of this study are organized as shown in Table 1. To ensure urban safety, this study defines an explicit flood control objective of achieving a 70% average risk reduction rate, in alignment with the Shanghai Flood Control and Drainage Plan (2020–2035) (Shanghai Municipal Water Authority, 2020).

Table 1 Dimensions of the research framework

Dimension	Components			Metrics
Research framing	Alternative options to generate robust and adaptive pathway			Definition of flood control objective
Scenarios generation	Increased rainfall	Rain island effect	Drainage decrease	Latin hypercube sampling (LHS)
Alternatives generation	Drainage increased	Increase of green area	Deep tunnel with 30%, 50%, or 70% of runoff absorption	Predefined by local flood control plan
Model simulation	Hydrology	Flood risk	Geospatial statistics	Grid aggregation
Robustness analysis	Performance (ARRR)	Measure Cost (Life cycle cost)	Benefit	Laplace and Domain criterion
Adaptiveness analysis	Signpost	Valid period	Flexibility	PRIM
Multi-objective Trade-off	Robustness		Adaptiveness	Metric evaluation
Robust adaptive pathway	Candidate pathway identification, roadmap generation, and monitoring of signposts			Transition scenarios

The robustness analysis serves as the foundation of our methodology, ensuring that the proposed solutions can withstand future uncertainties. Once robustness is assessed, we proceed to the adaptiveness analysis, which allows us to account for flexibility in response to unforeseen challenges. The trade-off optimization in terms of robustness and adaptiveness was of particular significance to providing iterative stress tests over many plausible scenarios using robustness metrics and identifying valid

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periods and flexibility to generate alternative pathways. Following the structure of robust decision-making pathway framework, Figure 2 illustrates the entire procedures for long-term flood control planning in the Shanghai case study.

