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Dynamic adaptive engineering pathways for mitigating flood risks in Shanghai with regret theory

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Uncertainty in sea level rise and future extreme climate events presents a great planning challenge for flood defence in coastal mega cities like Shanghai. While academic literature has largely focused on uncertainty analysis, engineering solution design requires effective uncertainty management. Here we incorporate the regret theory of economics and decision science into the dynamic-adaptation-pathways framework and assess the impacts of high rates of changes on the flood defence systems in Shanghai. Specific options are developed to manage flooding on the Huangpu River from tidal water levels, river flows, rainfall, drainage inflows and combinations of these flood sources including sea level rises of up to 3 m. Dynamic adaptation pathways are developed where the timing of tipping points from one intervention to the next depends on the actual changes in sea level, rainfall and other variables that affect the future design. This framework is potentially applicable for planning 'no regrets' flood-defence systems in other low-lying coastal cities.

Climate hazards over the past decades have had enormous adverse impacts on global society. Lessons from the past and the foreseen increase in the frequency and intensity of compound extreme climate events present fundamental challenges to the planning and designing of urban defence systems. Questions relating to when and how much to adapt, what adaptation systems may work, how they work and what the outcomes will be afterward are in essence difficult to comprehend, answer and agree among experts and decision-makers[1,2]. Such a high degree of uncertainty has led to the emergence of new methodological frameworks to support decision-making and guide adaptation decisions under the high degree of future uncertainty. These frameworks include adaptive policy making[3,4], adaptation pathways[5,6], scenario planning[7], multi-layer decision analysis[8] and robust decision-making[9,10]. These approaches have been applied in flood management. Examples include the Rhine Delta in the Netherlands[11], New York in the United States[12,13], Perth in Australia[14] and the Thames Estuary in the UK[6,15–18]. These applications calibrated a range of scenarios, conducted informative scenario analyses and involved information exchange and sharing among stakeholders, aiming to develop robust systems with a dynamic perspective.

While uncertainty analyses improve our understanding of the complex interactions across different systems, resilient engineering solutions have to work with an expected certainty that a solution can perform a required function under stated conditions for a specified period of time[19,20]. To design a plan with a long time horizon to the future, long-term scenarios of future change are needed but the precise details of the scenarios can be very uncertain. The required conversion from uncertain future changes to engineering solutions can be

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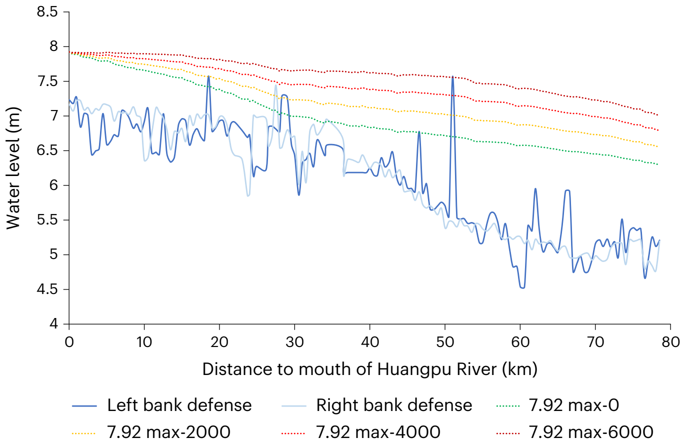

Fig. 1 | Impacts of drainage discharges on water levels. Note: 1,000-year tide + 1 m. 7.92max-0, 7.92max-2000, 7.92max-4000 and 7.92max-6000 stand for peak level 7.92 m plus drainage inflows of 0, 2,000, 4,000 and 6,000 m^3 s^{-1}, respectively.

facilitated by the 'no regrets' perspective of the regret theory, which has been formalized recently in the literature of economics and decision-making science[21,22]. In the regret theory, the term regret describes the human emotion experience when one or more non-chosen alternatives perform better than the chosen one in terms of one or more criteria[23]. In the words of Von Neumann, any choice or decision made by one individual or a group of people automatically evokes the experience of regret or rejoicing, in relation to what could or might be later on[24]. The regret theory highlights the following three key points: first, regret is commonly experienced; second, people tend to anticipate and avoid the experience of future regret; and third, avoiding regret is different from preventing risk[25,26]. The regret theory justifies a distinct attention to the worst-case scenarios because the expected value of loss from an extreme disaster might be small owing to the tiny probability attached to it, but the potential regrets and negative sentiments of the unpreparedness or failure of a defence system can be very high and widely shared. The 'no regrets' perspective promoted by the regret theory intends to identify measures and solutions that can be enacted now in a precautionary sense without being certain about all dimensions of future changes, and thus can facilitate the formation of a non-probabilistic robust approach to manage deep uncertainty as demonstrated in this paper. The measures and strategies identified by the 'no regrets' approach deal with both adaptation and mitigation challenges, and enable their benefits to continue even if the effects of forthcoming climate change are not as horrific as currently anticipated[27].

In this Analysis, we incorporate the above insights of the regret theory into the framework of dynamic adaptation pathways, with the aim to develop flood defence pathways on when, how much and how fast to intervene along the Huangpu River Estuary. The research intends to provide a theory-backed robust and practical approach for developing a long-term flood defence strategy on the Huangpu River, taking account of the need to design resilient engineering works with fixed thresholds and levels. This procedure allows us to consider large future changes as implied by the non-stationary dynamics of sea level rising and extreme climate events, to make viable conversion from the uncertain future changes to the engineering solutions, and to show the long-term implications of a flood barrier on the flood defence system including the future need to raise upriver defences with the barrier in place.

The InfoWorks ICM (v. 9.0) hydraulic and hydrologic modelling tool[28] was used to assess the impacts of compound flood scenarios, which include combinations of high tidal water levels that take account of sea level rise, river flows, rainfall and drainage inflows (defined as compound events), and to facilitate the pathway development with multiple measures. Adaptation actions (for example, raising of flood dikes, a new flood-control barrier near the mouth of the Huangpu River, drainage improvements and combinations of measures) are triggered in response to the changing threat. The modelling framework is applied to alternative adaptation strategies in order to identify intervention thresholds at which major changes are needed to the flood management system. In view of the very high vulnerability of Shanghai to tidal flooding and the potential non-stationary dynamics of sea level rise, the strategies are designed to provide a high level of flood protection to the city. While the costs of the adaptation actions are far less than the potential damages under the worst-case scenarios, the selection of a preferred adaptation strategy should take other factors into account including navigation, impact on the city, landscape and access to the river. The conclusion includes reflections on the theoretical contributions of the approach to uncertainty management and on the applicability of this integrated framework for planning flood-defence systems in other low-lying coastal cities.

