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# Strategic storm flood evacuation planning for large coastal cities enables more effective transfer of elderly populations

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 Check for updates

Jie Yin <sup>1,2</sup>✉, Yuhan Yang <sup>1</sup>, Dapeng Yu <sup>3,4</sup>✉, Ning Lin <sup>5</sup>, Robert Wilby <sup>3</sup>, Stuart Lane <sup>6</sup>, Bindong Sun <sup>7</sup>, Jeremy Bricker<sup>8,9</sup>, Nigel Wright <sup>10</sup>, Lili Yang<sup>11</sup> & Mingfu Guan <sup>4,12</sup>✉

Emergency responders in coastal cities are anticipated to provide effective evacuation of at-risk populations during the preparedness and response phases of coastal floods due to land-falling storms or cyclones. However, existing contingency plans primarily focus on the evacuation of the general public rather than special arrangement for elderly populations who constitute a large proportion of flood fatalities. Here we present a system-level methodology to elaborate citywide coastal flood evacuation plans for optimal deployment of shelters and effective transfer of elderly people with special needs. We conduct a comparative analysis between Shanghai and New York City, which are both among the most exposed coastal cities to storm-induced flooding but represent two distinct institutional systems of emergency operation. The results show marked disparities in evacuation patterns for elderly residents in the two cities. Storm flood evacuation is more challenging in Shanghai due to insufficient provision of shelter capacity (~230,000). Implementing risk-informed and strategic planning could not only meet the potentially huge demand of vulnerable elderly (~520,000) but also improve the overall efficiency of evacuee transfer by a factor of 3. Our work provides new insights into operational emergency evacuation decisions and informs flood management policy development for major coastal cities globally.

Recurring coastal flooding caused by storm surge and astronomical tide can be witnessed globally each year and appears to be more frequent and devastating as climate-induced sea level rise (SLR), possible changes in storm characteristics, growing population, urbanization and human-induced subsidence, leading to considerable losses and

substantial impacts in many low-lying coastal areas around the world<sup>1–3</sup>. Recent coastal flood catastrophes in Shanghai (1997), New Orleans (2005), New York City (NYC, 2012) and Macau (2017) illustrate that coastal cities in both developing and developed countries are particularly vulnerable to storm surge flooding, owing to their concentration

<sup>1</sup>State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, China. <sup>2</sup>Key Laboratory of Geographic Information Science (Ministry of Education), East China Normal University, Shanghai, China. <sup>3</sup>Geography and Environment, Loughborough University, Loughborough, UK. <sup>4</sup>Previsico Ltd, Loughborough, UK. <sup>5</sup>Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA. <sup>6</sup>Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland. <sup>7</sup>Research Center for China Administrative Division, East China Normal University, Shanghai, China. <sup>8</sup>Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA. <sup>9</sup>Department of Hydraulic Engineering, Delft University of Technology, Delft, the Netherlands. <sup>10</sup>School of Engineering, University of Birmingham, Birmingham, UK. <sup>11</sup>Department of Statistics and Data Science, Southern University of Science and Technology, Shenzhen, China. <sup>12</sup>Department of Civil Engineering, the University of Hong Kong, Hong Kong, China. ✉e-mail: [jiyin@geo.ecnu.edu.cn](mailto:jiyin@geo.ecnu.edu.cn); [D.Yu2@lboro.ac.uk](mailto:D.Yu2@lboro.ac.uk); [mfguan@hku.hk](mailto:mfguan@hku.hk)

of population and assets, the changing hydrologic regime (for example, increasing imperviousness and wetland loss), the worsening topographic situation (for example, land subsidence and coastal erosion) and/or inadequate investments in integrated management<sup>4–7</sup>. Even if adaptation measures maintain present defence standards or constant flood probabilities, projected climate change combined with expanding human footprints may further aggravate flood exposures and risks in major coastal cities worldwide<sup>8,9</sup>. In the 136 largest coastal cities, total population exposed to 100-year coastal floods is estimated to grow more than threefold from 38.5 million in 2005 to 150 million by the 2070s, and the economic damage is expected to dramatically increase to more than ten times the current levels (that is, US\$6 billion in 2005) by 2050 (refs. 10,11).

As recognized by White<sup>12</sup>, ‘Floods are acts of God, but flood losses are largely acts of man’. In response to evolving coastal flood hazard, there is a huge demand to minimize or even prevent the potential adverse consequences during extreme storm (for example, hurricane, typhoon or cyclone) for flood-prone coastal cities<sup>13,14</sup>. Although large-scale coastal ‘flood control’ projects, such as barriers and levees, are often regarded as the most cost-effective way to protect the city against flooding, it has long been known that, in some cases, such structural measures tend to provide the perverse incentives for occupation of flood-prone areas along with a widespread lack of awareness of the associated risks, and thus contribute to floodplain occupants’ underestimation of their exposure and vulnerability to coastal flooding<sup>15,16</sup>. In addition, raising the height of flood defences to increase protection for an exposed community can still magnify flood hazard in another poorly protected place of coastal floodplain. In particular, by fostering floodplain development in many coastal cities like Shanghai and New Orleans, large-scale construction and improvement of levee systems (the so-called levee effect) have actually led to much larger losses from catastrophic storm floods when the levees were eventually overtopped or failed<sup>1,6,17</sup>. Hence, it is crucial to fully understand and inform the vulnerable people’s perception of, and engagement in, the lifecycle of flood management for coastal cities.

Given the inherent uncertainties and limitations of long-term coastal resilience strategies (risk management), municipal government is always required to provide effective operations to protect its coastal populations during the preparedness and response phase of a storm flood emergency<sup>18</sup>. The leading and foremost used means involving the challenging tasks may be the evacuation of people from vulnerable communities, generally 24–72 h in advance of threatening storms and associated floods<sup>19</sup>. Despite the importance of evacuation, in case of an impending disaster, many citizens are eventually unable or unwilling to leave, due to several reasons such as health issues and the false belief that their homes would be safe<sup>20</sup>. At the same time, a substantial number of evacuees put heavy demands on the transportation network and shelter system in a short timespan<sup>21</sup>. In a survey conducted after Hurricane Katrina<sup>1</sup>, while an estimated one quarter of New Orleans residents chose to stay in their homes or to take refuge in the overcrowded Superdome and Convention Center, as many as a million people in the metropolitan area have responded to public calls for evacuation, creating one of the largest traffic jams in US history. Such failures, primarily attributed to insufficient planning of mass evacuation and limited coordination among various stakeholders, have proved costly in terms of lives lost and again raise the question of whether and how to evacuate before floods hit.

Successful evacuation management is far more than issuing a mandatory, recommended or voluntary evacuation order for a given place. Based upon a better understanding of household evacuation demands and a clearer risk communication to improve order compliance, emergency plan may also suggest when people should evacuate through which route and to which location in a timely manner. During past decades, considerable progress has been made in the development and application of storm flood evacuation strategies