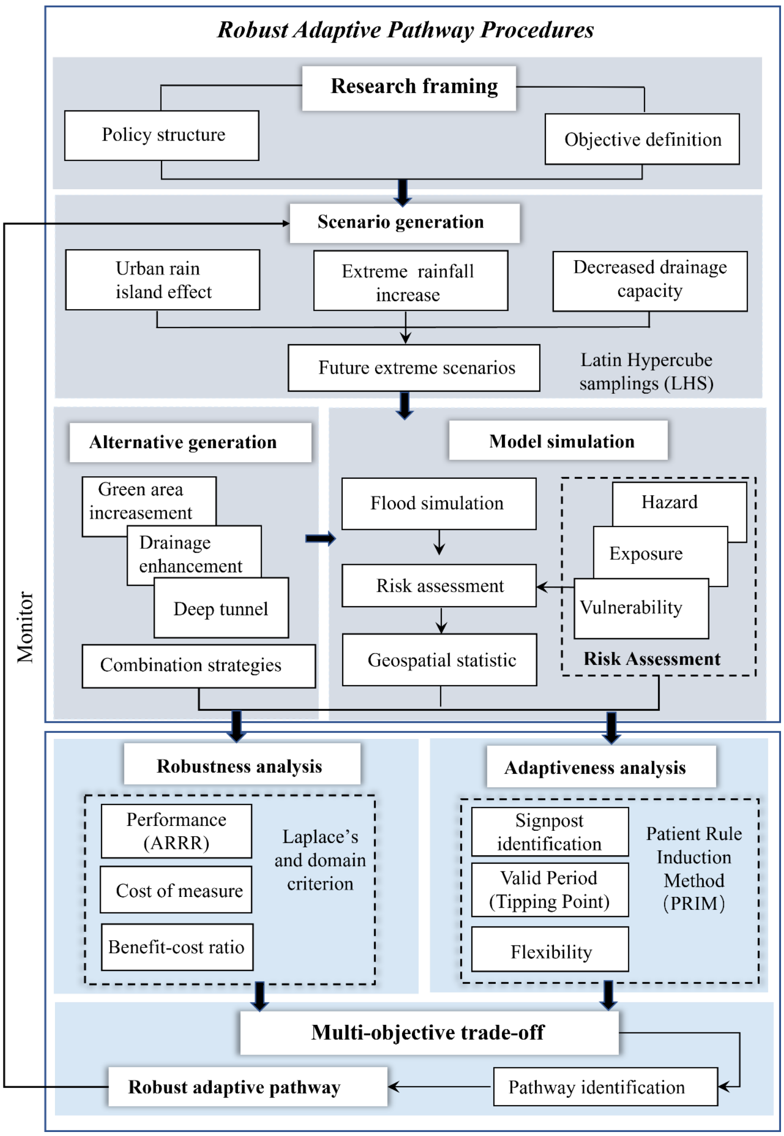

Figure 2 Framework of robust adaptive decision-making pathway, which incorporates the robustness, adaptiveness, multi-objective trade-off, and pathway generation (blue boxes).

3.3 Scenario generation

Precipitation is predicted very likely to increase in the Yangtze River Basin in the 21st century (Hui et al., 2018), and the frequency and intensity of extreme rainstorm events may continue to increase (uncertain factor of the α). Shanghai's spatial rainfall patterns reveal a significant "rain island effect" between urban centers and suburbs (Liang and Ding, 2017) (uncertain factor of the β). In addition, land subsidence has been a persistent issue due to the groundwater exploitation and construction of high-rise buildings (Yang et al., 2020). By 2050, it is projected that the current river embankment and drainage systems in Shanghai will experience a 20-30% reduction in capacity due to a likely relative rise in sea level of 50 cm (compared to the year of 2010), caused by both sea level rise and land subsidence (Wang et al., 2018). The uncertain factor of the decrease of drainage capacity(γ) is designed to be the degradation effect of restraining the water from the urban drainage system flowing to the river system due to the high river water level caused by the continually rising sea level, land subsidence, and other degradation factors.

This study focused on a record-breaking convective rainfall that occurred on September 13, 2013 and had an intensity record of 140.7mm within 3 hour (at 17-19h). The variation interval of each uncertainty factors was clarified, and Latin Hyper Cube Sampling (LHS) was used to construct 100 future scenario cases based on the historic "913" extreme rainfall event in 2013 (Supplementary materials Text 1).

3.4 Alternative generation

It is acknowledged that the current Shanghai flood control infrastructure is insufficient to protect the city from long-term inundation risk (Shanghai Municipal Water Authority, 2020). Three options, drainage improvement, increase of green area, and construction of deep tunnel, are pre-defined with stakeholders of experts and decision-makers following the Shanghai Flood Control and Drainage Plan (2020-2035). The solution district locates in the core business district (CBD) of Shanghai and is highlighted in Figure 1. We defined the existing structure of flood control measures as the baseline and evaluated alternative measures' performance verse the baseline control level in the flood simulation model (Table S4).

3.5 Model simulation

Simulations of extreme pluvial flood inundation under climate change scenarios are carried out using the Shanghai Urban Inundation Model (SUIM) (Supplementary materials Text 2). It was created to couple multiple simulation processes, which consists of the SCS-CN hydrological model, statistical analysis of flooding results, risk assessment, and assessment of adaptation measures. Appropriate socioeconomic indicators were selected to characterize the exposure of the elements at risk and the vulnerability curve to evaluate the flood risk in all plausible scenarios (Supplementary materials Text 3). We then coupled the hydrological module and risk assessment module to assess the future risk (Supplementary materials Text 3). Three climate adaptation options are quantitatively characterized in the risk assessment system. The benefit-cost ratio (BCR) of all options is calculated according to the performances of the risk

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reduction rate over the life cycle cost (Supplementary materials Text 4).

4 Results

4.1 Robustness analysis

This section presents the performance evaluation results, including average risk reduction rate (ARRR) and Benefit-cost ratio (BCA), to reflect the robustness of potential climate adaptation options (Supplementary materials Text 3). Benefit-cost is the evaluation dimension for the robustness metrics, we evaluated their robustness under various plausible scenarios (Equation 1 in Section of 'Methods'). It should be noted that benefit-cost, was defined as the average risk reduction rate (ARRR) per unit cost based on the robustness metrics of Laplace's Insufficient Reason. Given that drainage capacity reduction (γ) is the main factor affecting the solutions' performance, thus the study selects γ as the only explanatory indicator to explore the failure scenario of options based on the PRIM method.