Present-day and future extreme flood events

Extreme tidal events

This study simulates the changes in the water level of the Huangpu River under the current situation (1,000-year-event level of 6.92 m at Wusong at the confluence with the Yangtze, distance 0 km) and with sea level rise of 0.5, 1, 2 and 3 m (for more details, see Supplementary Fig. 1). Matched with the spatial differences in land use and socio-economic development in the areas along the Huangpu River, the protection standard of the flood wall in the upper reaches (50-year level) is much lower than the middle and lower reaches (1,000-year). A 1 m increase in sea level would cause overtopping of most of the defences during a 1-in-1,000-year surge tide (Supplementary Fig. 1). The flood defence crest levels include a 1 m freeboard allowance for uncertainty in design water levels and other factors (except port areas, where the freeboard is 0.5 m). This means that the present-day 1,000-year level plus 1 metre is the theoretical design crest level for the defences between 0 km and 40 km from Wusong.

Sea level rise scenarios

There is deep uncertainty in future sea level rise. Global projections for 2020–2100 are typically in the range of 0.5–1.0 m. When considering the non-stationary dynamics of sea level rise, relative sea level rises of 0.5, 1, 2 and 3 m were used in the model simulations to represent a range of potential future scenarios. Additional tests were also carried out for sea level rise in the 2030s and 2050s, as the defence system may have to accommodate these water levels before a tidal barrier can be constructed (for more details, see Supplementary Fig. 2). The 1-in-1,000-year surge tide would provide design water levels for the Shanghai area and the 1-in-50-year surge tide would provide design water levels further upriver. For this analysis, the business-as-usual (BAU) reference rate of absolute sea level rise is assumed to be 3 mm year^{-1}, based on historical trend information obtained from the China Sea Level Bulletin[29]. The extent of land subsidence is currently estimated at 5 mm year^{-1} on average[30]. Thus, the estimated BAU level of increases in relative sea level from 2020 onward are 80 mm by 2030 and 240 mm by 2050 on average across the coastal area of Shanghai.

Extreme compound events

Compound events are those involving more than one source of flooding. For example, flooding can occur from tidal water levels and heavy rainfall during a typhoon (which also can cause flooding from waves on the coast). For the Huangpu River, an analysis was carried out to assess the impact of drainage inflows during a high tidal event and whether pumping of drainage water can be carried out during a high tidal event. The inflows are applied over a 6 h period at the time of the highest high tide. This is a worst-case scenario, as it assumes that the rainfall will

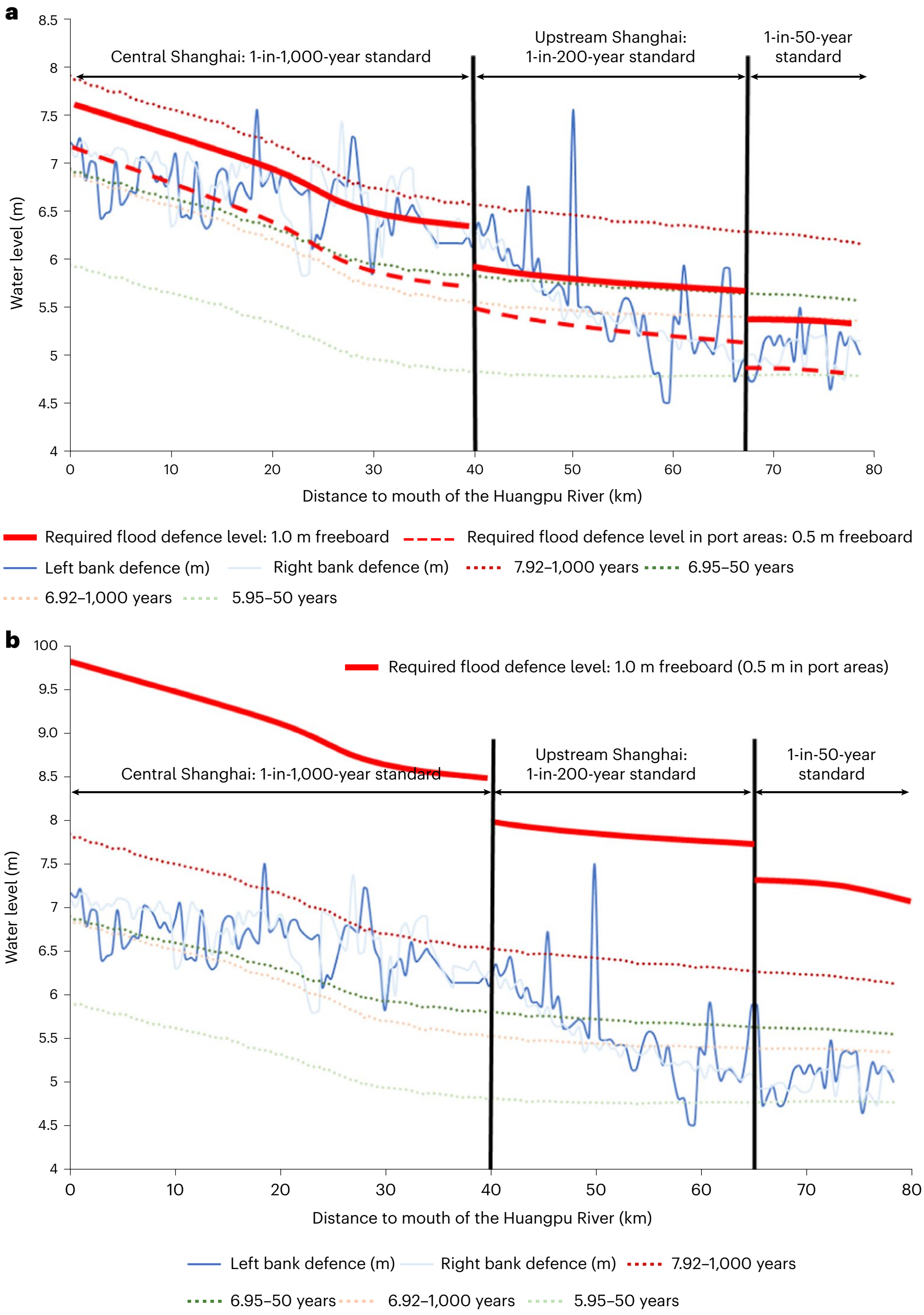

Fig. 2 | Required defence levels. (**a**) In present day and (**b**) with a 2 m increase in sea level.

coincide with the peak tidal water level during the typhoon. The tidal event used is the 1,000-year tide + 1 m (peak level 7.92 m). The following drainage inflows are used: 2,000 $m^3 s^{-1}$, 4,000 $m^3 s^{-1}$, 6,000 $m^3 s^{-1}$. The fluvial inflow on the Huangpu River is 350 $m^3 s^{-1}$.