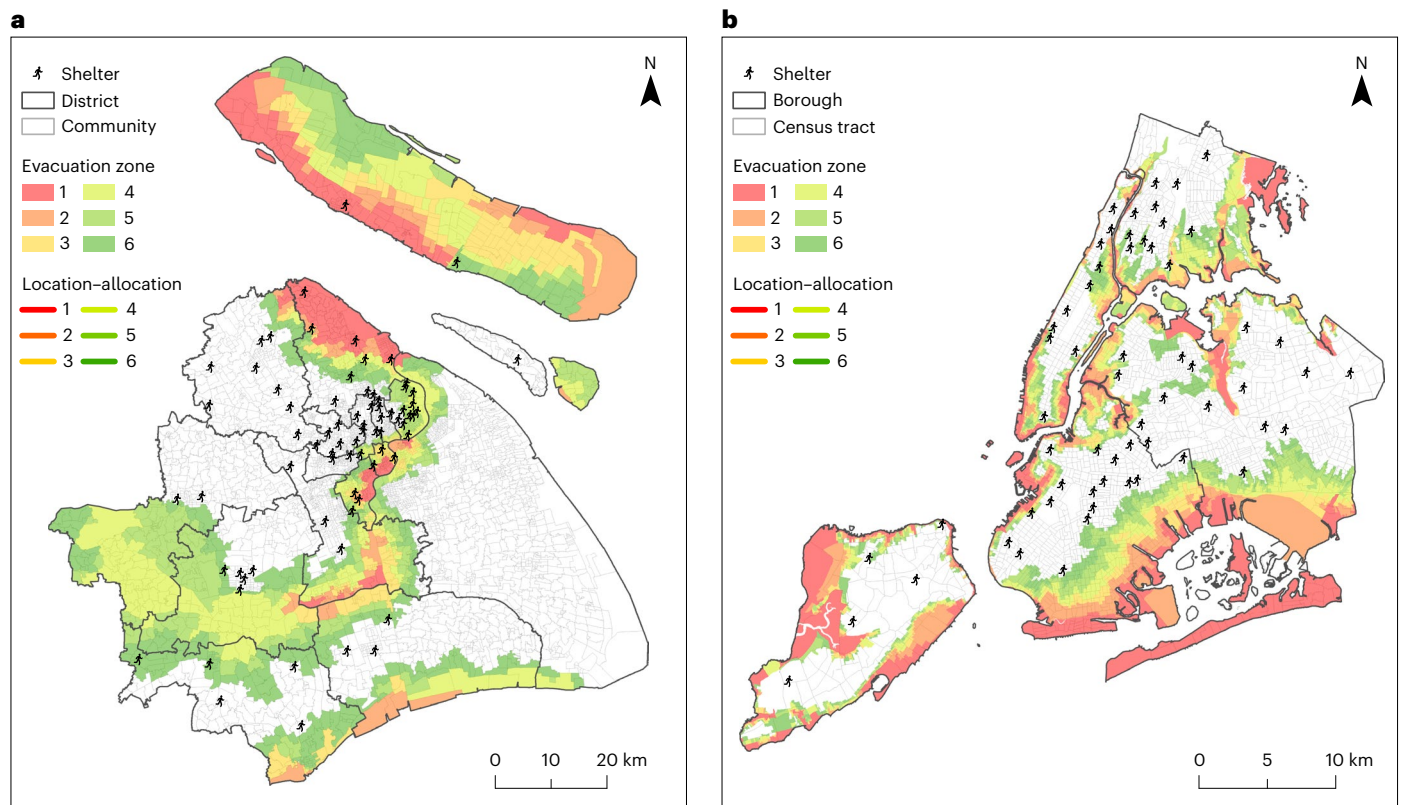
and plans for vulnerable coastal cities, mainly including evacuation zoning, sheltering and routing<sup>22,23</sup>. According to the interpretation of storm surge modelling, the Federal Emergency Management Agency has proposed a procedure to guide the establishment of hurricane/flood evacuation zones for major coastal cities in the United States<sup>24,25</sup>. A variety of evacuation planning and management approaches, including location–allocation models and traffic assignment models, have been developed to determine the number and location of shelters as well as to assign evacuees to shelters and routes<sup>26–28</sup>. In general, existing studies primarily focused on the evacuation of the general public by means of private vehicles. Recently, a draft point-to-point sheltering for ambulatory elderly residents has been designed by the New Orleans’ City Assisted Evacuation Plan-2022 to provide a mechanism for seniors (over the age of 65) without major medical needs to receive direct transportation from pre-identified living facilities to designated shelters. However, regional or city-scale evacuation plans have not yet adequately addressed a system-level multi-objective optimization problem that aims to provide strategic positioning of shelter facilities with procedures for the effective transfer of vulnerable populations, making them less practical for widespread applications.

Through the summary of the experiences gained and lessons learned from the past, ‘The Sendai Framework for Disaster Risk Reduction 2015–2030’ adopted by the Third United Nations World Conference on Disaster Risk Reduction urges local authorities to strengthen their capacities to efficiently and equitably evacuate persons living in disaster-prone areas. Yet, so far, there is inadequate means of doing this and insufficient evidence of the limits of existing approaches. In this article, we propose a generalizable and scalable methodology that can support governments of coastal cities to elaborate more robust contingency plans for capacity-enhancing prioritization in shelter systems as well as coordinated transfer of elderly groups during an emergency evacuation to a major coastal flood due to a land-falling cyclone. We demonstrate the approach to Shanghai and NYC, which are not only both among the most exposed coastal cities to storm-induced flooding globally but also represent two contrasting institutional systems of emergency operation, namely vague plan but strong organization (Shanghai) versus clear plan but personal responsibility (NYC). Our analysis is informed by surveys of residents’ evacuation behaviour in Shanghai and NYC<sup>29</sup> (Supplementary Information section 1). We then explore disparities in hurricane/flood evacuation patterns with a comparative analysis of the two coastal megacities, and show the improved performance of risk-informed, well-organized emergency evacuation plans by combining a commonly used zoning method and a network-based optimization formulation. As far as we are aware, this is the first attempt to explicitly demonstrate the effectiveness and potential benefits of well-prepared, citywide government evacuation plans in particular for elderly people, thereby providing new insights into operational emergency management decisions for major coastal cities facing significant storms and flooding challenges.

## Results

### Evacuation zoning and sheltering

The NYC Office of Emergency Management designated six hurricane evacuation zones in 2013 as part of the city’s Hurricane Sandy After-Action report (Fig. 1b). The NYC evacuation zone system was primarily based on (1) the risk of coastal flood resulting from storm surge; (2) the geography of the city’s low-lying neighbourhoods; and (3) the accessibility of the neighbourhoods by roads and bridges<sup>30</sup>. Zone 1 encompasses the city’s coastline and low-lying areas that are most likely to be inundated with storm surge (under high tide initial water level) in the near worst-case scenario of a west–northwest bearing Category 1 hurricane. Zones 2–6 cover additional neighbourhoods that are subject to the flood impact of more extreme storms (a Category 1 hurricane and above). The higher the zone number, the lower the flood risk (see the definitions of zones 1–6 in Supplementary Table 1). Table 1 summarizes



**Fig. 1 | Hurricane/flood evacuation zones and emergency shelters in Shanghai and NYC. a, b,** Hurricane/flood evacuation zones and emergency shelters in Shanghai (a) and NYC (b). NYC hurricane evacuation zones (b) were designated by the NYC Office of Emergency Management after Hurricane Sandy in 2013.

the areal and population coverage of NYC hurricane evacuation zones. All of the evacuation zones occupy almost half (~49%) of the city area and include over 3 million New Yorkers accounting for ~39% of the total population derived from the 2010 NYC census. Particularly, ~41% (18.9 thousands) of the elderly (people over 75 years old) who are always disproportionately affected by coastal flooding, are estimated to reside within the boundaries of evacuation zones 1 through 6. Hence, such vulnerable people (including the elderly) are highly concentrated in NYC evacuation zones with a population density of 8,270 people km<sup>-2</sup> (compared with a city average of 10,448 people km<sup>-2</sup>).