As depicted in Table 2, the ARRR is calculated (Equation 2) to analyze the effectiveness of (the combination of) options. The average yearly cost of single options, which includes increasing drainage capacity (Dr), expanding green areas (GA), and constructing a deep tunnel with 30% runoff absorption (Tun30), is at a comparative level, ranging from 39 to 41 million USD per year. Their performance is relatively unsatisfactory (the ARRR is less than 0.39.) However, the ARRR for the combined option (D+G), drainage improvement and public green area, is higher (0.62) than the sum of two single options (0.51), indicating that the composite option will be more

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effective of reducing flood risk. Furthermore, it demonstrates that the combined options (i.e., D+G and D+G+T30) are satisfactory in terms of ARRR performance but not economically attractive due to their relatively higher costs.

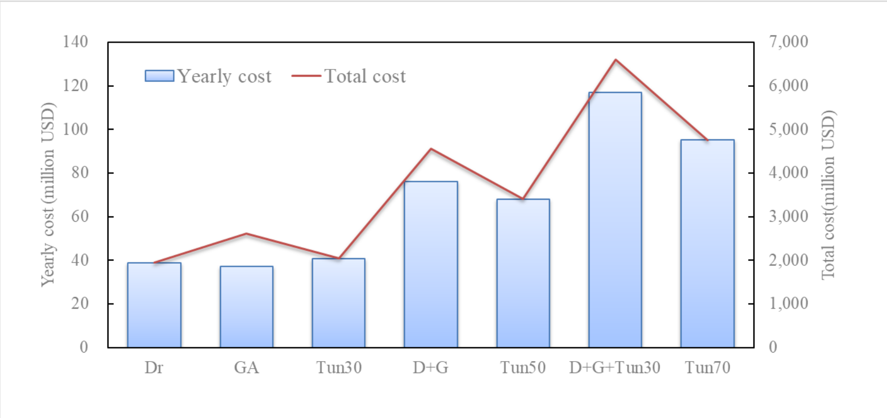

Figure 3 Yearly cost and total cost of alternative options

While two single options of deep tunnel (namely Tun50, Tun70) seem very attractive (achieving high ranks in both ARRR and BCR).

Table 2 The ratio of the benefit-cost of each adaptation options

Option	ARRR (without control target, %)	Cost (million USD / year)	Benefit-cost ratio (%)
Dr	0.25	39	0.09
GA	0.26	37	0.10
Tun30	0.39	41	0.14
D+G	0.62	76	0.12
Tun50	0.74	68	0.16
D+G+Tun30	0.85	117	0.10
Tun70	0.87	95	0.13

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4.2 Adaptiveness analysis

Scenario discovery validates the decrease of drainage capacity is the most critical uncertainty in defining the risk reduction rate of performance objective. The failure scenarios could be identified when the flood control target is not met. We further interpret failure scenarios by selecting subspace of each alternative options under flood control target using PRIM algorithm to optimize the combined value of coverage and density. The valid period is determined as the point when the single options or the combinations cease to fulfill the flood control target, indicated by the time which is characterized by γ (the reduction in drainage capacity).

According to the results in Table 3, it was found that within the 70% risk reduction control target (Equation 3), the single options of Dr and GA performed less favorably (relatively smaller ARRR) and can quickly fail to meet the risk reduction target (with no larger than 0.1 of γ). Tun30 and D+R are very comparative since they preform very closely (similar results on ARRR and γ) but still not attractive. While Tun50 seems very attractive in terms of ARRR (0.89) however, it does not possess higher valid period (γ) than both D+G+Tun30 and Tun 70. Surprisingly, both D+G+Tun30 and Tun70 can function well in an effective way for a longer time. So far, D+G+Tun30 and Tun70 have proven to be highly competitive in terms of cost-effectiveness and valid period over time.