Figure 1 shows that water levels in the Huangpu River 30 km upriver of Wusong would increase by about 0.2–0.3 m for each 2,000 $m^3 s^{-1}$ increase in drainage inflows (total of 43 Mm^3 inflow). This increase reduces to zero at the mouth of the river, where the water level is fixed in the modelling. As the amount of pumping is increased, the water level would rise and the amount of defence overtopping would increase. While these changes will affect peak water levels in the river, the changes are modest. The impact of drainage inflows will change if a tidal flood barrier is constructed because water cannot discharge into the Yangtze when the barrier is closed. This is investigated as part of the assessment of the barrier option in the following section.

Engineering options for mitigating future compound flooding risks

Option 1: raise the standards of existing defences

Raising defences without a barrier or barrage means that the required Standards of Protection should apply under present-day and future conditions. Figure 2a shows the predicted tidal water levels for 1,000-year and 50-year surge tides together with an estimate of the 200-year level between 40 km and 68 km from Wusong at the mouth of Huangpu River. The full red lines indicate the addition of a 1 m freeboard and therefore provide an estimate of the present-day flood defence levels required to achieve the existing design standards. The 'present day' panel in Table 1 shows the approximate amount of defence raising needed to achieve the required levels based on the defence crest level data that has been obtained for this study. It shows that an average increase in flood defences crest levels of 0.6 m is needed to achieve the required present-day standards of protection. It is apparent from Fig. 2a that there is a gradual transition in defence standard between 40 km and 68 km and the use of a single defence standard in this section is not appropriate, and that defence raising is needed for most of the river in order to achieve the required present-day defence standards. The rate of sea level rise is projected to increase, and therefore the magnitude of subsequent defence raisings will be greater. A 2 m increase in peak surge tide levels would cause a 1,000-year peak water level at Wusong of 8.92 m and a defence level requirement of 9.92 m, reducing to about 8.9 m at 40 km from the mouth of the river. This would require defence raising at Wusong of 2.5–3 m. The impact of a 2 m increase in peak surge tide levels is shown in Fig. 2b. The date when this scenario will occur depends on the rate of sea level rise, but it could occur before 2300 on the basis of some current projections[31].

Table 1 | Defence levels and required raising in present day and by 2050

Section of Huangpu River		Required standard	Required defence level (m)[a]	Defence raising required (m)[a]
Description	Distance from Wusong (km)			
Present day				
Central Shanghai	0 to 40	1 in 1,000 years	7.9 to 6.6	0 to 1.3; average 0.6
Upstream Shanghai	40 to 68	1 in 200 years	6.2 to 6.0	0 to 1.5; average 0.6
Rural and peri-urban	68 to 78	1 in 50 years	5.6	0.1 to 0.9; average 0.5
By 2050				
Central Shanghai	0 to 40	1 in 1,000 years	8.1 to 7.1	0 to 1.6; average 0.9
Upstream Shanghai	40 to 68	1 in 200 years	6.7	0 to 1.8; average 1.2
Rural and peri-urban	68 to 78	1 in 50 years	6.3	0.6 to 1.4; average 1.2

Note: [a]levels and raising are 0.5 m less in port areas.

Option 2: barrier

An alternative to defence raising along the full length of the Huangpu River is to construct a tidal flood barrier near the river mouth. Two locations for the barrier are considered. The first location is on a bend in the river near the river mouth, and this location is preferred by the Shanghai Water Engineering Design & Research Institute (SWEDRI). It will be necessary to raise downriver defences on the Huangpu River and the coastal defences. It may also be necessary to raise the upriver defences as the sea level rises and barrier closures become more frequent. An additional concern is that there may be problems with navigating large ships through a barrier on a bend. The second location is on a straight reach further upstream. This location is chosen with navigation in mind, as a straight reach will be easier for shipping. Sites for barriers further upriver have not been considered. This is because longer lengths of high defences downriver of the barrier would be needed, and this should be minimized as far as possible.

A key parameter in the planning of a flood barrier is the lowest high tide level at which the barrier must be closed. This is determined by the levels of the existing upriver defences. The reason that this parameter is important is that it affects the number of closures that might occur. On the basis of simulations of barrier closure at different levels for various extreme events as presented in Section S1.2 of Supplementary Information, it is concluded that the barrier must be closed for all tides greater than 5.0–5.5 m above datum depending on the magnitude of the inflows. For high inflows, a level of 5.0 m should be used, and for low inflows a level of 5.5 m may be satisfactory.

The number of barrier closures per year is another important parameter because navigation is not possible when the barrier is closed and also because the more the barrier is closed the greater the risk of a failure occurring. There is a finite probability of failure during any closure, although this is very small. However, the annual risk of failure will increase as the number of closures increases. In addition, as the number of closures increases, the time available for maintenance reduces, and this further increases the probability of failure during a closure. A further consideration is accurate forecasting of closures to minimize the number of unnecessary closures, as this further increases the annual number of closures.

The mitigation measure for controlling the number of closures is to raise the upriver defences. The analysis shows that the defences would have to be raised when the sea level has risen 0.7 m with a 5.0 m closure level, and 1.2 m with a 5.5 m closure level. This means that upriver defence raising would be needed towards the end of the twenty-first century or early in the twenty-second century on the basis of current projections of sea level rise. The alternative to this mitigation measure would be a tide-excluding barrage.

Different timings of barrier closure were investigated in the modelling, and it was concluded that closure at low tide before the tidal surge would be the best time because (1) it would avoid reflected waves and surges caused by closure when tidal flows are high and (2) it would maximize the available storage volume for fluvial and drainage inflows upriver of the barrier. However, this would have a greater effect on navigation because the barrier would be closed for about 8 h during a single tide.

Option 3: combination of options 1 and 2

Option 3 is done in the following sequence: (1) raise defences to provide the design standards of protection for the period until the barrier is operational; (2) construct barrier and raise downriver defences as for option 2 (barrier). This option depends on how rapidly a barrier could be constructed. A barrier appears to be the preferred option for Shanghai, and therefore investment in raising the defences through Shanghai would not be worthwhile unless there is a long delay before a barrier is commissioned. If a barrier is not commissioned until 2050, the defences could be raised now to the required level in 2050 as indicated in Fig. 3.

The following assumptions are made for this scenario: period of construction of raised defences, 2020–2030; assumed rate of relative sea level rise (including land subsidence), 8 mm year^{-1} (the BAU rate); required increase in design crest level from present day, 8 mm year^{-1} × 30 years = 240 mm. Thus, the 1,000-year peak tide level would be 6.92 + 0.24 = 7.16 m and the required defence crest level would be 8.16 m at Wusong when the barrier is commissioned. The general defence raising requirements upriver of the barrier are shown in the 'by 2050' panel in Table 1. The crest level of the barrier was set at 9.4 m above Wusong datum, which is based on current projections of sea level rise and subsidence to the year 2130. This is about 2 m above current defence levels.