Given the absence of an official zoning plan for storm flood evacuation in Shanghai, we delineated the borders of evacuation zones for the city in accordance with the regulations of coastal flood management in China and the general principles of NYC Hurricane Evacuation Zoning. We begin by identifying coastal flood levels with various return periods and amounts of SLR utilizing a 2D flood inundation model (see Methods for details and Supplementary Fig. 1). We then use the generated flood maps to define and classify vulnerable communities and associated accessible neighbourhoods into six evacuation zones (Fig. 1a). Zone 1 includes the city's low-lying and poorly protected waterfront areas that are susceptible to a present 100-year flood event, whereas zones 2–4 further extend to the coastal and Huangpu River floodplains depending on the severity of longer return period events (200-, 500-, 1,000-year) under current conditions. Considering the local effect of relative SLRs in Shanghai, zones 5 and 6 are at risk from future high-end scenarios (that is, 1,000-year floods under 2030 and 2050 sea levels), respectively (Supplementary Table 1). As shown in Table 1, approximately ~37% (over 8.4 million) of the city's population live within the zones of 2,795 km<sup>2</sup>, equivalent to ~41% of the land area of Shanghai. Meanwhile, the percentage coverage of the evacuation zones for the elderly people (75+) is found to be relatively high (~46%).

Perhaps most notable is that the spatial distribution of the residents is strongly uneven across the six evacuation zones, with zones 6 and 1 being the top two most densely populated areas.

Both cities provide a number of evacuation shelters to meet the basic needs of evacuees during a coastal flood or other emergency. NYC's shelter system consists of 60 evacuation centres that are generally well positioned outside of the evacuated area. They are designed to accommodate up to 600,000 people when fully activated for all evacuation zones (Fig. 1b). The provision of NYC emergency sheltering is considered to be sufficient because among residents who evacuated during Hurricane Sandy, 78% stayed with friends or relatives, and only 2% sought shelter<sup>30</sup>. In Shanghai, there are a total of 91 emergency shelters scattered throughout the city, including 74 indoor facilities (for example, schools and stadiums) and 17 outdoor places such as open spaces. Of those indoor shelters suitable for flood emergency (Fig. 1a), ~34% (25) fall within the six evacuation zones and the remaining ~66% (49) will be functional with a full capacity of over 230,000 people, representing less than 3% of resident population and 45% of elderly people in all evacuation zones. It is noted that according to the evacuation behaviour survey (see Supplementary Information section 1), the residually limited capacity of operational shelters significantly mismatches the potentially huge demand of flood evacuation, which is usually organized by local government in China rather than predominantly by individual evacuees in the United States. Such a large capacity–demand mismatch may impose an excessive burden on the city's emergency evacuation services, potentially leading to substantial inequalities in accessibility among population groups.

### Evacuation routing and planning

There exists worldwide evidence that aged and infirm populations are the prime victims of the destructive flooding, the botched evacuation,

**Table 1 | Areal and population (percentage) coverage of coastal flood evacuation zones in Shanghai and NYC**

Evacuation zone	Shanghai			NYC		
	Area (km <sup>2</sup> )	Population	Elderly (75+)	Area (km <sup>2</sup> )	Population	Elderly (75+)
Zone 1	289.17 (4.27%)	1,055,066 (4.58%)	66,167 (5.79%)	123.69 (15.81%)	516,241 (6.31%)	36,329 (7.87%)
Zone 2	237.34 (3.51%)	330,400 (1.44%)	22,902 (2.00%)	79.07 (10.1%)	429,171 (5.25%)	30,175 (6.54%)
Zone 3	438.23 (6.47%)	844,650 (3.67%)	54,299 (4.75%)	36.31 (4.64%)	348,325 (4.26%)	19,939 (4.32%)
Zone 4	503.53 (7.44%)	1,623,265 (7.05%)	102,439 (8.96%)	45.00 (5.75%)	534,995 (6.54%)	31,876 (6.90%)
Zone 5	669.92 (9.90%)	1,934,135 (8.40%)	121,175 (10.60%)	49.51 (6.33%)	593,086 (7.25%)	32,153 (6.96%)
Zone 6	656.42 (9.70%)	2,657,732 (11.55%)	154,900 (13.55%)	50.32 (6.43%)	753,007 (9.21%)	38,621 (8.37%)
Zones 1–6	2,794.62 (41.28%)	8,445,248 (36.69%)	521,882 (45.66%)	383.91 (49.07%)	3,174,825 (38.84%)	189,093 (40.96%)

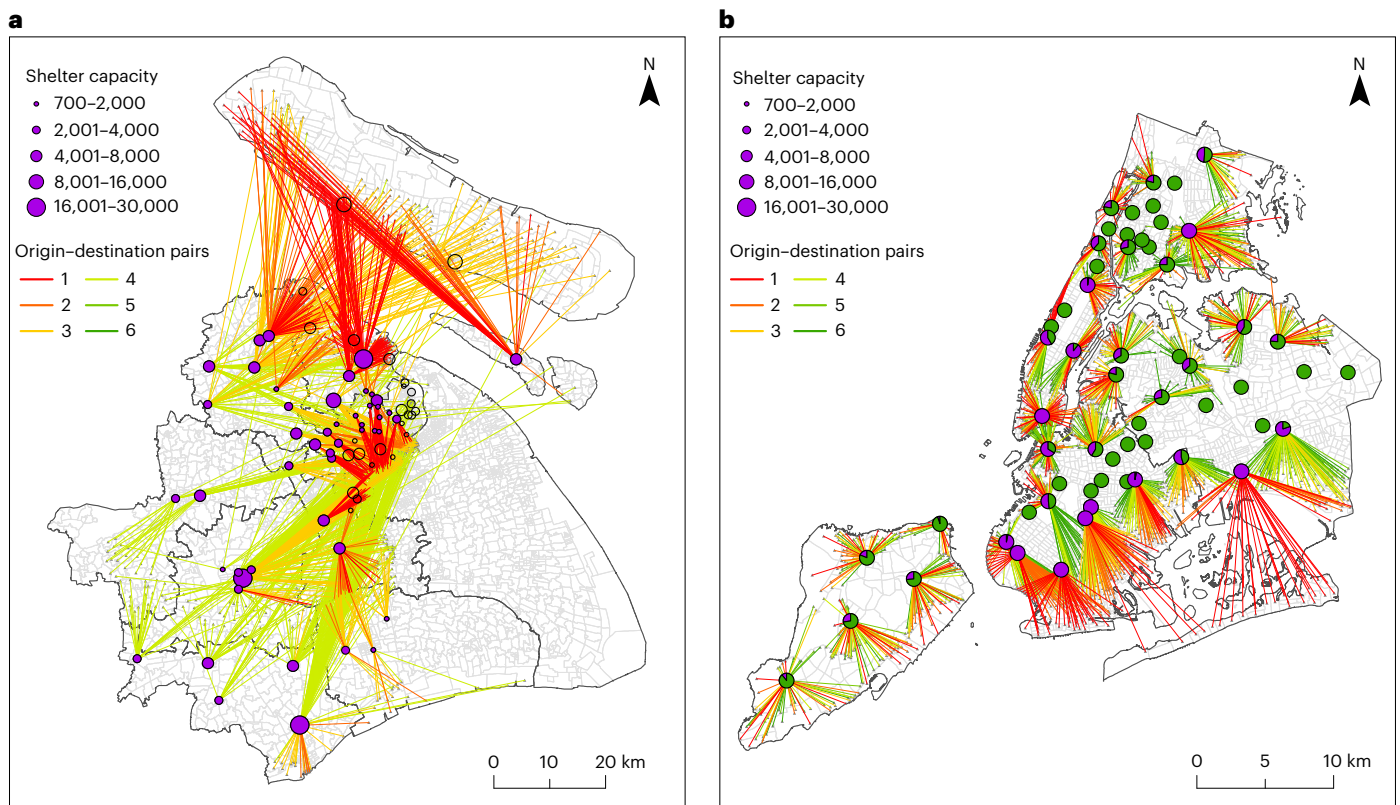
and the inadequate shelter<sup>1,31–33</sup>. For example, approximately ~71% of the flood victims associated with Hurricane Katrina (in 2005) were over 60 years old, and ~47% of those were older than 75, attributing to a progressively increasing (with age) physical inability to flee from danger<sup>34</sup>. Therefore, the aged who are least able to evacuate to safe places outside of the impact areas during a flood emergency should be given the top priority, regardless of disparities in disaster response behaviours. We assume that, in advance of a forecasted storm, an organized and phased evacuation operation will be implemented under a mandatory evacuation order, providing transportations (for example, buses) to orderly evacuate elderly population from zones nearest to the hazard before others who are in less danger. Here we present a system-level network analysis to enhance city-scale coordination of evacuee transfer and make efficient use of shelter capacities, exclusively focusing on the people over 75 years old who are most dependent on mass-transit emergency evacuation, drawing on the results of the household evacuation behaviour survey (Supplementary Information section 1). Specifically, we conduct a multi-objective multi-phase origin–destination (O–D) estimation for city-wide pre-event evacuation, based on a maximal covering location–allocation model. Then we apply a time-dependent routing algorithm to identify critical emergency corridors and to minimize average evacuation times for each city (see Methods for details).