Table 3 ARRR and coverage and density of success scenarios in each option combinations under 70% risk reduction control standard

Option	ARRR (with	Coverage	Density	Decreased drainage

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	control target, %)			capacity (γ) (valid period)
GA	0.59	1	0.22	0.04
Dr	0.62	1	0.20	0.07
Tun30	0.73	1	0.75	0.1
D+G	0.74	0.9	0.82	0.11
Tun50	0.89	0.95	0.98	0.29
D+G+Tun30	0.86	0.99	0.98	0.48
Tun70	0.87	1	1	0.5

we define flexibility as the number of transitions by enumerating overall option combinations regarding adaptive transferable pathways from the original option (current flood control infrastructure) to the destination options (e.g., D+G+Tun30 and Tun70, Figure 5). For example, the D+G+Tun30 comprises three single options, allowing it to begin with any of the three and delay further action until a tipping point approaches, giving it a convertibility score of three (Table S6). Therefore, each single option has a value of one for convertibility.

4.3 Multi-objective trade-off

Robustness analysis suggests Tun50 and Tun70 might be attractive while adaptiveness analysis indicates D+G+30 as the most appealing. Therefore, the single-objective metrics yield different decision choices, it is crucial to evaluate all the metrics to conduct a multi-objective trade-off among the alternative options to assist the robust and adaptive decision making. Multi-objectives of (the combination of) options consider all four metrics, including BCR, and performance of the risk reduction control criteria (ARRR>70%), valid period (γ), and the flexibility. We solved the multi-objective problem using normalized and equally weighted metrics (Equation 4). Figure

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4 depicts the results of BCR, ARRR in control criteria, valid period, and flexibility of each option's combination. The higher the normalized rating, the greater the payoff. The outcome demonstrates that both GA and Dr perform poorly, whereas Tun30 and D+G are not robust enough compared to Tun 50, D+G+Tun30, and Tun70. It needs to be highlighted that Tun 50, D+G+Tun30, and Tun70 possess high priority; however, D+G+Tun30 outperforms due to its well-balanced overall risk control performance and high value of flexibility (Table S7).

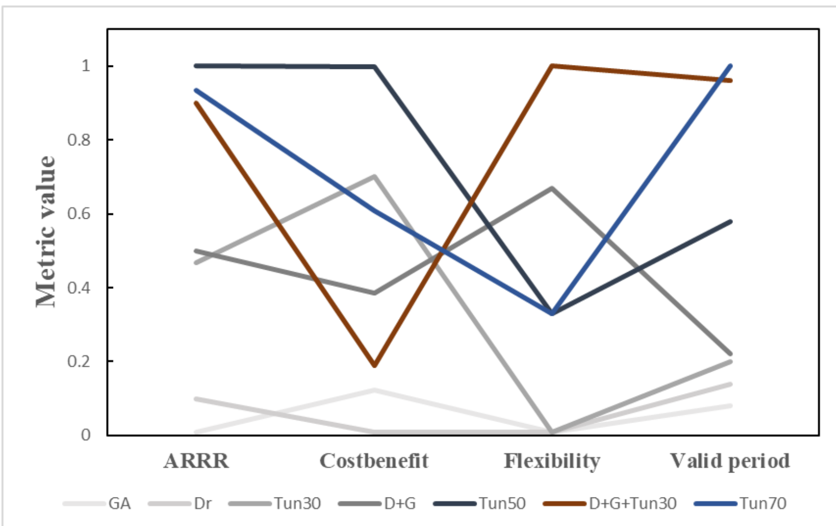

Figure 4 Multi-objective trade-off of alternative options with normalized value of robustness metrics (the preference of priority is accepted from low(bottom) to high(top)).

4.4 Robust adaptive pathway

Pathway identification

The candidate pathway was identified by enumerating the possible combinations of options. In this study, we found two potential pathways including from Tun30 to

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Tun70, and from Dr or GA to D+G+Tun30. It can be observed from Figure 5 that when γ increases, the performance of options of Dr (or GA, vice versa) steadily diminishes until the risk control target are not satisfied.