Dynamic adaptation pathway for mitigating flood risks and managing uncertainty

Figure 4 positions the option-specific pathways into an integrated framework with the aim to develop dynamic adaptation pathways that are capable of mitigating extreme flood risks with 'no regrets'. Major steps shown in Fig. 4 are as follows. (1) An initial phase of defence raising to bring the defence system up to the required standard. If a barrier is

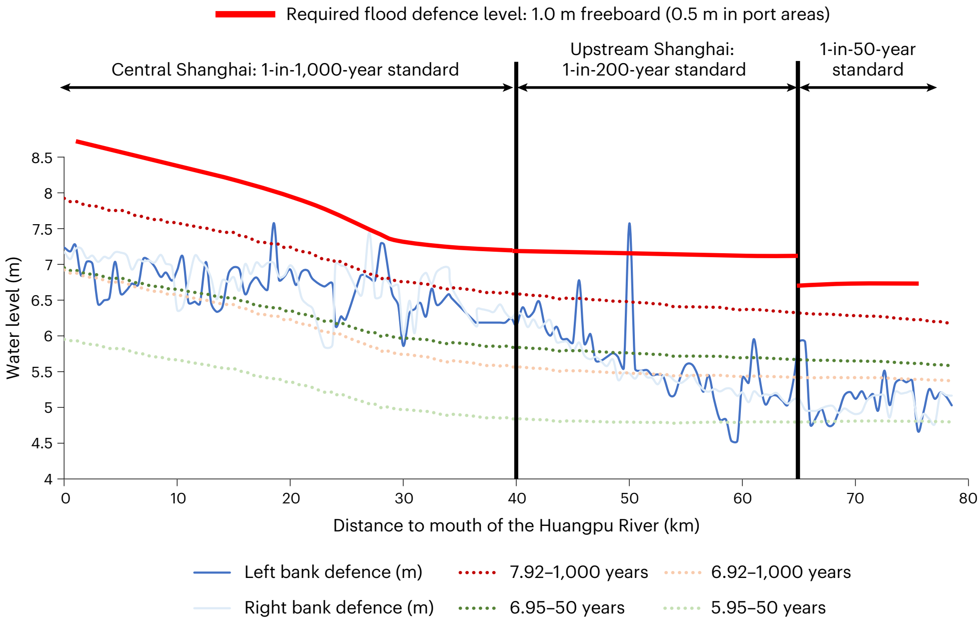

Fig. 3 | Required defence levels in 2050. Under the assumptions that (i) a barrier is not commissioned until 2050, (ii) the raised defences are constructed in 2020–2030, and (iii) the relative sea level rises by 8 mm year^{-1}.

to be built, this stage could be omitted but the risk of flooding would be greater than the design standard of 1 in 1,000 years. (2) For the raised defences options, two further phases of defence raising are shown. (3) A barrier option that would follow the initial phase of defence raising. As the sea level rises and barrier closures become more frequent, locks may be required for navigation and eventually a tide excluding barrage may be needed. (4) The potential need for raising defences upriver of the barrier to limit the number of barrier closures. Two stages of upriver defence raising are shown in the figure. (5) The potential effects of fluvial and drainage inflows on the interventions are shown. As the inflows increase the water levels, a greater volume of storage is needed upriver of the barrier. This means that the level of the upriver defences may have to be raised, particularly in the relatively rural areas upriver of Shanghai. This would bring forward the dates when some upriver defence raising would be needed. The stepwise development of adaptation pathways for each of options 1–3 discussed above is presented in Section S1.3 in Supplementary Information.

The way in which fluvial and drainage inflows from the Shanghai area will therefore have an important impact on the adaptation pathway. If Sustainable Drainage Systems (SuDS)[32] and other means of retaining stormwater in the urban area can be implemented, the inflows into the Huangpu River during typhoons would reduce and the future dates for upriver defence raising would be delayed.

Modelling simulations have been done for all possible pathways in Fig. 4. The results include flood defence crest levels and operational information for the barrier. For example, if focusing on 'raise defences' without considering a barrier, the average increase in defence crest levels would be about 1.1 m by 2080. Further defence raising would be needed after this date. However, such highly raised defences would block views of the river and require extensive works to provide access to the riverside both for the public and commerce. This consideration makes the option of a tidal barrier more desirable. An example of one highly plausible adaptation pathway by adding blue arrow lines in Fig. 4 is shown in Supplementary Fig. 11. The scenario underpinning this pathway is that inflows can be managed so that early upriver defence raising is not needed. The major paths on the pathway are as follows: (1) raise upriver defences to provide the required defence standard until the barrier is built; (2) construct a barrier and raise the downriver defences for a future amount of sea level rise; (3) when the barrier closure limit is reached, raise the upriver defences (by a small amount, perhaps 0.5 m); (4) when the barrier closure limit is reached with the raised upriver defences, raise the upriver defences for a second time (by a small amount, perhaps 0.5 m); and (5) a future navigation constraint is reached, when locks are required (either a barrier with locks or a tide-excluding barrage with locks).

As discussed in Methods, the choice of pathways and the dates for implementing interventions will depend on the rate of climate change and the rate of ground subsidence. As it has already been shown that the existing flood defences for Shanghai are below the required design crest level for the peak sea levels caused by a 1-in-1,000-year typhoon event, there is a need to implement improved flood defences (for example, raise defences stage 1 in Fig. 4) as soon as possible. Assuming that a barrier could be built by 2050 and the flood defences raised in stage 1 (defence raising of about 0.9 m on average through the centre of Shanghai) effective protection would be provided until that date. In this case, the pathway moves from the first horizontal blue arrow line to the second horizontal blue arrow line in Supplementary Fig. 11.

However, the rate of sea level rise and the rate of subsidence of the flood defences are uncertain. In addition, future drainage inflows into the Huangpu River are unknown. These will depend on the drainage works to be constructed in the future. Therefore, there are a number of major uncertainties concerning the planning of future flood control measures for Shanghai. This study indicates that a 'no regrets' process for dealing with these uncertainties should include the follows: (1) Prepare a design of flood defence plan for each of particular future scenarios of sea level rise. The designs should include a sequence of interventions, to be implemented when particular thresholds of sea level rise are reached. (2) Monitor the rate of sea level rise and other variables that could affect the future design, for example, the rates of subsidence of river levees and sea walls, and future drainage inflows. (3) Plot the rates of change for each key variable and estimate a revised date when each intervention must be implemented. (4) Revise the programme with the new dates. (5) Continue to monitor and update.