Figure 2 shows the spatial distribution of the generated O–D pairs for evacuee–shelter assignments in Shanghai and NYC. We observe distinct evacuation patterns for both cities associated with varying shelter capacities and demographic characteristics. As illustrated in Fig. 2a, the existing non-uniform distribution and capacity constraint on sheltering would cause a massive, chaotic evacuation in Shanghai. Only the elderly who live in zones 1–3 and the vast majority of zone 4 can be mobilized during a large-scale evacuation of zones 1 through 6. In particular, due to a complete loss of shelter functions in Chongming Island, evacuees who need assistance and want to leave their home neighbourhoods would mostly be transferred to mainland Shanghai where many operational facilities are located. Additionally, major destinations of zone 4 evacuees from the city center, are two mega-shelters in the southwestern suburb, according to the residual capacities of the system. Supplementary Information includes a description of the patterns of O–D pairs for zones 1–5, independently (Supplementary Fig. 2). Unlike in Shanghai, shelter capacities are not a bottleneck of hurricane evacuation in NYC. All targeted people within zones 1–6 can be distributed to the closest evacuation centres in an efficient, structured way. Even if several facilities (for example, around Jamaica Bay and Manhattan Island) are heavily occupied or operate at full capacity, the first tier of the city's emergency shelters in close proximity to the edge of evacuation zones is still enough to accommodate the maximum estimated numbers of the elderly residents who need special assistance during a coastal storm (Fig. 2b). An emergency evacuation plan that implements such a demand-oriented strategy would result in a more balanced allocation of shelter facilities to vulnerable neighbourhoods throughout the city.

In terms of evacuation routing and timing, Fig. 3 displays the estimates of the evacuee transfers and associated time costs between origin neighbourhoods and shelter destinations in the transport systems of Shanghai and NYC. Consistent with the characteristics of the O–D patterns, we find clear differences in the spatio-temporal distributions of evacuees' mobility across the two cities. Dozens of critical evacuation arteries can be readily identified from the vessel-like structure in Shanghai, according to the estimated number of transfers (Fig. 3a and Supplementary Fig. 3). For instance, cross-island emergency evacuation will lead to heavy use of multiple routes (that is, a ferry route, a bridge + tunnel and several highways) from Chongming Island to Mainland Shanghai, with the corresponding time costs typically exceeding 1.5 h under baseline traffic condition. Although a great number of evacuees who will be transported from the city centre to the periphery may overload critical roads, the evacuation times are found to be relatively low (0.5–1.5 h) if appropriate traffic control measures are applied. The critical routes in NYC are less discernable than in Shanghai, because the distribution of evacuee transfers generally matches well with the distribution of shelter capacities via the city's high-density and well-developed road network (Fig. 3b). However, we still detect several important roads and bridges (for example, Belt Parkway and Cross Bay Boulevard) with mass evacuation flow around Jamaica Bay, which connect zones with high risks (for example, Rockaway Peninsula and Coney Island) to places with high capacities. In addition, apart from Rockaway Peninsula, the travel times for NYC evacuation neighbourhoods are markedly less than 20 min (Fig. 3d), whereas each trip of flood evacuations can take up to 3–4 h in Shanghai (Fig. 3c).

### Strategic positioning of shelters

The selection, modification and/or construction of shelters play a crucial role in addressing the high demand–capacity gaps across the system and thus increase the effectiveness and fairness of city-scale emergency evacuation. As the NYC emergency plan (including evacuation centres) is well prepared and the evacuation arrangements has previously worked well during coastal flood emergencies such as Hurricane Sandy, only the shelter system in Shanghai should be supplied with additional resources in locations and quantities to enhance shelter capacity throughout the city. Therefore, we design two alternative strategies for shelter deployment in the city. One strategy requires only minimum additional resources being focused on the combination of all existing shelters to meet the evacuation demands of the elderly within zones 1–6, whereas the other provides strategic optimization of the shelter system by ensuring sufficient capacity in key locations to minimize the total evacuation time for each route. Our analysis uses a multi-coverage facility location model to select and deploy additional shelters outside of the city's evacuation zones for both strategies, assuming that the capacities of these facilities range from 2,000 to 30,000 people based on the local design standard of emergency shelter. We also conduct a sensitivity analysis to evaluate the spatial



**Fig. 2 | Spatial patterns of O–D pairs for city-wide flood evacuation in Shanghai and NYC. a, b,** Spatial patterns of O–D pairs for city-wide flood evacuation in Shanghai (a) and NYC (b). The hollow circles in a represent non-functional shelters located in the evacuation zones of Shanghai. Green-coloured evacuation centres in b are completely vacant, while purple-coloured shelters are fully occupied. Evacuation centres with mixed green and purple wedges in

NYC (b) indicate the occupied (in purple) versus residual (in green) capacities of the shelters. The grey triangles denote the origin locations. The different coloured lines with numbers 1–6 denote the O–D pairs belong to corresponding evacuation zones; for example, the red lines are O–D pairs of zone 1 and the dark-green lines are O–D pairs of zone 6.

and temporal performance of the model with varying shelters (see Methods for details).

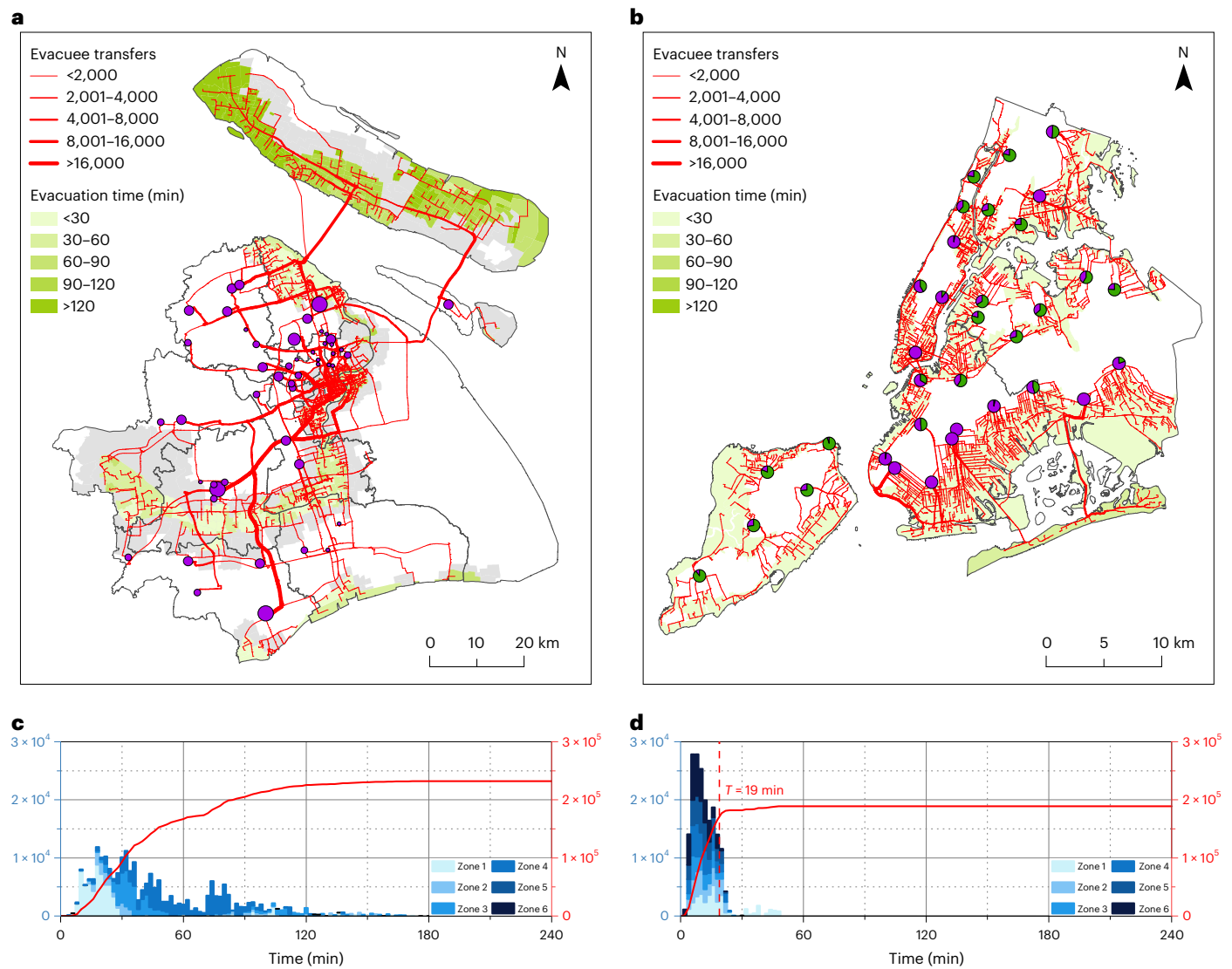
Figure 4 shows the deployment of shelters and the resultant distribution of O–D pairs for both strategies. While only 22 additional shelters are installed across the city in the first strategy, 128 shelters are strategically deployed in the periphery of the city's evacuation zones with the second optimization strategy, including 7 existing shelters, 115 candidate shelters and 6 potential mega-shelters that need to be constructed on Chongming and Hengsha islands. Though strategy 1 can accommodate all the elderly at city scale, it does not effectively mobilize evacuees due to the spatial mismatch between shelter capacity and evacuation demand. Almost all shelters would be heavily or fully occupied and a great number of cross-island and long-distance journeys are evident (Fig. 4a). Conversely, the O–D pattern of evacuation with strategy 2 is similar to that of NYC. Evacuees could be transferred locally to a nearby facility in an orderly manner, by deploying shelters in lower-capacity zones such as the downtown area of Shanghai and Chongming Island (Fig. 4b). As a result, tens of thousands of evacuees in Chongming Island do not have to be transported to shelters in mainland Shanghai via bridges, tunnels and ferries. Moreover, the total capacity of the shelters reaches up to approximately 686,000 people, providing more than 30% redundancy. This would improve system reliability in the case that some facilities are unavailable during extreme weather conditions or if there are more demands from other vulnerable groups such as people with very bad health.

Figure 5 depicts the spatio-temporal distributions of evacuee transfers and travel times between O–D pairs via the city's transport system for large-scale coastal flood evacuation plans with the first and

second strategies, respectively. An immediate finding is that the estimates with the optimization strategy, as expected, greatly outperform that of strategy 1, in terms of both evacuation efficiency and equity. In the first strategy, the general pattern of evacuation routes and times is similar to what has been found in Fig. 3a. The critical evacuation routes are still in place and would be further overloaded by the transfer of more evacuees from Chongming Island to Mainland Shanghai and from the city centre to the periphery (Fig. 5a). Despite the low efficiency in the remote islands, the estimates of evacuation time for 90% of the elderly is approximately 80 min under the baseline traffic condition (Fig. 5c), a slight reduction when compared with the initial evacuation plan in Shanghai (Fig. 3c). This can be explained by the presence of additional shelters that provide alternative options to transfer evacuees more promptly via less crowded routes, particularly in the Huangpu River floodplain. If more shelters are deployed using this methodology, the performance of the emergency evacuation could be gradually improved (Supplementary Fig. 4). In contrast, major emergency routes would be offloaded even more with the second strategy for optimal coastal flood evacuation (Fig. 5b). The long-distance evacuation arteries would be virtually replaced by capillary-like local roads in the city. Consequently, the travel times for 90% of total evacuees would be further reduced to only 23 min under baseline traffic condition and up to around 1 h when heavy congestion occurs (Fig. 5d).

## Discussion

We present a methodology to explore city-wide coastal flood evacuation plans in a systematic way and develop shelter deployment strategies for optimal transfer of at-risk elderly populations (Fig. 6).



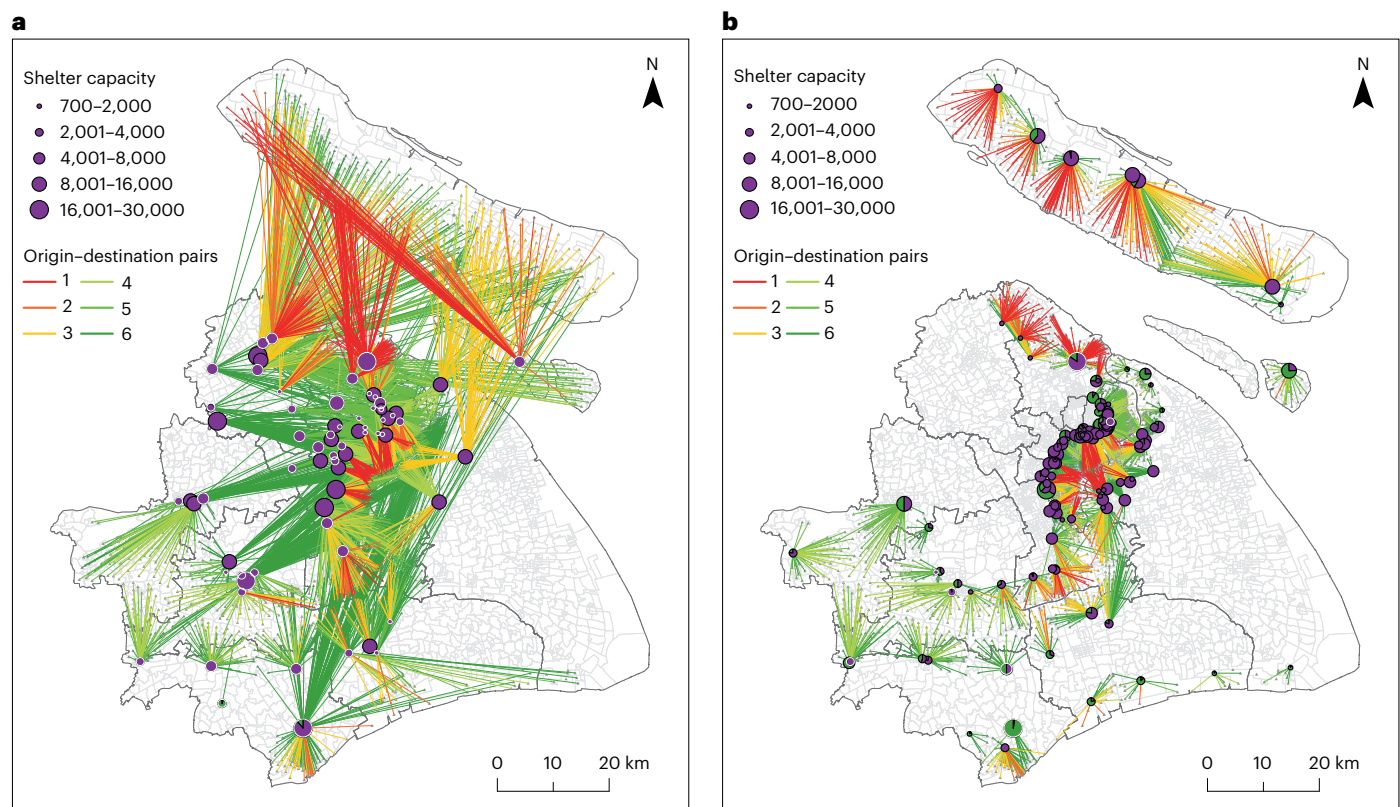
**Fig. 3 | Distributions of evacuee transfers and time costs between O-D pairs in the transport systems of Shanghai and NYC.** **a,b**, Distributions of evacuee transfers and time costs between O-D pairs in the transport systems of Shanghai (a) and NYC (b). The grey areas in **a** denote the evacuation zones where the

vulnerable people are unable to be transferred to shelters. **c,d**, Time series of evacuee transfers under baseline traffic condition for Shanghai (c) and NYC (d). Red-coloured line and axis represent the cumulative number of evacuees. The dashed line in **d** marks the time to transfer 90% of total evacuees in NYC.

A cross comparison between Shanghai and NYC demonstrates marked disparities in evacuation patterns due to the geographies of the cities, shelter provisions, flood zones and distinct institutional operations of coastal flood response, and reveals how stressed the emergency provisions would be in Shanghai in meeting the surge demands of low-probability storm flood. Such comparative analysis highlights the importance of incorporating risk informed zoning and strategic shelter positioning into exhaustive government evacuation programs that are usually missing in the coastal cities of the developing world. It also preliminarily accounts for population vulnerability in the context of environmental injustice that has already exposed large inequality in hurricane/flood emergency preparedness in the United States and some other wealthy nations<sup>35</sup>. Our method could assist emergency managers in better understanding the inadequacies of the existing contingency plans and assessing the effect of the targeted policy interventions. Given the generalizability and scalability, our approach presented herein could be readily adopted for applications in other flood-prone coastal cities around the globe such as Mumbai, Bangkok, Jakarta, Ho Chi Minh City, Miami and Tokyo to prioritize

the equitable allocation of resources and facilitate more effective operation of emergency evacuation.

Coastal cities in developed nations such as the United States attach great emphasis on advanced contingency planning ahead of catastrophic extreme events, but the actual evacuation process is often disorganized and evolved to an individual responsibility. On the other hand, many heavily populated cities in emerging or developing countries such as China are often strong in evacuation organization for vulnerable populations but insufficient in flood risk analysis and advanced evacuation planning. However, as coastal societies with rising populations and living standards become more sensitive to disastrous flood events, both nations have begun to strengthen their emergency management process by improving the organization and planning of evacuation. China is carrying out a first nationwide flood risk assessment and emergency evacuation planning, and the United States has also begun to attach greater importance to providing organized evacuation services for vulnerable groups during coastal flood emergencies. In practice, first responders in New Orleans (Office of Homeland Security and Emergency Preparedness) have conducted



**Fig. 4 | Strategic positioning of shelters and the resultant distribution of O-D pairs for strategy 1 and strategy 2 in the City of Shanghai. a, b,** Strategic positioning of shelters and the resultant distribution of O-D pairs for strategy 1 (a) and strategy 2 (b) in the City of Shanghai. The circles with black outlines indicate the new shelters.

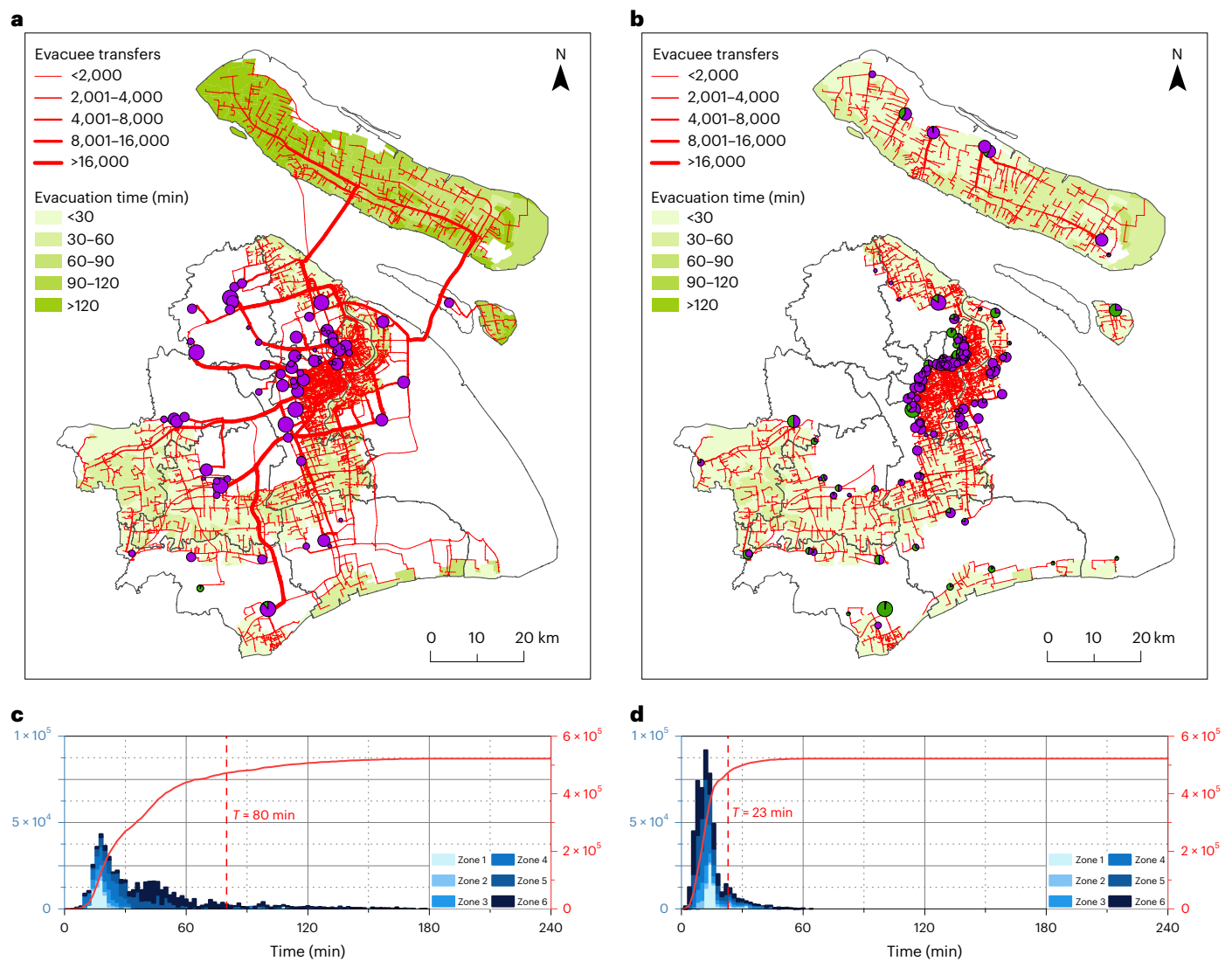
community-based registry to pre-identify seniors (65+) who were in need of assistance and provided specialized transit service to evacuate them outside of the impacted area before a hurricane emergency.

Of particular concern, we found that vulnerable neighbourhoods on the periphery of coastal cities are most exposed to storm-induced flooding whilst being least able to transfer to activated shelters outside of the evacuation areas, suggesting that improvements in resilience need to be geographically targeted at specific areas (hotspots). In many coastal cities, zones with higher shelter capacity are always located in urban areas, rather than within the zones with higher demands on emergency services. Despite lower population densities compared with downtown areas, the communities in the peri-urban/rural areas tend to be populated by special need groups including the aged. Notably, a large proportion of evacuation demands may arise from offshore islands such as Chongming Island in Shanghai, where it is much harder for emergency responders to gain access to transfer evacuees in good time. This uneven landscape of population vulnerability together with the centralization of shelters would exacerbate the criticality of emergency evacuation across the city, thus leaving the exposed neighbourhoods in peripheral zones predominantly underserved during extreme flood conditions. On the other hand, the government's push to decentralize the capacity could alleviate the poor performance of coastal flood evacuation in the periphery, but at the same time, may reduce emergency provisions to vulnerable populations in urban areas, especially in cities where local resources are often strained.

Effective plans for city-scale evacuation during coastal flood emergencies are largely dependent on continued functioning of the transport network, thereby requiring strong coordination capacity to direct large numbers of transit vehicles at a system level. The stage-based evacuation operations proposed here not only enable transfer of endangered populations with the highest flood risk at each phase,

but also, to a large extent, offload heavy use of public transit and road system simultaneously. Meanwhile, various operational traffic interventions such as the application of shoulder lanes and contraflow operations can be used as a complement to increase evacuation flow and route capacity at critical roads thereby avoiding severe congestion. The most common contraflow plan that reverses all inbound lanes to the outbound direction is estimated to provide a 70% increase in traffic flow. Single lane reversals and the use of outbound shoulder lanes are expected to improve road capacity by 30% and 8%, respectively<sup>36</sup>. In addition, advanced navigation systems and intelligent transportation systems can help emergency responders effectively design operation details for each neighbourhood such as pick-up location and departure time, ensuring the safety, efficiency and speed of evacuations. Overall, the right mix of such measures should be tailored to particular coastal cities, depending on levels of risk, funding and resources, coordination capacity and infrastructure conditions.

Given the ever-changing nature of coastal flood risk, it is important to maintain flexibility to adapt evacuation plans as new information about future scenarios becomes available<sup>37</sup>. We recommend that further research on coastal flood evacuation take into account effects of climate change, coastward urbanization and adaptation measures. In Europe, if no actions are taken, the expected number of people exposed to coastal flooding annually is estimated to unprecedentedly increase from 10.2K in 2010 to 1.52–3.65 million by 2100 (mostly in the major cities), due to rising extreme sea level and continued socio-economic development<sup>38</sup>. Also, recent studies have indicated that expanding and subsiding cities in South, Southeast and East Asia, as new hotspots, are increasingly vulnerable and exposed to relative SLR along with the associated coastal floods<sup>3,39,40</sup>. In addition, many coastal cities are or will be investing in risk reduction through multiple lines of defence (for example, the Big U project for NYC and the Huangpu River Barrier for



**Fig. 5 | Spatial distribution of evacuee transfers and travel times for large-scale coastal flood evacuation plans with strategy 1 and strategy 2 in Shanghai. a, b, Spatial distribution of evacuee transfers and travel times for**

large-scale coastal flood evacuation plans with strategy 1 (a) and strategy 2 (b) in Shanghai. c, d, Time series plot of evacuee transfers under baseline traffic condition for strategy 1 (c) and strategy 2 (d).

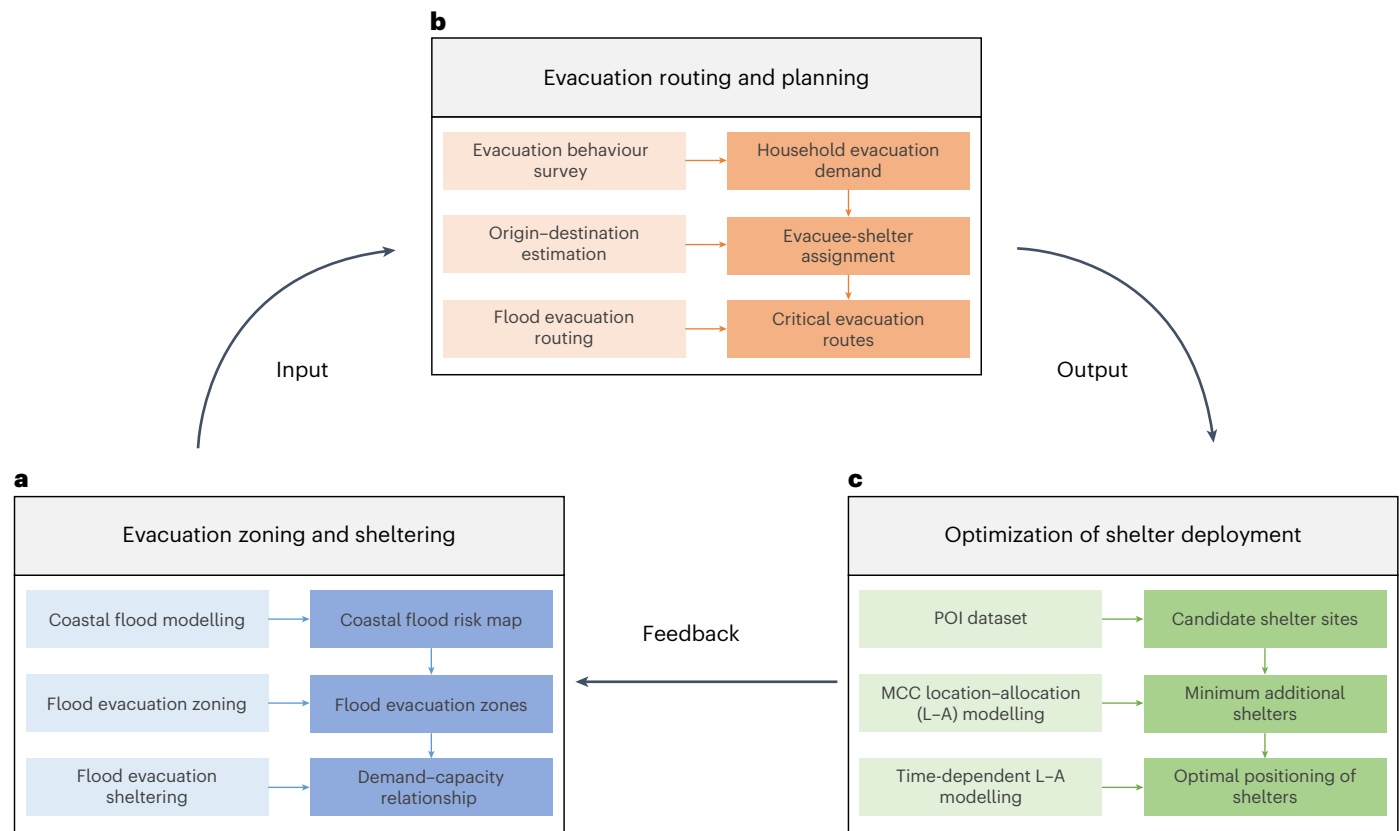
Shanghai) that in turn profoundly change flood hazard footprints and the corresponding evacuation zoning. Thus, emergency evacuation plans in coastal cities would need to be routinely reviewed perhaps every decade, in case of extreme conditions (beyond the design standards or failures of flood protection infrastructures). Ultimately, as an essential part of a resilient society, developing equitable, efficient and sustainable flood evacuation plans for coastal cities worldwide would contribute to several targets (for example, 1.5, 9.1, 11.5, 11.b and 13.1) of the United Nations Sustainable Development Goals.

## Methods

### Coastal flood inundation modelling

The flood areas for NYC were developed by the National Weather Service using Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, with the recommended interpretation of hurricane category, storm bearing, the size of the storm, and other information from the National Hurricane Center<sup>30,41</sup>. Here we utilize a simplified 2D hydraulic model (FloodMap-Inertial), developed by Yu and Lane<sup>42</sup>, to derive coastal flood inundation maps for Shanghai. It adopts a computationally efficient inertial algorithm to solve the 2D shallow water equations

in a raster-based environment<sup>43</sup>, with the Forward Courant-Freidrich-Levy Condition approach to calculate the time step. The model has been calibrated and validated in a number of coastal cities, including Shanghai and NYC<sup>44,45</sup>. To drive the coastal inundation modelling, boundary conditions and floodplain topography are required. Based on the frequency analysis undertaken by the Shanghai Water Authority, we generate dynamic boundary conditions (spatial and temporal grids) for 100-, 200-, 500- and 1,000-year flood return periods under the current condition, by interpolating station-based water levels and subsequently scaling Typhoon Winnie's stage hydrographs. We further combine the present 1,000-year flood boundary conditions with localized SLR (including subsidence) projections under RCP 8.5 (relative to the baseline year of 2010, Supplementary Information section 2) estimated by Yin et al.<sup>46</sup>, enabling future (2030 and 2050) flood scenarios to be formulated. Next, a 'bare earth' digital elevation model (DEM) constructed from 0.5-m topographic contours is available for Shanghai, with a grid cell resolution of 50 m. Since the improvement of flood defences can be highly uncertain, it is assumed that the current seawalls and floodwalls in Shanghai remain constant over the next several decades. We use the dike reliability functions,



**Fig. 6 | Theoretical framework of strategic storm flood evacuation planning for effective transfer of elderly population in large coastal cities. a, Evacuation zoning and sheltering. b, Evacuation routing and planning. c, Optimization of shelter deployment.**

developed by the authors<sup>46</sup>, to identify potential failure locations of seawall along the coast as well as floodwall along the Huangpu River (see details in Supplementary Information section 3). The potential breaching segments are removed and the heights of remaining flood defences are then overlaid onto the original DEM for each scenario. Finally, we use an empirically based floodplain roughness coefficient (Manning's  $n = 0.06$ ) in the simulations to represent the effect of urban features on flow routing<sup>47</sup>.

### Network-based geospatial analysis

Our evacuation mapping adopts a network analysis method to derive near-optimal shelter location-allocation and to identify critical emergency routes at city scale. We treat the location-allocation process as a maximize capacitated coverage problem, which selects facilities such that the greatest amount of evacuation demand can be served without exceeding the capacity of any facility. To solve the evacuation routing problem, we apply a modified Dijkstra's shortest-path algorithm with travel impedance weighted by travel time rather than distance. We create an O-D matrix of fastest-path costs between all the facilities and demand point locations along the network. If the total demand is greater than the capacity of a facility, only the demand points that maximize total captured demand and minimize total weighted impedance are allocated. We further consolidate shelters allocated with only a small number of evacuees to nearby operational facilities for the trade-off between time costs and effective use of capacities. The best O-D estimation is generated on the basis of search heuristics in ArcGIS Network Analyst and thus the number of evacuee transfers can be derived for each route section.

The spatial distributions of potentially vulnerable populations are represented by the most detailed level of 2010 census data, and the finest demographic units (that is, census block in NYC and community/

village in Shanghai) of evacuation zones are used as the origin neighbourhood locations. The transport networks of all roads, bridges and ferry routes in both cities, previously established by the authors<sup>18,46</sup>, include features such as speed limits, road hierarchy and one-way traffic. Driving regulations such as traffic signals and turn restrictions that emergency vehicles are exempt from during blue-light response are not considered. In the network analysis setting, travel speeds for different types of road are specified and assigned to each road section for both cities, including the baseline speeds (50% of the speed limits) and 80% reduction to represent different levels of traffic congestion, since the time cost for a normal trip was estimated to increase by a factor of ~2–5 during hurricane and coastal flood evacuation<sup>21</sup>.

### Deployment of additional shelters

The strategies for selection of sites for additional shelters require a modification to the constraint on the capacity and distribution. We firstly obtain more than 1,000 candidate shelter sites that could be used by proper retrofitting from the 'point of interest' (POI) dataset throughout the City of Shanghai, mainly including schools, stadiums, convention centres and the existing shelters that are outside the evacuation zones. The capacity limits are then assigned to each site, according to the design standard of emergency shelters in China (that is, 1–1.5 m<sup>2</sup> per person for level I, 1.5–2 m<sup>2</sup> per person for level II, and 2–3.5 m<sup>2</sup> per person for level III facilities). For the first strategy, additional shelters at a minimum can be determined from the POI candidate sites using the maximize capacitated coverage location-allocation model. To investigate the model performance in determining shelter locations and capacities, a sensitivity analysis is conducted by varying the number of facilities (at increments of ten shelters) as a control variable in the model run.

In terms of the second optimization strategy, a tolerance factor (that is, evacuation time  $\leq 1$  h) is specified in the model to ensure that

the evacuation time for each route is less than or equal to 1 h under the baseline condition. Due to a lack of adequate candidate shelters in the non-evacuation zones of Chongming and Hengsha islands, we create 248 grid cells with 1 km × 1 km resolution using the Fishnet tool in ArcGIS and set the grid cell center as the potential location of mega-shelters with a capacity of 10,000 people. Evacuation priorities are also assigned to the existing shelters rather than candidate sites and potential locations by introducing different weights. We further run the time-dependent location–allocation module to select shelters from all the facilities (that is, existing shelters, candidate shelters and potential mega-shelters) and then generate a preliminary O–D estimation at city scale. To save critical emergency resources, the shelters allocated with a very limited number of evacuees ( $\leq 100$  people in this case) are consolidated to nearby larger facilities across the system. Finally, an optimal solution of shelter deployment can be derived to ensure the effectiveness and fairness of coastal flood evacuation for the city.

### Data availability

The traffic network data, demographic data, evacuation centre data and evacuation zone map for NYC are freely available from the United States Census Bureau (<https://www.census.gov/>) and the NYC Open Data Portal (<https://opendata.cityofnewyork.us/>). The transport network and POI data in Shanghai are obtained from the AMAP Data Portal under licence. Shelter data in Shanghai are derived from the Shanghai municipal civil defence office (<https://mfbwz.mfb.sh.gov.cn/mfbwz/mfb/yjbnscs/map.html#>). The population census data are provided by the Shanghai Statistics Bureau. The topographic data and seawall/floodwall data are collated from Shanghai Municipal Institute of Surveying and Mapping and Shanghai Water Authority, respectively. Certain datasets of Shanghai are available from the authors upon reasonable request and with permission of the parties that provided the data.

### Code availability

Data analysis and results representation were produced by using Origin software (<https://www.originlab.com>) and ESRI ArcGIS (<https://www.esri.com>). FloodMap modelling software was used with permission from co-author D.Y.

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## Author contributions

J.Y. conceived the study, prepared the dataset, interpreted the result and drafted the manuscript. J.Y. and D.Y. designed the initial emergency evacuation model. R.W., N.L., N.W., S.L., J.B. and M.G. contributed to the further development of the methods and provided guidance on the optimization of shelter deployment. J.Y. and Y.Y. performed flood inundation modelling and network-based geospatial analysis. B.S. and L.Y. assisted in the questionnaire survey. All authors commented on the manuscript and gave final approval for publication.

## Competing interests

The authors declare no competing interests.

## Additional information

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**Correspondence and requests for materials** should be addressed to Jie Yin, Dapeng Yu or Mingfu Guan.

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