The drainage capacity, affected by the compound event of land subsidence, sea level rise, and storm surge, is deemed to be undermined (which is reflected by drainage capacity reduction rate γ) over time. Figure 5 illustrates the concept of an option combination's valid period using Dr+GA+Tun30 as an example. ARRR to begin with Dr is 0.62, with an increase in γ, Dr fails (γ=0.07), and ARRR will decrease further if no additional options are taken. The addition of GA can increase the ARRR to 0.74 before Dr and D+G fail (γ= 0.11). The ARRR will continue to decrease if options are not strengthened. Before D+G completely fails, incorporating Tun30 can increase the ARRR to 0.86; as γ increases, D+G+Tun30 fails at γ=0.48. To ensure the adaptive robustness of the combination of options, decision-makers can increase the service coverage area and rainwater absorption capacity of the deep tunnel project in the core area prior to the total failure of D+G+ Tun30. In other words, the transition from Tun30 to Tun50 and even Tun70, along with the combination of options, will be stable over the long-term time horizon.

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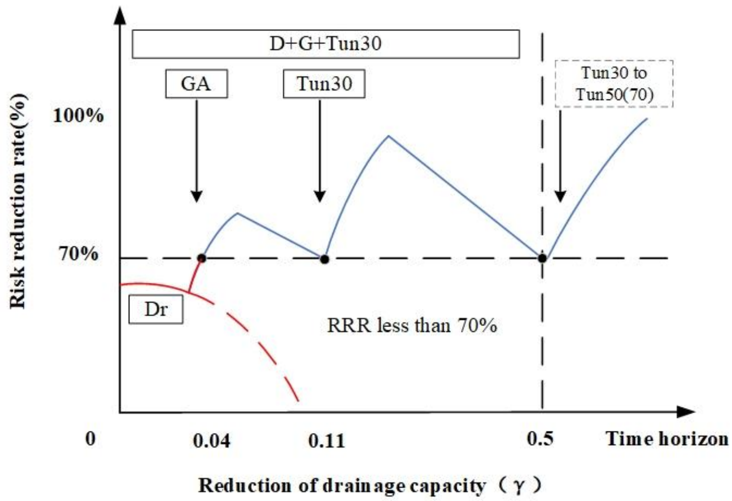

Figure 5 Flexible pathway of combination options of drainage improvement (Dr), green area increment (GA), and deep tunnel with 30% absorption (Tun30), representing the risk reduction rate undermines with the reduction of drainage capacity. An example of Dr+GA+Tun30

Pathway generation

We comprehensively evaluated the candidate pathways by considering performances, BCR, valid period, and flexibility. The time frame lacks an absolute time reference but still offers a relative tracking of the rate at which relative sea levels are rising.

Figure 6 depicts two robust transition pathways: D+G to D+G+Tun30 and Tun30 to either Tun50 or Tun70. The two pathways D+G+Tun30 and Tun30 to Tun70, provide adaptive short and long-term pathway schemes from a flexibility standpoint. The short-term options are used as transitional schemes, and new options can be added before their failure, i.e., pathway transition, to maintain the risk control objectives. In addition,

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the two schemes can complement each other and incorporate new options before the system's long-term robustness is compromised. Additionally, D+G+Tun30 and Tun70 leave room for upgrading to the costlier and more durable D+G+Tun70 in the long run when γ exceeds 0.5 (e.g., sea level or land subsidence exceeds observing increase speed).

Tun70 possesses the highest robustness and the longest valid period; however, the early investment in large gray infrastructure will lead to a path-dependency dilemma if the mild scenarios unfold in the future. Considering that Dr and GA have been gradually implemented according to Shanghai Urban Rainwater Drainage Planning (2020-2035) (Shanghai Municipal Water Authority, 2020) and that combining green and grey options is in line with the direction of sustainable urban development and has been widely adopted domestically. In conclusion, A promising robust adaptive pathway should initially begin with GA and Dr, followed by a combination of D+G. Ultimately as time goes by with gradually undermined drainage capacity, it should incorporate Tun30 with the flexibility to expand to Tun70.

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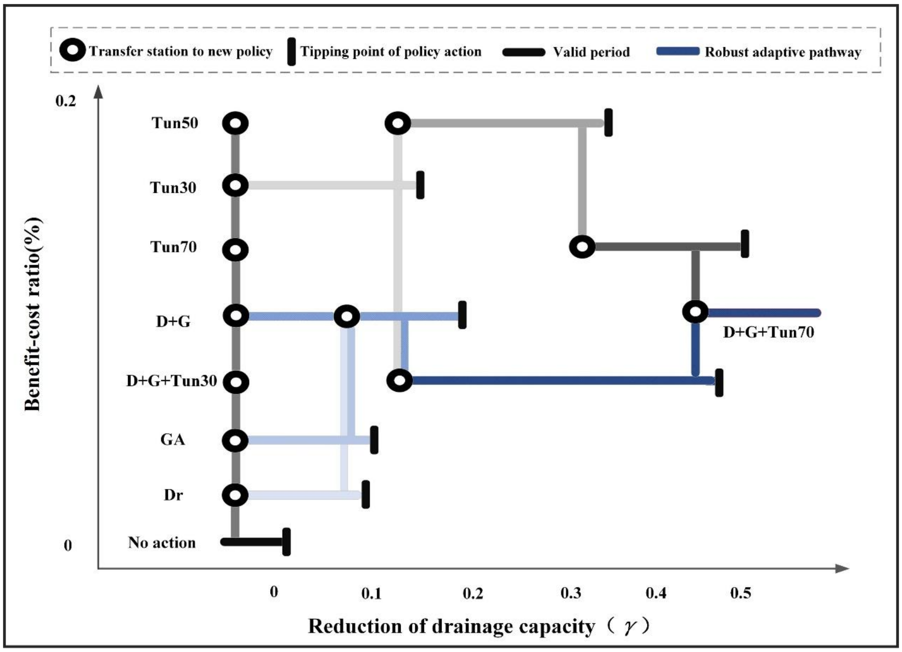

Figure 6 Generation of robust adaptive pathways with two potential pathways from either Dr or GA to D+G+Tun30, and from Tun30 to Tun70 as the reduction of drainage capacity over time (x-axis). The options are sequenced in an upward relative higher BCR (y-axis, also see in Table 2).

5 Discussion

5.1 Key findings

Applying this framework to the case of the reoccurrence in the 2050s (of the extreme rainfall events on 13 September 2013) in Shanghai reveals informative findings to urban planners and other stakeholders. First, the performance of climate adaptation options (for addressing pluvial flood risk) decreases as the drainage capacity reduction rate (γ) increases (Table 3). This result is indirectly supported by events in June 2015 and July 2021, which caused severe inundation in central Shanghai for days because the high water levels of rivers in the region prevented rainwater from being pumped or drained from the drainage system into the river network. This finding also suggests that drainage capacity is a key determining factor for the performance of options in other delta cities which may rely on discharge to the rivers (e.g., Guangzhou, Ho Chiming City, London, etc.) (Hu et al., 2019). Urban planners in those cities need to consider scenarios of high-water levels in the river with a joint of extreme storm surge under typhoon takes place in a high astronomical tide period at estuary. Such an event would significantly undermine the drainage capacity thus leading to severe flooding inside the city and bringing potential disastrous impacts (e.g. Zhou et al., 2019).

Second, as the drainage capacity decreases(γ), valid periods of different option combinations varied significantly, showing a discrete distribution, which ranged from 0.04～0.5 with a corresponding ARRR ranging from 0.59～0.89 (Table 3). Moreover, the most cost-effective solution may not always offer the longest valid period within an explicit flood control target (e.g. 70% risk reduction as a target in our case study), and therefore cannot be considered satisfactory (Figure 4). The findings highlight the importance of the discussion regarding the long-term robustness of solutions which has been overseen in many flood- risk control works in delta megacities. It is also further implying that if there is no consideration of the flood risk reduction target, discussions about a robust decision plan with stakeholders is meaningless. This urges to pay great attention to be proactive by strengthening the dynamic pathway and closely monitoring the decrease of the drainage capacity ahead of the pace of relative sea level rising (Figure 5).

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5.2 Robustness and adaptiveness trade-off

The comparison in Section 5.1 brings up a vital decision-making issue on the trade-offs between the benefit and cost of alternative options. In general, options with better performance required higher costs, which was also proved in any distinctive option in Table 2 and Table S6. It is also demonstrated that the combination of alternative options such as D+G showed a better performance than the single option of Dr and GA at the same cost. However, the cost of an option is not strictly proportional to its benefit (risk reduction rate) (Figure 3). For instance, Tun 50 possesses better performance in reducing inundation risks associated with the relatively low yearly economic cost compared to D+G. Because it is difficult to measure the pros and cons of the costly solution to maintain a higher protection standard and economical solution to possess an acceptable performance (cost-effectiveness), planners typically underestimate both influences by a large margin.

In recognition of this limitation, it can be realized that single-objective targets e.g., flood control performance (ARRR), or financial control (BCR) may lead to biased decisions or maladaptation for the long-term horizon. For example, Table 2 shows that Tun50 has the highest cost-effectiveness (0.16), while the D+G+Tun30 is positioned at an average level, both of which performed well in reducing flood risk. In sharp contrast, the adaptiveness analysis shows that the D+G+Tun30 behaved significantly better during a reasonable period than Tun 50, which is a more flexible and adaptive option for long-term planning (Figure 6). Therefore, it tends to a biased decision if the decision maker only focus on economic return (BCR). Besides, it illuminates the decision maker

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that priorities on grey infrastructure (e.g., Tun 50) at the starting point yields good performance (74% of ARRR) but may lead to over-investment and path dependency. Moreover, there is concern that the valid period could be shorten if decision-makers opt for the most cost-effective solution (Tun50) instead of choosing a more expensive but very effective combination (D+G+Tun30). This example enriches the literature on “no regret” planning, which should be robust, adaptive, and financially efficient at the starting point for decision-makers, keep options open (flexible), and avoid lock-ins. To minimize regret in the near to long future, the adaptation solutions should pay great attention to both robustness and adaptiveness, which also illuminates the importance of multi-objective trade-off as mentioned in previous work (Kirshen et al., 2015; Ramm et al., 2018a).

5.3 Optimization of the synthesis framework

Although there is a myriad of research running flood risk simulations and assessing the BCR of solutions in Shanghai and other megacities in the coastal areas, seldom of which considers the entire process in making the applicable decision (Du et al., 2020; Sun et al., 2021; Ward et al., 2017). In filling up this niche, this study has proposed a synthesized planning-supporting framework that is capable of considering the entire cascade of procedures from the uncertainties of future urban rainfall pattern, to the sampling of future scenarios, to the hydrological modeling, and to flood risk assessment for the robustness and adaptiveness of alternative options, allowing for making robust and adaptive pathways (refer to Figure 1).

Compared to other DMDU theories, the synthesized framework asks for finding

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proxies for solutions' performances in reducing risk, decision-making in terms of cost and benefit, and identifying priorities and adaptive pathways from option combinations in the multi-objective fusion process. The conversations established a fast modeling-interpreting-remodeling feedback mechanism between the analyst and decision maker, which helps reduce the complexities and uncertainties encountered in ROA or other related work (e.g. Kind et al., 2018), and defining explicit objective (Raso et al., 2019). Upon that, incorporating the multi-dimensions of constraints allows for rapidly minimizing disruption factors, balancing alternative solutions' interpretability, coverage, and density, and visualizing the applicable pathway.

The advantage of our decision-supporting tool in running comprehensive evaluations for thousand combinations of scenarios within one or a few days and with moderate demand for input data implies its disadvantage in lack of details at the finer grid-cell level, e.g., 10m or even smaller grid-cells, or at larger research area. The second limitation is that the risk assessment in our work considered only the direct losses caused by inundation while ignoring influences on transportation and other urban functions and the cascading effect across urban sectors. Moreover, when discussing cost-benefit analysis, there is a limitation in fully accounting for the social and environmental benefits. These overlooked aspects lead to a narrow focus on financial costs, while the broader impacts on communities and ecosystems are neglected. Besides, cost should not be limited to financial expenditure alone. Human resources, such as the effort and time required for design and implementation in cross-sector collaboration, are significant components of cost, particularly when implementing nature-based

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solutions. Additionally, it is important to consider whether Shanghai has sufficient land resources available for the expansion of green spaces, as this is a critical factor in the cost assessment.

In addition, further work needs to discuss the determination the weights of multi-objectives when conducting trade-off analysis. The balance between robustness and adaptiveness may vary depending on whether the priority is for immediate, high-impact actions or long-term sustainability. The weight assigned to each factor should reflect the specific goals. Besides, scenario discovery was implemented to find the combination option rather than an optimization algorithm to search for the best optimal combinations in many alternative options. Future work may apply machine learning methods, for example genetic algorithms, to solve complex problems of multi-objective targets under different robust metrics.

6 Conclusion

From short to long-term planning, managing inundation risk caused by future extreme flooding events is challenged by physical, environmental, social-economic and political uncertainty, etc. This research presents a robust adaptive pathway framework that integrates robustness and adaptiveness to evaluate flood-control options. The new framework was tested to carry out the research on robust adaptive pathways regarding the multi-objective that includes solutions' performance, cost-effectiveness, valid period, and flexibility under many plausible climate change futures.

The results showed that traditional evaluation criteria, such as effectiveness and cost-efficiency, are insufficient for addressing long-term robustness in climate adaptation options, as they may result in biased and path-dependent outcomes. Therefore, integrating valid period and flexibility metrics will offer more rational insights for developing adaptive pathways that can respond to future dynamic changes. Our case study showed that the high robustness option (e.g., Tun 50 and Tun 70) performs well under flood control targets and may yield a better BCR(Tun50). While it possesses low flexibility if the decreased of drainage capacity(γ) induced by future sea level rising and land subsidence unfold to be not attractive/satisfactory. D+G+Tun30, achieves the highest score of multi-objective trade-off if both robustness and adaptiveness are taken into account in long-term planning under uncertainty.

This work can not only provide a scientific framework for Shanghai's adaptation strategic policies planning in coping with extreme weather and climate events under climate change, but also provide both the theoretical foundation of decision-making methods and best practices to support the decision-making process for other coastal megacities to adapt to the changing climate and mitigate the extreme pluvial flood risk.

Acknowledgment

This research was funded by the Shanghai Philosophy Social Science Planning General Project (Grant No. 2024BJC014), and National Natural Science Foundation of China (Grant No. 42171080 and 42171282).

Code/Data availability

Case study region data in Shanghai can be found via Shanghai Statistic Yearbook, Shanghai Flood Control and Drainage Plan (2020-2035). Figures are made in ArcGIS

Pro 3.0 and Microsoft Excel. Models in this paper are mainly coding in Rust environment. All the data and software will be opened to the research community upon acceptance of publication. Data sample can be found via open-accessed figShare via following URL:

Hu, Hengzhi (2023). Robust Adaptive Pathway for Long-term Flood Control Planning: Urban Delta in Coping with Pluvial Flood Risk under Future Deep Uncertainty. Multi-criteria trade-off.xlsx. figshare. Dataset. https://doi.org/10.6084/m9.figshare.24899340.v1

Author contribution

Hengzhi Hu conceived the study, designed the framework, collected the data and led the analysis of the result and responsible for writing the manuscript and ensuring its intellectual content. Qian Ke contributed to the design and implementation of the decision-making framework, and conduct the manuscript writing and revising. Wei Wu supported the climate projection of the case study area of Shanghai and identified the scenario uncertainties. Min Zhang validated the simulation result of pluvial flood and funding support. Jiahong Wen supervised the project and provided expertise in flood risk management, and assisted in finalizing the manuscript.

Competing interests

The authors declare that they have no competing interests.

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