A generalization of the above process is shown in Fig. 5. It shows the threshold value of sea level rise when the intervention is needed and the observed value and projected range of sea level for the design

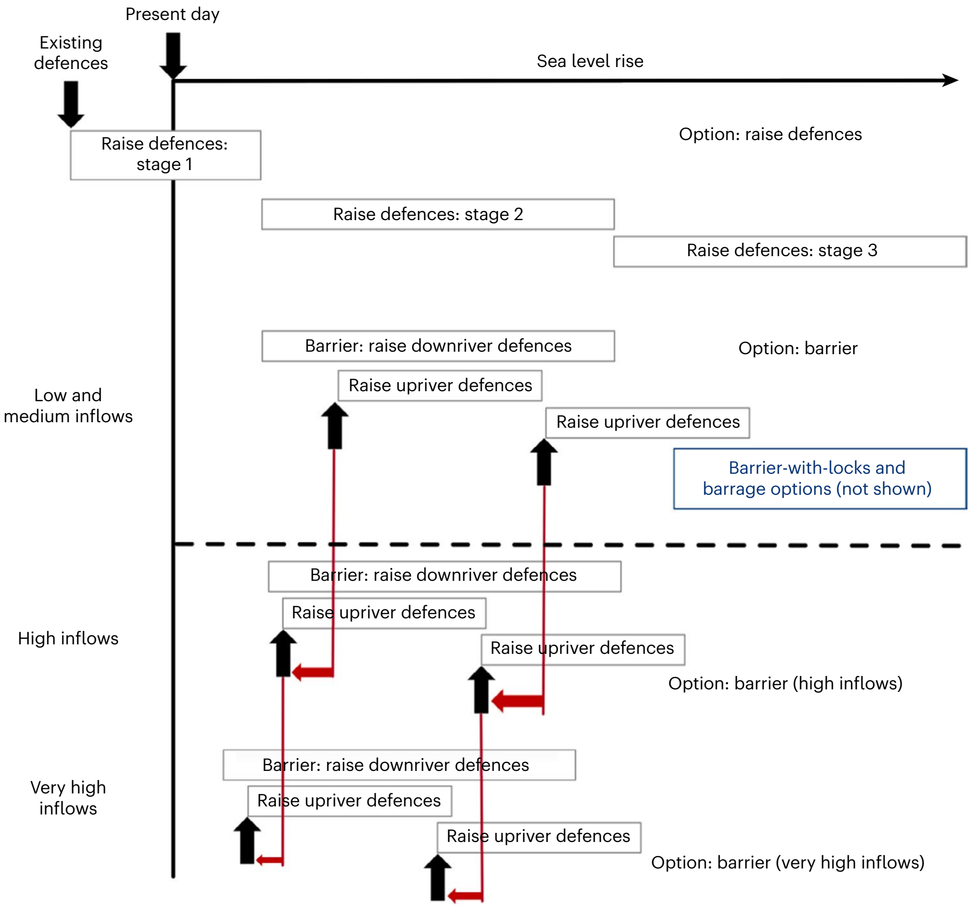

Fig. 4 | Dynamic pathway for flood mitigation. With two sets of options for the Huangpu River: (i) raising defences and (ii) constructing a tide-excluding barrage with locks for shipping.

standard of 1 in 1,000 years. The projected range can be based on the most up-to-date projection of sea level rise currently available or more practically based on an estimation of non-stationary dynamics of sea level rising that is produced via a dialogue between scientists, policy makers and other stakeholders, as done in this research. The upper and lower bound of sea level rise in Fig. 5 correspond to different climate change scenarios. The upper bound shows a higher rate of sea level rise, which means the threshold level will be reached sooner. The lower bound shows a lower rate of sea level rise, which means the threshold level will be reached later. By monitoring the rates of change of the relevant parameters including sea level rise, it is possible to adjust the date when the intervention must be completed. A decision point is needed to give enough time for planning and construction of the works, and this is also indicated. The decision point will occur earlier for the upper bound case and later for the lower bound. In this way uncertainty is managed by changing the timing of the works and not the works themselves.

Conclusions

Sea level rise, land subsidence and increases in the frequency and intensity of future extreme climate events present a major infrastructure planning challenge for mega cities sitting on low-lying coastal zones. Uncertainties on the rate and magnitudes of these changes add further challenges to the planning efforts. The existing large body of literature on uncertainty analyses demonstrates the complex interactions across different systems. However, engineering solutions have to work with an expected certainty that a solution is able to perform required functions under stated conditions for a specified period of time. To bridge the gap between uncertainty analysis and uncertainty-management requirements in climate-resilient engineering solution design, the ‘no regrets’ perspective from the regret theory in economics and decision science has been incorporated into the framework of dynamic adaptation pathways, and applied to develop flood defence pathways on the Huangpu River Estuary in Shanghai. This integrated framework helps to make a viable conversion from the uncertain future changes to the engineering solutions. This conversion includes (1) establishing plausible worst-case scenarios; (2) designing interventions for future thresholds, which can be defined with certainty; (3) monitoring change to determine when the intervention is needed. This conversion enables engineering works to be designed for fixed threshold values with the dates of implementation vary depending on the rate of change in key variables including sea level and drainage inflows into the Huangpu River. Monitoring of these variables will allow dynamic updating of the dates for completing each step of the adaptation pathway and minimize the risk of regrets.

This regret theory enhanced framework of dynamic adaptation pathways contributes to the existing literature in following two ways. First, current practices in upgrading the design standards of flood defence systems are typically based on the analyses of historical records under the implicit assumption that hydroclimatic extremes fluctuate within a stationary envelope of variability[33–35]. However, the literature on hydroclimatic extremes suggests that these extremes are not bounded within a stationary envelope of variability owing to the influence of multiple drivers such as changes in climate, land cover and other human factors[36]. Despite the efforts to develop a theoretical background for computing climatological design factors under

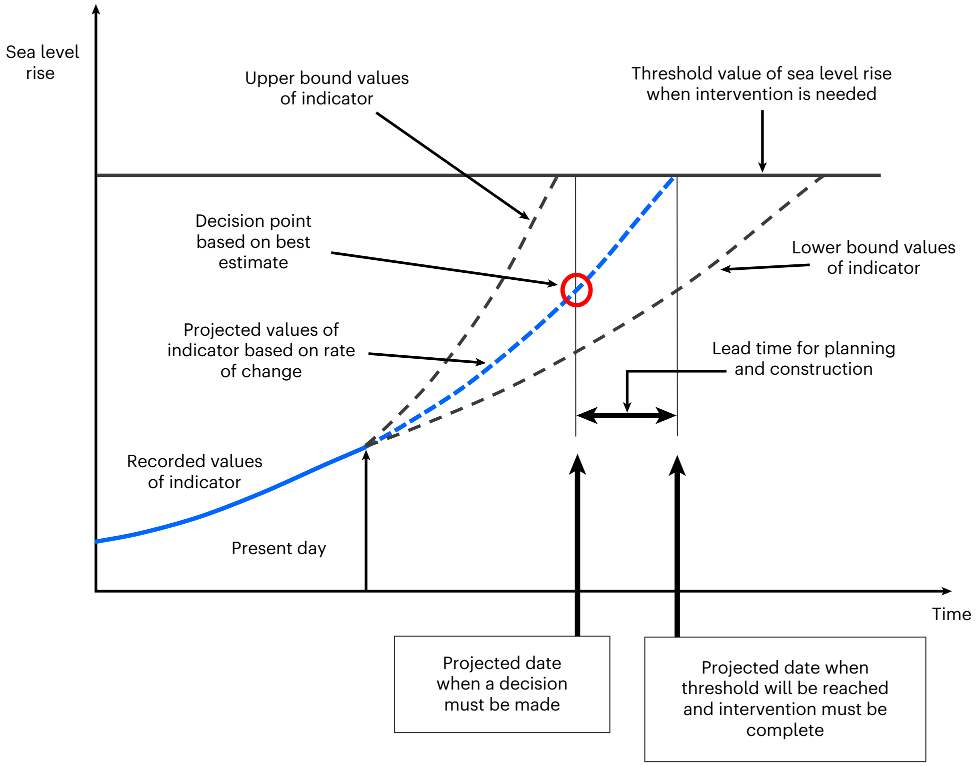

Fig. 5 | Management of uncertainty. (i) designing interventions for future thresholds so that the main uncertainty becomes the dates of the interventions, and (ii) monitoring key climate change variables and updating projections of change and the timing of interventions.

non-stationary conditions, a number of obstacles have prevented the practical and standardized implementation of these methods[37]. It has also been acknowledged that non-stationary models introduce additional sources of uncertainty and the existing non-stationary models do not make the non-stationary signals emerge more clearly than before[38]. We cannot afford to wait and have to develop practical tools for managing future non-stationarity and uncertainty now[36]. By incorporating holistic storylines into the rigorous quantitative simulations, this research contributes such a practical tool. The calibration of storylines in this research is based on a thorough exploratory data analysis. Such a calibration of storylines allows researchers to intelligibly translate sciences, envision futures with multiple non-stationary drivers, and frame narratives including no-regrets options that are meaningful to decision-makers[39,40].

Second, both the return period and risk-based approaches in the existing urban flood defence literature are based on the probabilistic assumption of perfectly known distributional information on hydroclimatic extremes. These two approaches require the joint probability distribution functions and the statistical dependence between the uncertain variables. However, data limitations, measurement errors and concerns about the non-stationarity as discussed above represent major setbacks to probabilistic flood risk modelling, making probabilistic models perform poorly where the actual flood events differ from the assumed probability distribution functions[41]. By contrast, our framework provides a non-probabilistic robust alternative to the existing approaches. Our approach does not require the full distributional information of the uncertain variables; instead, the uncertainty is quantified by a calibration of storylines that accounts for possible realizations of the uncertainties. In this way, our approach has the advantage of better tractability, is less computational demanding and, more importantly, has the ability to incorporate interdependence of uncertain factors without adding complexity. These advantages can facilitate meaningful dialogue between scientists, policy makers and other stakeholders, enable the incorporation of the users' latent knowledge into the overall scientific and engineering synthesis, and help build stakeholder capacity to use the project outcomes in decision-making[42–44]. The above features and comparative advantages of our approach make its applications to other low-lying coastal cities much easier and more comprehensive than the existing probabilistic approaches.

Methods

Study area

Shanghai is a mega city sitting on the low-lying coastal zone of Eastern China (Supplementary Fig. 12). It is surrounded on three sides by water bodies including the Yangtze River Estuary, the Hangzhou Bay and the East China Sea, with an average elevation of 3–4 m above sea level. The Huangpu River passes through the main urban area of the city. As a result, the city is prone to flooding from the sea. The main source of tidal flooding to the central part of Shanghai is from the Huangpu River, but there is also a risk of tidal flooding directly from the estuary and the coast. The main sources of flooding are discussed in Section S2.1 in Supplementary Information.

Shanghai is in an alluvial plain with uneven terrain. Its northern, eastern and southern boundaries are higher than the west and central parts, with elevations of 4–5 m. The southern margin is higher than the northern margin, with the highest points being over 5 m. The trend of water flow is slightly inclined from east to west. The Huangpu River flows through the centre of Shanghai. The river is tidal, and water levels are dominated by the tide. From the mouth at Wusong, the timing of high (and low) tide gradually delays with distance upriver, the tide range decreases, the duration of the rising (flood) tide decreases and the duration of ebb tide increases[45].

Shanghai suffers from flooding from typhoons, high river flows and rainstorms. Typhoons cause raised sea levels and heavy rainfall, and therefore tidal flooding and surface water flooding in the city behind the tidal flood defences can occur at the same time. River flows include high flows in the Huangpu River from the Taihu Basin. Section S2.1 in Supplementary Information presents more details on major drivers of flooding disasters in Shanghai and the flood defence systems in the city. According to a study[46] using a Coastal City Flood Vulnerability Index, Shanghai is considered to be the most vulnerable major city in the world to severe flooding and future climate change will further intensify flood exposure in Shanghai. It is apparent therefore that the existing flood defence systems for Shanghai are inadequate for protecting against future flooding events.

Data and model

Data used. This study is data intensive. Data collected include river bathymetry (cross-section), land topography, coastal and river embankment data (including Huangpu River and Suzhou Creek), drainage capacity data, land use data, and demographic and socioeconomic data. Historical compound events in Shanghai that were analysed include typhoons, astronomical tides, heavy rain and upstream inflow. Historical flood events that were analysed include the '9711' typhoon in 1997, 'Haikui' typhoon in 2012, 'Fitow' typhoon in 2013 and a record-breaking rainstorm on 13 September 2013. Supplementary Table 2 presents the content, sources, format and quantity (or number of observations) of these data. All data have undergone strict quality control and pre-processing. For example, the projection of GIS data is unified to the Shanghai local coordinate system, and the elevation is unified to the Wusong datum.

The modelling tool. The main focus of the research is on tidal flooding from the Huangpu River, and a detailed 1D model of the river has been constructed. This model has been combined with a 2D model of the floodplains and flood defences to produce a 1D/2D model of the Huangpu River, the floodplains and the coastal defences. This is done because it is apparent that, during a typhoon event, flooding can occur from the coast due to high sea levels as well as the Huangpu River. Drainage from the city can also contribute to flooding from the Huangpu River, and it was therefore decided to use the 1D/2D model to investigate surface water flooding and drainage discharges. The software package used for both 1D and 2D components is InfoWorks ICM (v. 9.0). This software is widely used in China (and in Shanghai in particular) for urban drainage analysis.

Model calibration and validation was performed as follows. (1) The 1D model of Huangpu River between Wusong and Mishidu gauge was constructed using 165 river cross-sections with an average spacing of 500 m, and the 1D model of Suzhou River was constructed using 109 river cross-sections with an average spacing of 320 m. The 1D model of Huangpu River was first calibrated for the Fitow Typhoon (6–10 October 2013) and then validated for the maximum water levels during the Haikui typhoon (6–10 August 2012) using observed water levels at Wusong gauge. The validation results show a very close match between the predicted and observed maximum water levels (Supplementary Fig. 17). Section S2.2 in Supplementary Information presents the details on the calibration and validation of the 1D model. (2) The 1D Huangpu River model was combined with a 2D model of the floodplains including the coastal area and coastal defences, with the resolution of 100 m × 100 m. The 1D/2D model was first calibrated for the '9711' typhoon (19–23 August 1997) and then validated for the 'Haikui' typhoon of 2012. The validation results (Supplementary Fig. 20) indicate that the general flood depths predicted by the 1D/2D model have a good match with the observations. Sections S2.3 in Supplementary Information discusses the details on the calibration and validation of the 1D/2D model. The baseline modelling for scenario analysis is presented in Section S2.4 in Supplementary Information.

Design of the future extreme flood event scenarios

Tides. The current intended standard of protection for Shanghai is 1 in 1,000 years. The combination of the present-day extreme tidal water level, extent of land subsidence and sea level rising scenarios lead to peak 1,000-year tidal levels at Wusong of 6.92 (present day), 7.42, 7.92, 8.92 and 9.92 m above Wusong datum, respectively. Future sea level rise is uncertain, and these values have been selected to investigate what would happen under very severe conditions of sea level rise and the mitigation measures that would be needed to develop long-term 'no-regrets' adaptation pathways. Section S2.5.1 in Supplementary Information presents a detailed analysis of the present-day extreme tidal water levels and then the development of future tidal water levels under a sequence of sea level rising scenarios of up to 3 m.

Fluvial inflows into the Huangpu River. The fluvial inflow to the model on the Huangpu River is the estimated 100-year flood event at Taihu Gate, which has a peak flow of 1,220 $m^3 s^{-1}$ (ref. 47). Future scenarios are based on increases to this flow, and the following percentage increases in this level of flow have been assumed: (1) 100-year + 50% fluvial inflow in Huangpu River; (2) 100-year + 100 % fluvial inflow in Huangpu River. The increases are applied to the entire flood hydrograph. These represent large future flows but do not correspond to any particular epoch or specific climate change scenario. It is also understood that this does not match the current operation of Taipu gate, but the purpose of this analysis is to understand the potential impacts of large increases in river flows in order to develop long-term 'no-regrets' adaptation pathways. Section S2.5.2 in Supplementary Information presents a detailed discussion on present-day extreme fluvial inflows and then the development of future extreme fluvial inflows into the Huangpu River.

Drainage. In view of the limited information on pumped inflows into the Huangpu River that has been identified for this study, the impacts of drainage inflows are assessed by scenarios of drainage inflows that are assumed to be constant steady flows for the duration of the typhoon events. The current urban drainage pumping capacity is almost 4,000 $m^3 s^{-1}$. A scenario that might be indicative of present-day conditions is to use an average inflow of 2,000 $m^3 s^{-1}$ over a 6 h period. Future plans indicate an increase in pumping capacity to about 7,400 $m^3 s^{-1}$. Future representative scenarios of pumping into the Huangpu River are selected as 4,000 $m^3 s^{-1}$ and 6,000 $m^3 s^{-1}$. For the purposes of this study, three drainage inflows into the Huangpu River are therefore used, as follows: present-day scenario: 2,000 $m^3 s^{-1}$; medium future scenario: 4,000 $m^3 s^{-1}$; high future scenario: 6,000 $m^3 s^{-1}$. These are used in the study to identify the impact of the inflows on flood levels and the effect on potential flood mitigation measures and the long-term 'no-regrets' adaptation pathways. Background information on drainage systems in Shanghai and the rationales to support the above scenario settings are presented in Section S2.5.3 in Supplementary Information.

Extreme rainfall. The base rainfall scenario is a concentrated rainfall for 3 h in a 100-year event, in line with the 2017 Guideline of the Shanghai Municipal Bureau of Quality and Technical Supervision. The rainfall distribution during the 3 h period is shown in Supplementary Fig. 23 in Section S2.5.4 in Supplementary Information. The total rainfall is 150 mm in 3 h, and the maximum rate is just over 25 mm in 5 min. The future rainfall scenarios are set by adding the increments from the base rainfall scenario to the current 200-year, 500-year and 1,000-year tidal events, respectively.

Combinations of high tides, high river flows and drainage inflows. Combined events (also referred to as 'compound events') are those where more than one source of flood water occurs during a flood event. The two main sources of flooding (high tidal water levels and rainfall) can occur at the same time during a typhoon. Inspection of historic data was therefore undertaken to consider the likely co-incidence of these sources of flooding. Data for tidal water levels, river flows and rainfall during some historic events were obtained, and the combinations that caused the worst flood conditions in Shanghai were identified, which are the 9711 (1997) and Haikui (2012) typhoons as presented in Supplementary Fig. 25 in Section S2.5.5 in Supplementary Information. It is apparent that heavy rainfall coincided with high tidal water levels in both cases. In the largest event (9711), the peak tide occurred just after the heaviest rainfall as shown in Supplementary Fig. 26. There is clearly a very high probability that heavy rainfall and high sea levels will coincide in the case of Shanghai, and this is assumed to be the case in the analysis. As these are the two main sources of flooding, detailed joint probability analysis has not been undertaken at this stage but can be undertaken in future more detailed research.

Development of dynamic adaptation pathways using engineering options

The main engineering measures include raising the standards of the existing defence systems and constructing a major tidal barrier/barrage. Raising defence standards without a barrier or barrage will require raising the defences throughout the Huangpu River and the coastal lines. This option will be suitable in the short term without substantial rise of the sea level. The construction of a tidal flood barrier near the Huangpu River mouth is favoured by the SWEDRI, and investigations are in progress. A tidal barrier consists of a structure with gates that are open under normal circumstances but are then closed when a tidal surge occurs, so that it has minimal impact on navigation and river flows under normal conditions.

Outline designs of these two types of defence measures are prepared for the different scenarios of extreme flooding events. These outline designs make it possible to identify the changes that would be needed to move from one scenario to another.

The next step is to identify thresholds when changes should be made. The most important threshold identified is the sea level rise that would require raising of the barrier structure and gates. Other thresholds included the sea level rise that would lead to an excessive number of barrier closures. A high number of barrier closures would have an adverse impact on navigation, and, more seriously, would affect the reliability of the barrier to close during surge tides. The standard of reliability of the barrier must be very high to maintain a 1-in-1,000-year standard of protection. If there is a large annual number of closures, the time available for maintenance activities will reduce and the risk of a barrier failure will increase. It is therefore proposed that the number of barrier closures is limited to 50 per year on the basis of experience at the Thames Barrier[48]. In this case, the mitigation measure to prevent a larger number of closures will be to raise the upriver defences.

These thresholds define when a specific set of major interventions would be needed to the flood defence system. Each option consisted of a sequence of interventions, with each intervention taking place when a threshold is reached. Supplementary Fig. 27 in Section S2.6 in Supplementary Information illustrates this concept. In the figure, the threshold is shown as the probability of flooding that must not be exceeded and is referred to as 'the design standard'. The baseline flood probability increases with sea level rise and is shown by the green line. When the threshold value is reached, an intervention is needed to reduce the flood probability below the threshold level. As the sea level continues to rise, further interventions are needed. This corresponds to a sequence of interventions to reduce flood probability and prevent the probability of flooding exceeding the target value. It must also be possible to undertake additional works when the future condition is reached, and the interventions must therefore be adaptable for further interventions in the future.

In practice, the interventions must be constructed before the thresholds are reached where the flood probability exceeds the design standard. This requires monitoring of sea level rise and other climate drivers. The results are used to update the projections of the dates when critical thresholds will be reached. A decision is then made to proceed with the intervention. The 'decision point' must allow enough time to plan, design and construct the works. Supplementary Fig. 28 illustrates this concept for the case of sea level rise. It shows the amount of sea level rise when the intervention is needed, and the timing of the decision point to ensure that the work is completed in time. This means that designs are not carried out for a particular future date, but for a particular future threshold level. The date of the intervention will change as the rate of sea level rise changes, and therefore monitoring is needed so that the date of the decision point can be updated. There will be choices of different interventions and therefore different options for managing flood risk in the long term. Each option can be represented as a decision pathway in which each intervention is plotted against the key climate driver, as presented in the 'Dynamic adaptation pathway for mitigating flood risks and managing uncertainty' section.

Limitations

It is worth noting that the analysis presented in this paper is high level and is intended to support the development of a strategic plan for flood management into the long-term future. It includes simplifications, assumptions and approximations, and is limited in detail. Once the strategic approach has been established, much more detailed work would be needed to explore the options in details including justification for selecting particular engineering options.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Datasets for this research are available from existing publications and official sources as presented in Supplementary Table 2 in Supplementary Information.

Code availability

The analysis was carried out using InfoWorks ICM (v-9.0) hydraulic and hydrologic modelling tool (https://www.innovyze.com/en-us/products/infoworks-icm), which is a commercial software developed by HR Wallingford Group (Innovyze is a software subsidiary of HR Wallingford Group).

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Author contributions

Z.T., D.R. and L.S. conceived and designed the research. Z.T., D.R., L.S. and Y.H. performed the experiments. Z.T., D.R., L.S., Y.H., H.Z. and J.L. analysed the data and contributed materials/analysis tools. Z.T., D.R. and L.S. wrote the paper.

Competing interests

We declare the authors have no competing interests as defined by Nature Research, or other interests that might be perceived to influence the interpretation of the article.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used in data collection
Data analysis	InfoWorks ICM (v-9.0) hydraulic and hydrologic modelling tool (https://www.innovyze.com/en-us/products/infoworks-icm), which is a commercial software developed by HR Wallingford Group (Innovyze is a software subsidiary of HR Wallingford Group).

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Datasets for this research are included in the following published papers (and their supplementary information files and OSF repository) and books: Dong et al. (2020), Hu et al. (2019), Ke et al. (2018), Shan et al. (2019), China Sea Level Bulletin 2021, Shanghai Municipal Government (2017), Shanghai Urban Planning and Land Resource Administration Bureau (2018), Statistic Year Book of Shanghai (annual series from 2010 to 2020).

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	N.A.
Population characteristics	N.A.
Recruitment	N.A.
Ethics oversight	N.A.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

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All studies must disclose on these points even when the disclosure is negative.

Study description	We develop climate change resilient engineering pathways for mitigating future compound flooding risks in Shanghai, with an emphasis on planning “no regrets” flood defence systems in low-lying coastal cities.
Research sample	Data collected include river bathymetry (cross-section), land topography, coastal and river embankment data (including Huangpu River and Suzhou Creek), drainage capacity data, land use data, and demographic and socioeconomic data. Historical compound events in Shanghai that were analysed include typhoons, astronomical tides, heavy rain, and upstream inflow. Historical flood events that were analysed include the “9711” typhoon in 1997, “Haikui” typhoon in 2012, “Fitow” typhoon in 2013, and a record-breaking rainstorm on 13 September 2013.
Sampling strategy	The regret theory justifies a distinct attention to the worst case of flooding events in the past, therefore, we selected the top four worst cases of flooding events in Shanghai for model calibration and verification. These four cases are the “9711” typhoon in 1997, “Haikui” typhoon in 2012, “Fitow” typhoon in 2013, and a record-breaking rainstorm on 13 September 2013.
Data collection	(1) Weather/climate/hydro data and physical geographical data: Weather/climate/hydro data include typhoons, astronomical tides, heavy rains, upstream inflow, and hydro-meteorological monitoring data. physical geographical data include underwater (cross section) and land topography data, coastal and river embankment data (including Huangpu River and Suzhou Creek), drainage capacity data, and land use data. These data were obtained from Shanghai Water (Ocean) Bureau, Shanghai Waterway Bureau, Shanghai Meteorological Bureau, Shanghai Institute of Surveying and Mapping, Shanghai Municipal Bureau of Quality and Technical Supervision, and Shanghai Hydrological Stations; China Sea Level Bulletin 2021; and the publications (and their supplementary information files and OSF repository) of Dong et al. (2020), Hu et al. (2019), Ke et al. (2018), and Shan et al. (2019). (2) Socioeconomic data: were collected from Shanghai Municipal Government (2017), Shanghai Urban Planning and Land Resource Administration Bureau (2018), Statistic Year Book of Shanghai (annual series from 2010 to 2020).
Timing and spatial scale	1997-2100+. 100m x 100m grid-cells across Shanghai.
Data exclusions	No data were excluded from the analysis.
Reproducibility	Modeling methods are reported in detail in Methods and Supplementary Information.
Randomization	No random sampling in this research.
Blinding	Blinding is not relevant as no experiments were involved.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Fieldwork conditions were very good in general.
Location	Shanghai and Taihu Lake Administration, China.
Access & import/export	Accesses to local experts were facilitated by the local collaborators in the research projects.
Disturbance	No disturbance was caused by the study.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

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☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging