Flood relief logistics planning for coastal cities: a case study in Shanghai, China

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Abstract: Coastal cities are becoming more vulnerable to flood risks due to climate change, rising sea levels, intense storm surges, population growth, and land subsidence. Developing emergency preparedness and response strategies can reduce the impact of coastal flooding and –improve ~~enhance~~ a city's resilience. This article presents a flood relief logistics planning approach aimed at providing decision-makers with a feasible framework. The framework integrates geographic information system (GIS) network analysis and resource allocation optimization models. Considering the equity ~~fairness~~ of resource allocation, a bi-objective allocation model that minimizes the total transportation cost and maximum unsatisfied rate is developed. This flood relief logistics planning approach is applied to Shanghai, China, –to present~~s~~ feasible distribution strategies. ~~And, t~~The case study indicates that the current capacity of emergency flood shelters (EFSs) and the supplies stored in emergency reserve warehouses (ERWs) are adequate to meet the demand of the elderly population if affected by a 100-year coastal flood scenario. However, such capacity and supplies ~~they~~ would not be sufficient to cover the demand in a 1000-year coastal flood scenario and would be able to~~could only~~ serve only half of the affected elderly people. The results also suggest that the city-level ERW in Jiading District and the branch warehouse in Minhang District play ~~a~~ crucial role~~s~~ in distribution. Additionally, the study highlights the importance of increasing resource investments to tackle the inherent inequity~~unfairness~~ caused by resource shortages. This study provides a scientific reference for developing flood relief logistics plans in Shanghai, and it presents a transferable framework that is applicable to other coastal cities.

Keywords: Coastal flooding; Flood relief logistics planning; Relief distribution; NSGA-II; Bi-objective allocation model; Emergency flood shelters; Emergency reserve warehouses.

1. Introduction

Flooding is among the most frequent and catastrophic natural hazards, causing substantial global casualties and losses.~~.~~ Over the past two decades, the number of major flood events has more than doubled, claiming approximately 1.2 million lives and impacting over 4.03 billion people (Mizutori and Guha-Sapir, 2020). In particular, coastal cities, where population and assets are concentrated, have been severely affected by storm-

39 induced flooding(Cook and Merwade, 2009). For example, Hurricane Katrina-induced flooding overwhelmed 80%

40 of New Orleans in 2005, resulting in approximately 1833 fatalities, displacing approximately 770,000 residents,

41 and causing over $100 billion in losses (Kates et al., 2006; Townsend, 2006). Hurricane Sandy, which made

42 landfall near Atlantic City in 2012, triggered a catastrophic storm surge in New York City, causing disruptions of

43 city's systems ~~and~~, 43 deaths, and approximately $19 billion in losses (Bloomberg, 2013). ~~Furthermore,~~

44 ~~s~~Although the threat is already considerable, various ongoing trends could greatly amplify flood risks in the

45 coming years. Sea level rise (SLR) and storm surge intensification, driven by climate change, exacerbate the risk

46 of coastal flooding (Field et al., 2014), and the frequency of coastal flooding is predicted to double in the next few

47 decades (Vitousek et al., 2017). Moreover, the trend of rapid urbanization in coastal zones is expected to continue

48 in the future (Hallegatte et al., 2013), which may further amplify the impact of flooding (Jongman, 2018). Disaster

49 risk management systems face increasing challenges in adapting to evolving risk profiles (~~Intergovernmental~~

50 ~~Panel on Climate Change (~~IPCC, 2023). Hence, as the most crucial pathway for enabling governmental actors to

51 respond to this threat, the operational implementation of coastal flooding adaptations in emergency management

52 must be examined. ~~Hence, as the most crucial pathway for enabling governmental actors to respond to this threat,~~

53 ~~the operational implementation of coastal flooding adaptations in emergency management must be examined.~~

54

55 In recent decades, the increase in the frequency and intensity of coastal flooding has attracted growing attention

56 from the public, researchers and decision-makers worldwide (Moftakhari et al., 2017; Couasnon et al., 2020). In

57 response, society has sought to address this threat~~reduce the coastal flooding ris~~, with ~~k, with global policy~~

58 ~~frameworks and national strategies gradually emerging to address the threat.~~ global policy frameworks and

59 national strategies gradually emerging to reduce coastal flooding risk. In the 21 century, disaster preparedness and

60 emergency response have been emphasized as the priorities of the Hyogo Framework for Action 2005-2015 and

61 the Sendai Framework for Disaster Reduction 2015-2030, respectively (ISDR, 2005; UN/ISDR, 2015). Moreover,

62 ~~The~~ the New Urban Agenda outlines actions to strengthen cities' capacities to reduce disaster risk and mitigate

63 their impacts ~~.~~(Habitat III, 2017). The Making Cities Resilient 2030 (MCR2030) initiative advocates for

64 incorporating climate risk projections into disaster risk reduction and resilience strategies (~~United Nations Office~~

65 ~~for Disaster Risk Reduction(~~UNDRR), 2022). Yin et al. (~~Yin et al.,~~2024) demonstrated the improved performance

66 of risk-informed, strategic evacuation planning in advance of coastal flooding. ~~initiative for incorporating~~

67 ~~(Intergovernmental Panel on Climate Change (IPCC), 2023)I(Naheed, 2021)~~

68

69 In disaster ~~emergency~~ management, disaster relief logistics ~~is~~ are essential to save human li~~ves~~fe and reduce

70 damage (Qin and Liu, 2017). However, ~~there are many deficiencies in~~ disaster relief logistics systems have many

71 deficiencies, such as ~~a~~ resource shortage ~~of resources~~, ineffective communication regarding supply and demand

72 information, and improper allocation of resources(Hu et al., 2019; Zhang, 2016). During ~~the~~ Hurricane Katrina,

73 numerous American citizens experienced profound levels of ~~physical and psychological~~ distress while ensconced

74 in shelters ~~for extended durations~~, devoid of sufficient provisions ~~such as water, food, and medical attention~~

75 (Brodie et al., 2006). In the aftermath of the Great East Japan Earthquake, the failure of certain systems,

76 unreasonable warehouse placements, and other issues resulted in the irrational distribution of emergency supplies

77 and a state of chaos (Ranghieri and Ishiwatari, 2014). Thus, developing disaster relief logistics strategies to ensure

the availability of adequate supplies and capacity is essential to prepare for coastal flooding and effectively manage emergencies~~achieve effective emergency management~~.

The mechanism of disaster relief logistics plays a vital role in ensuring the efficiency of emergency response efforts (İvgin, 2013). In past decades, numerous studies have been conducted in the field of disaster relief logistics, with the majority focusing on developing mathematical optimization models to solve this problem (Rawls and Turnquist 2010; Wang et al. 2019). Previous relevant research has focused primarily~~mostly focuses~~ on facility location, stock pre-positioning, and relief distribution (Caunhye et al., 2012; Kundu et al., 2022). For example, Rawls et al. (2010) developed an emergency response planning tool that ~~used~~ uses a two-stage stochastic mixed-integer programming model to determine the locations and quantities of multiple types of emergency supplies to be prepositioned. Zhang et al. (2022) proposed a distributional robust optimization model to determine the optimal location of emergency facilities and ~~make~~ resource allocation ~~decisions~~. Jana et al. (2022) proposed a probabilistic fuzzy goal programming model for making decisions to manage the supply of emergency relief materials. The goal of disaster relief logistics decision-making is primarily ~~focused on~~ to improv~~ing~~e the effectiveness and fairness of an emergency response. For instance, ~~Fiedrich et al. (2000) developed a dynamic combinatorial optimization model to allocate available resources with the goal of minimizing fatalities.~~ Huang et al. (2015) developed a triobjective allocation network model with a focus on life-saving utility, delay costs and equity. Additionally, Halit Üster et al. (2017) designed a strategic emergency preparedness network that aimed to minimize the maximum travel distance for an evacuee and the overall system cost. And, Ghasemi et al. (~~Ghasemi et al.,~~ 2022) proposed a scenario-based stochastic multi-objective model to minimize the expected total cost, maximum unsatisfied demand for relief personnel, and total probability of unsuccessful evacuations.

Despite considerable research in the field of disaster relief logistics, only a few studies have examined the impact of floods on resource distribution logistics, particularly the disruptions caused by the inundation of emergency facilities and roads.~~While considerable research has been performed in the field of disaster relief logistics, less attention has been given to flood relief logistics modeling. Only a few studies~~ For example, ~~have combined the use of a geographical information system (GIS) with an optimization model to conduct analyses.~~ Rodríguez-Espíndola et al. (2015) used GIS to create flood maps and developed a multiobjective optimization model to determine the locations of emergency facilities, assess the allocation of prepositioned goods, and establish a distribution plan based on ~~the~~ flood pattern~~s~~. Christopher Mejia-Argueta et al. (2018) evaluated flood hazards using GIS and proposed a multicriteria optimization model that considered evacuation and distribution flow-time and budget usage to evacuate people and distribute relief supplies. Additionally, considering uncertainties in the scale and impact of flooding, Garrido et al. (2015) proposed a stochastic programming model to optimize the inventory of emergency supplies as well as vehicle availability in flood emergency logistics.~~-~~ However, it is noteworthy that these existing studies were primarily based on historical flood scenarios and did not adequately consider the potential increased risks posed by extreme flood events under future climate scenarios. Moreover, most of these studies focused on optimizing the efficiency of resource distribution, whereas relatively little research has focused on ensuring equity in the allocation process.~~However, these studies lack consideration of future extreme flooding scenarios under climate change. And, few studies have focused on the issue of how to distribute supplies equitably when there is a shortage of supplies in disaster relief logistics planning.~~

118

119   In this paper, we introduce~~e propose~~ a scenario-based approach to flood relief logistics planning for coastal cities

120   through a combination of GIS analysis and resource allocation models. GIS-based analysis is used to estimate

121   facility availability and relief resource demand under future coastal flood scenarios. Then, resource allocation

122   models based on the estimation of supply and demand are developed and implemented to determine the locations

123   of active warehouses and to support resource allocation planning. This approach ~~is~~ has been applied to the

124   metropolitan region of Shanghai, which, ~~globally,~~ is one of the coastal cities that is most exposed to flooding in

125   the world (Balica et al., 2012). ~~Specifically, based on future coastal flood mapping, we use GIS and resource~~

126   ~~allocation models to analyze flood relief logistics schemes under various scenarios.~~ This study~~-~~ aims to provide

127   scientific and technical support for enhancing contingency plans for coastal megacities, and to offer new insights

128   into operational emergency management decisions for major coastal cities facing significant flood risks. ~~provides~~

129   ~~scientific and technical support for improving contingency plans for coastal megacities.~~ The rest of this paper is

130   organized as follows. In Section 2, the modelling methodology is presented. Section 3 describes the case study

131   results. The conclusions are summarized in Section 4.

132

133   **2. Methodology**

134   **2.1. Problem description**

135   As storm-induced flooding poses a significant threat to coastal cities, emergency authorities may be required to

136   respond by evacuating vulnerable populations to emergency flood shelters (EFSs) and providing them with

137   necessary supplies. In distributing these resources, emergency responders must assess the needs of evacuees to

138   develop an effective allocation plan. ~~When supply exceeds demand, emergency managers tend to focus on~~

139   ~~maximizing efficiency to optimally allocate resources. Conversely, if supply cannot meet demand, managers must~~

140   ~~consider both efficiency and fairness in their resource allocation schemes to avoid the humanitarian inequalities~~

141   ~~that are caused by unbalanced allocation.~~ In this study, we propose a flood relief logistics planning framework

142   (Fig. 1) that can assist decision-makers in addressing the challenge of distributing resources to vulnerable

143   populations affected by coastal flooding at the city level. The methodology integrates GIS with resource allocation

144   models to present a planning framework based on coastal flood mapping. We evaluate available candidate

145   facilities, the remaining road network and affected people and obtain information regarding basic population needs

146   and the shortest path through GIS analysis. Then, the obtained information is used in allocation models to

147   determine which ~~emergency reserve warehouses (DATAs)~~ERWs to activate and how to supply resources to the

148   activated shelters.

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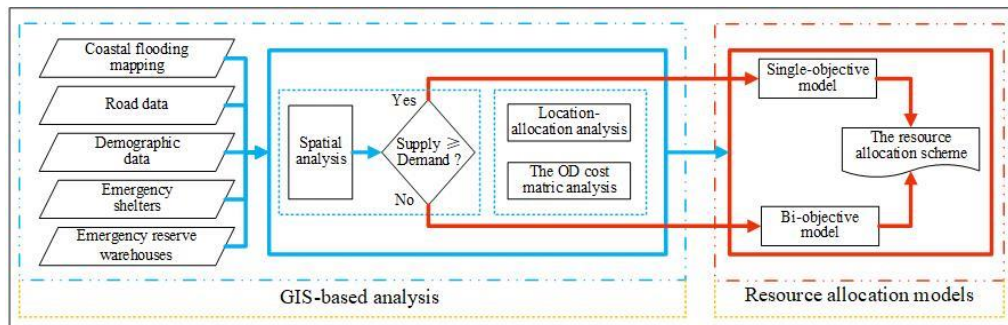
150   Fig. 1. The flood relief logistics planning framework.

151

2.2 Assumptions

In the development of the proposed methodology, ~~to simplify the model~~, the following assumptions were made to simplify the model:

A1: The numbers, locations and capacities of emergency facilities such as warehouses and shelters are known.

A2: Pedestrians and vehicles are not allowed to use roads with ~~a~~ flood inundation depth~~s~~ greater than 30 cm, which is the common standard for urban roads that are closed due to waterlogging (Yin et al., 2016b).

A3: Flooded EFSs will be set as invalid shelters. ERWs located in areas with flood inundation depths above 30 cm or that cannot be reached by vehicles are ~~set as~~considered invalid warehouses.

A4: Only the needs of the elderly population in the affected areas are considered ~~. This is~~ because these individuals are often most vulnerable to flood disasters ~~due to~~ given their limited ability to acquire information, make rapid judgements and take action.

A5: Resources refer to daily living supplies (e.g., water and food). A kit of goods can meet the requirements of a person during a flood evacuation.

A6: Resources are ~~only~~ transported only from ERWs to EFSs and not separately to ~~any~~ other areas.

A7: There is no limit~~ation~~ on ~~vehicle~~ number of vehicles, and each vehicle can transport one hundred kits.

A8: ~~Any allocation of resources in the city is within 12 hours of an individual arriving at a shelter. Notably,~~ Any resource allocation within the city can be completed within 12 hours. Notably, the 14th Five-Year National Comprehensive Disaster Prevention and Mitigation Plan in China stipulates that the basic living needs of affected individuals will be met within 12 hours~~the Ministry of Civil Affairs promises that affected people will have their basic living needs met within 12 hours~~.

A9: The affected elderly population is allowed to ~~go to~~ shelters in advance following a flood warning. The authorities can then establish strategies for distributing goods after evaluating the effects of flooding.

2.3 GIS-based analysis

Based on coastal flood mapping, the locations of available ERWs and EFSs as well as unsubmerged road networks and affected communities can be determined through GIS-based spatial and network analysis. Additionally, owing to the lack of more detailed spatial distribution data for the elderly population, this study assumes a uniform distribution within the community. The number of elderly individuals in each affected community can be calculated using Equation 1 ~~the number of elderly individuals in each affected community can be calculated using the following formula~~.

$$AP = \frac{IA}{A} * P \tag{1}$$

where AP represents the number of affected elderly people in the community~~;~~, IA is the inundation area in the community~~;~~, A is the total area in the community~~;~~, and P is the total number of elderly people in the community.

Then, according to GIS-based location-allocation analysis, the locations of activated EFSs and the number of elderly individuals in the activated EFSs can be identified. Specifically, all available shelters are candidate sites for activated shelters, and all affected community centroids are considered demand points and used to assign affected elderly people in the community to shelters by minimizing the total distance travel~~led~~ while considering shelter capacity constraints. In this way, we determine the number of affected elderly people at each activated

shelter. This information is used to determine how many kits of goods should be distributed to each shelter in subsequent resource allocation models. In addition, the matrix of the shortest path between available warehouses and activated shelters affected by flooding is used as an input for the resource allocation models, and this information is calculated ~~based~~ on the basis of origin–destination (OD ~~OD (origin destination~~) cost matrix analysis in GIS with the objective of minimizing the total route length.

2.4. Resource allocation models

Based on the above description and assumptions, models for resource allocation are designed. The following resource allocation models are used to establish allocation plans and their components, such as the number of activated ERWs that need to provide supplies and the quantity of kits that must be transported from ERWs to activated EFSs. Considering that emergency responders encounter two cases, namely, sufficient or insufficient supplies, a resource allocation model with two case outcomes is established.

2.4.1 Notations and definitions

The full mathematical model uses the following notation.

Indices and sets

I: set of available ERWs, indexed by $i \epsilon I$

J: set of activated EFSs, indexed by $j \epsilon J$

Parameters

c_{ij}: the unit transportation cost per unit distance per hundred kits transported between available ERW i and activated EFS j

d_{ij}: the shortest path between available ERW i and activated EFS j

P_i: the inventory of available ERW i

Q_j: the demand of activated EFS j

ω: the lowest satisfaction rate for each activated EFS

decision variables

X_{ij}: a binary value of 0 or 1, representing whether available ERW i serves activated EFS j ~~or not~~

Y_{ij}: a nonnegative variable, representing the quantity of allocated resources from available ERW i to activated EFS j

R_j: the satisfaction rate, representing the quantity of elderly individuals receiving supplies as a percentage of the total elderly population at each activated EFS j

2.4.2 Sufficient supply scenario

In a sufficient supply situation, the total available supplies in the city can meet the total demand of the refugee population during a flood~~ing~~. That is, everyone can obtain sufficient resources. Therefore, we establish a single-objective allocation model that ~~considering~~ considers only the efficiency objective. ~~It~~ This method aims to optimize system efficiency by minimizing the total transportation cost. The objective function can be defined as:

$$min f = \sum_{j \in J} \sum_{i \in I} c_{ij} d_{ij} Y_{ij} \tag{1}$$

~~s~~Subject to:

$$\sum_{i \in I} Y_{ij} = Q_j \qquad \forall j \in J \qquad (2)$$

$$\sum_{j \in J} Y_{ij} \leq P_i \qquad \forall i \in I \qquad (3)$$

Objective function (1) minimizes the total transportation cost. ~~Then, to~~To satisfy the demand of each EFS, the related constraint function is expressed in Equation (2) to ensure that the resources received are equal to the demand for each EFS. Equation (3) ensures that the supplies allocated from each ERW are less than its overall inventory.

2.4.3 Insufficient supply scenario

During times of catastrophic coastal flooding, we assume that the relief supplies of available ERWs are inadequate and thus cannot meet the demand of all evacuees. When supply is insufficient to meet demand, emergency managers should ensure that resources are distributed fairly across regions to avoid the humanitarian inequalities that result from unbalanced allocation. To consider both efficiency and ~~fairness~~equity, a bi-objective programming model with a trade-off between efficiency and ~~fairness~~equity is established to provide decision-makers with different options for resource allocation. Specifically, our model includes two possible objectives: objective (f1), which minimizes~~minimizing~~ the total transportation cost as the efficiency goal, and objective (f2), which minimizes~~minimizing~~ the maximum unsatisfied rate as the ~~fairness~~equity goal. ~~T~~The maximum unsatisfied rate refers to the highest unmet demand rate among these regions. By minimizing this rate, we aim to reduce disparities in unmet demand across regions, ensuring that no area experiences extreme shortages. The objective function can be defined as:

$$min f1 = \sum_{j \in J} \sum_{i \in I} c_{ij} d_{ij} Y_{ij} \qquad (1)$$

$$min f2 = max(1 - R_j) \qquad (2)$$

$$\left. \sum_{i \in I} Y_{ij} \middle/ Q_j \right. = R_j \qquad \forall j \in J \qquad (3)$$

~~s~~Subject to:

$$\sum_{j \in J} Y_{ij} = P_i \qquad \forall i \in I \qquad (4)$$

$$\sum_{i \in I} Y_{ij} \leq Q_j \qquad \forall j \in J \qquad (5)$$

$$R_j \geq \omega \qquad \forall j \in J \qquad (6)$$

Equation (3) is the formula for calculating the satisfaction rate R_j, which equals the total allocated resources as a percentage of the total demand at each EFS. Equation (4) ensures that the resources allocated from ERWs do not exceed the total inventory of ERWs. Additionally, the supplies received should be less than the demand for each EFS, and the constraint function is expressed in Function (5). Function (6) ensures that the minimum satisfaction rate is met for each EFS.

3. Case study

3.1. Study area

A case study is conducted in Shanghai, China. Shanghai is located on the west coast of the Pacific Ocean and is ~~located~~ in ~~a part of~~ the floodplain of the Yangtze River Delta. This city is one of the financial ~~centers~~ centres of China, and its gross domestic product (GDP) is among the top 10 in the world. It ~~has~~ a total population ~~of~~ is over 24 million, ~~with~~ and 16.3% of its residents ~~being aged~~ are 65 years old or older ~~and over~~ (Shanghai Municipal Statistics Bureau, 2021).

Coastal flooding has historically been a frequent issue in Shanghai. For example, Typhoon Winnie in 1997 resulted in RMB 635 million in economic losses and approximately 15000 affected people (Quan, 2014). In response, Shanghai has built emergency shelters and prepared relief supplies in ERW~~emergency reserve warehouses~~. By the end of 2020, 117 emergency shelters had been built in Shanghai ~~Shanghai had built 117 emergency shelters~~ to provide basic security protection for affected people. This work continues, and the goal of 1.5 m^2 of shelter space per capita is expected to be met by 2025 (General Office of the Shanghai Municipal People's Government, 2021). Currently, Shanghai has ~~over 200~~ emergency warehouses at three levels: the city level, district level and township level. There is one city-level warehouse, with the main depot in Jiading District and a branch depot in Minhang District.

3.2. Data sources

Data such as flood inundation maps, road data, demographic data, emergency warehouse information and emergency shelter information are obtained from different sources for this study (Table 1).

Table 1. Data Source~~s~~ Information.

Data Type	Source	Description
Flood Inundation Maps	Yin et al. (2020)	Simulated coastal flood inundation scenarios for 100-year and 1000-year return periods under the RCP 8.5 scenario.
Road Network	Key Laboratory of the Ministry of Education at East China Normal University.	Comprises approximately 243,000 road sections with attributes.
Demographic	Shanghai Municipal Bureau of Statistics	Detailed demographic information at the community level.
Emergency Warehouse	Shanghai Emergency Management Bureau	Includes information from 169 emergency warehouses
Emergency Shelter	Shanghai Emergency Management Bureau	Includes 117 emergency shelters divided into three classes.

~~F~~Future flood inundation scenarios in Shanghai are derived from Yin et al (~~Yin et al.,~~ 2020). In their previous work, coastal flood inundation caused by overtopping and dike breaching was simulated ~~using~~via a 2-D flood inundation model (FloodMap-Inertial) with a fine-resolution DEM for three representative return periods (10, 100,

291 and 1000 years) under current and future climate scenarios (RCP 8.5). ~~And, the~~The study considered climatically

292 driven absolute SLR by using probabilistic, localized SLR projections at the Lvsi gauge station located in the

293 Yangtze River Delta, provided by Kopp et al. (~~Kopp et al.,~~ 2014). This projection accounts for climatic factors

294 such as ice sheet melting, glacier and ice cap melting, and ocean thermal expansion. In addition, FloodMap-

295 Inertial, developed from FloodMap (Yu and Lane, 2006), has been thoroughly tested and applied in Shanghai (Yin

296 et al., 2016a, 2019), showing reliable performance in flood prediction. This model uses a computationally efficient

297 inertial algorithm to solve the 2-D shallow water equations (Bates et al., 2010), using the Forward Courant-

298 Friedrichs-Lewy (CFL) condition for the calculation of time steps. A complete description of the model structure

299 and parameterization can be found in Yu and Lane (Yu and Lane, 2006). In this study, we focused on the 2030

300 scenarios with 100- and 1000-year return periods under the RCP 8.5 scenario. The RCP 8.5 scenario represents

301 high radiative forcing and worst-case climate impacts. Thus, these two future scenarios represent extreme flood

302 inundation. The 2030 projections are the closest to the present, making them relevant for near-term planning.~~uture~~

303 ~~flood inundation scenarios in Shanghai are derived from Yin et al. (Yin et al., 2020). In previous work, the coastal~~

304 ~~flood inundation induced by overtopping and dike breaching was simulated using a 2-D flood inundation model~~

305 ~~(FloodMap-Inertial) with a fine-resolution DEM for three representative return periods (10, 100, and 1000 years)~~

306 ~~under current and future climate scenarios (RCP 8.5). We use future scenarios of flood inundation, a 100-year~~

307 ~~return period and a 1000-year return period under the RCP8.5 scenario in 2030. The RCP8.5 scenario represents~~

308 ~~high radiative forcing and worst-case climate impacts. Thus, these two future scenarios represent extreme flood~~

309 ~~inundation.~~

310

311

312 The road network data are from the 2013 Shanghai Traffic Navigation GIS dataset. Data are included on~~It includes~~

313 approximately 243,000 road sections with attributes such as road name, type, function, direction, and length. In

314 accordance with~~Referring to~~ the "Technical Standards for Highway Engineering of the People's Republic of China

315 (JTG B01-2003)", the roads are divided into five grades: superhighways, highways, main ~~road~~roads, secondary

316 ~~road~~roads and branch ~~road~~roads.~~superhighway, highway, main road, secondary road and branch road.~~

317

318 Shanghai's demographic data were collected during the Sixth National Population Census of China, which utilized

319 a household-level survey.~~Shanghai's demographic data are from the Sixth National Population Census, which was~~

320 ~~conducted in 2010 through a household-level survey, and the main results were published by the Chinese~~

321 ~~government in 2011.~~ The dataset provides the most detailed information on demographics at the basic

322 administrative level—community or village. According to these data, we calculated the elderly population (65

323 years old or older~~over 65 years old~~) in each community.

324

325 The emergency warehouse data for this study are from the Shanghai Emergency Management Bureau. We

326 obtained location information for 169 emergency warehouses. After filtering by facility name, 25 warehouses

327 were identified as potential ERWs~~ emergency reserve warehouses~~ that could provide daily living supplies for

328 281K affected people. Based on surveys and the Standard for the Construction of Relief Goods Reserve

329 Warehouses (Ministry of Civil Affairs of the People's Republic of China, 2009), it was assumed that city-level

330 (Level 1) warehouses can meet the basic needs of 200K affected people, district-level (Level 2) warehouses can

331 meet the needs of 5K people, and township-level (Level 3) warehouses can meet the needs of 3K people.

The data for the emergency shelters used in this paper are from the statistics of the Shanghai Emergency Management Bureau[1]. ~~Data on~~This includes 117 emergency shelters are included, ~~–~~with attributes such as name, capacity, and level. They ~~shelters~~ey are divided into three classes: class 1, class 2, and class 3. Generally, class 1 and class 2 are fixed emergency shelters, ~~:~~class 1 facilities have the capacity to hold more than 5K people, and class 2 facilities can accommodate 1K to 5K people. Considering the nature of coastal flooding, 74 shelters with indoor venues, such as schools, could be emergency flood shelters. These EFSs can accommodate approximately 330K people.

3.3. Results

3.3.1. GIS-based results

Figure 2 illustrates the spatial distributions of ERWs, EFSs and activated EFSs across Shanghai, as well as the affected areas in 100- and 1000-year coastal flood scenarios. Table ~~1~~2 ~~shows~~ ~~provides~~shows statistical information regarding emergency facilities and disaster situations in two coastal flood scenarios, including the number of available facilities, number of activated EFSs, number of affected communities and population of affected elderly, etc.

During the 100-year flood scenario, all 25 ERWs and 71 EFSs (96% of the total EFSs) are available. The available ERWs have the capacity to provide daily supplies for 281K individuals, and the available EFSs can accommodate up to 313,299 elderly people, accounting for 95% of the total capacity of EFSs. The impact of flooding is most pronounced in areas such as Chongming Island and Baoshan, Huangpu, and Xuhui districts. In this scenario, there are 562 affected communities with approximately 145K exposed elderly individuals. Thus, only 26 EFSs need to be activated to accommodate the impacted elderly population. The EFSs can house approximately 146,000 people, which represents 47% of the total available capacity.

As expected, the 1000-year flood scenario involves more extensive and severe flood inundation in the city. A total of 1,820 communities are exposed to coastal flooding, with approximately 534K elderly individuals in need of relocation to EFSs. In terms of critical facilities, only 21 ERWs and 61 EFSs (82% of the total EFSs) are available in the 1000-year flood scenario. The available supplies can meet the needs of 265K people (50% of the total demand), and the available EFSs have the capacity to accommodate 280,919 individuals. Thus, all 61 available EFSs need to be activated to accommodate the affected elderly population. Only 53% of the total affected elderly individuals can be accommodated at these EFSs.

Table ~~1~~2. Statistics for emergency facilities and disaster situations in two coastal flood scenarios.

Flood Scenarios	Available ERWs		Available EFSs		Activated EFSs		Affected Communities	Affected elderly
	number	stock	number	capacity	number	capacity	number	number
100-year	25	281,000	71	313,299	26	145,981	562	145,197

[1] https://gfdy.sh.gov.cn/yjbncs/

1000-year	21	265,000	61	280,919	61	280,919	1,820	534,079

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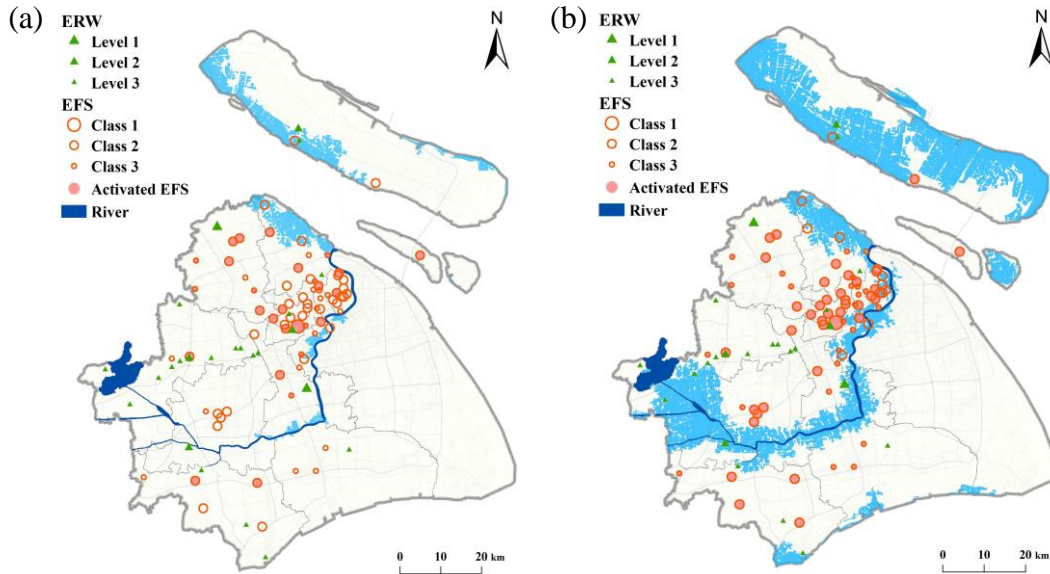

368   Figure 2. Spatial distributions of the emergency reserve warehouses (ERWs) and emergency flood shelters

369   (EFSs) in 100-year (a) and 1000-year (b) flood scenarios in 2030. (~~Level~~Levels 1~~/2/~~, 2, and 3 represent

370   ~~city/district/township~~city-level, district-level, and township-level ERWs, respectively~~Level 1/2/3 represent~~

371   ~~city/district/township~~)

372

3.3.2. Resource allocation in two coastal flood scenarios

374   For the 100-year flood scenario, the total amount of available supplies stockpiled in Shanghai can cover the needs

375   of all affected elderly individuals (Table ~~1~~2). Therefore, a single-objective model is employed to determine the

376   resource allocation scheme in this scenario. The resource allocation network comprises 25 available ERWs and

377   26 activated EFSs in total. In terms of the main model parameter, the unit transportation cost (c_{ij}) is assumed to

378   be 1 RMB~~, which~~ to prevent~~s~~ data unavailability issues. The results indicate that activating 17 ERWs could meet

379   the needs of all elderly people at 26 EFSs. The relative transportation cost is 22,764 RMB. Figure 3 and Table ~~2~~

380   3 show the resource allocation scheme and the service capacity~~-~~, respectively, of the activated ERWs in the 100-

381   and 1000-year flood scenarios in 2030~~, respectively~~.

382

383   As shown in Figure 3a, the demand ~~of~~ for activated EFSs can almost entirely be provided by the nearest ERW.

384   The city-level ERW in Jiading District (No. 24) and the branch warehouse in Minhang District (No. 25) play

385   prominent roles in emergency resource provision. In contrast, the ERWs located in the western region of Shanghai

386   are mostly inactive. For example, the city-level ERW and ~~the~~ branch warehouse provide emergency resources for

387   8 and 11 EFSs in Shanghai, accounting for 28.6% and 39.6% of the total demand, respectively (Table ~~2~~3).

388   Furthermore, Figure 3a indicates that EFSs in the central areas of Shanghai demonstrate significantly higher

389   demand than those in the suburbs; thus, the branch warehouse (No. 25), which is near downtown, provides most

of the supplies. The results also shows a cross-river supply route from the branch warehouse to an EFS (No. 26) located on a nearshore island; this route, which is the longest route identified in the scenario.

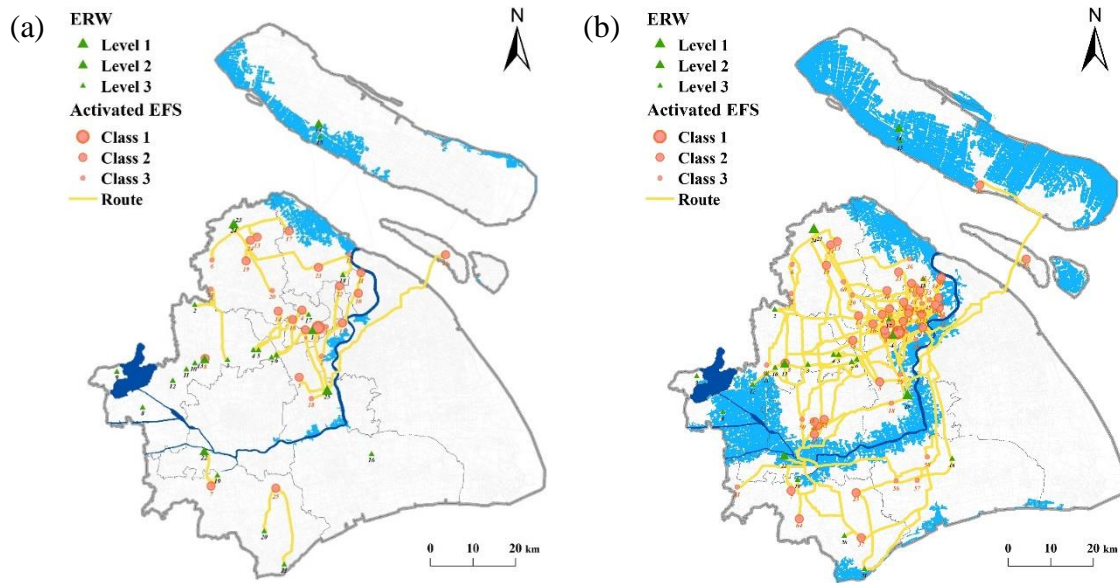



Figure 3. The rResource allocation scheme for thein 100-year (a) and 1000-year (b) flood scenarios in 2030.

Table 23. The sService capacity of the activated ERWs in two coastal flooding scenarios.

Level	ID	100-year		1000-year	
		EFSs served	Supplies (^10^2)	EFSs served	Supplies (^10^2)
Level 1	24	8 (30.8%)	416 (28.6%)	20 (32.8%)	1000 (35.6%)
	25	11 (42.3%)	574 (39.5%)	34 (55.7%)	1000 (35.6%)
Level 2	1	1 (3.8%)	50 (3.4%)	1 (1.6%)	50 (1.8%)
	13	1 (3.8%)	50 (3.4%)	5 (8.2%)	50 (1.8%)
	22	1 (3.8%)	14 (1.0%)	1 (1.6%)	50 (1.8%)
	23	1 (3.8%)	50 (3.4%)	2 (3.3%)	50 (1.8%)
Level 3	2	1 (3.8%)	30 (2.1%)	4 (6.6%)	30 (1.1%)
	3	1 (3.8%)	10 (0.7%)	1 (1.6%)	30 (1.1%)
	4	1 (3.8%)	30 (2.1%)	5 (8.2%)	30 (1.1%)
	5	2 (7.7%)	30 (2.1%)	1 (1.6%)	30 (1.1%)
	6	1 (3.8%)	30 (2.1%)	2 (3.3%)	30 (1.1%)
	7	3 (11.5%)	30 (2.1%)	4 (6.6%)	30 (1.1%)
	10	-	-	1 (1.6%)	30 (1.1%)
	11	-	-	1 (1.6%)	30 (1.1%)
	12	-	-	1 (1.6%)	30 (1.1%)
	16	-	-	2 (3.3%)	30 (1.1%)
	17	1 (3.8%)	30 (2.1%)	5 (8.2%)	30 (1.1%)
	18	1 (3.8%)	30 (2.1%)	1 (1.6%)	30 (1.1%)
	19	1 (3.8%)	30 (2.1%)	1 (1.6%)	30 (1.1%)
	20	1 (3.8%)	30 (2.1%)	1 (1.6%)	30 (1.1%)
	21	1 (3.8%)	20 (1.4%)	2 (3.3%)	30 (1.1%)

396   Note: The proportion of EFSs served to the total number of activated EFSs and the proportion

397   of supplies provided to the total demand are given in parentheses.

398

399   In terms of the 1000-year flood scenario, the total available supplies in Shanghai are insufficient to meet the

400   demand of affected elderly people. To ensure ~~fairness~~equity in the allocation of limited supplies, a biobjective

401   model is employed to determine the resource allocation scheme. This scenario involves the allocation of supplies

402   from 21 available ERWs to meet the basic needs of 265K affected people at 61 activated EFSs; these EFSs can

403   accommodate approximately 281K of the affected elderly individuals. The minimum ~~level of~~ rate of satisfaction

404   ω for each EFS is set to 1%. This bi-objective mathematical model is ~~implemented~~ solved ~~by~~via the ~~NSGA-II~~

405   ~~(Non-dominated Sorting Genetic Algorithm II) algorithm~~nondominated sorting genetic algorithm II (NSGA-II),

406   which is used to obtain a Pareto optimal solution in ~~multi-objective~~multiobjective optimization problems (Deb et

407   al., 2002). NSGA-II is an advanced multiobjective evolutionary algorithm that maintains population diversity

408   across generations through nondominated sorting and promotes a uniform distribution of solutions along the

409   Pareto front using a crowding distance measure. The NSGA-II algorithm is widely used in selected combinatorial

410   optimization problems and has the advantages of fast convergence speed, low computational complexity, and high

411   robustness (Ma et al., 2023; Verma et al., 2021). The corresponding algorithm settings for the solution in this

412   study are shown in Table 4.

413

414

415   Table 4. Optimization parameter settings for NSGA-II

Parameter	Population Size	Maximum Number of Iterations	Pareto Fraction	Crossover Probability
Value	500	3,000	0.4	0.8

416

417   Figure 4 presents the Pareto front for the resource allocation scheme obtained with the proposed biobjective

418   framework. This Pareto front depicts the relationship between the relative transportation cost and the maximum

419   rate of unsatisfied demand, with a total of 200 nondominated solutions. The resource allocation schemes that

420   ~~prioritizes~~ fairnessequity, resulting in low maximum degrees of unsatisfied demand, correspond to solutions that

421   are plotted~~plot~~ close to the x-axis. Conversely, the resource allocation schemes that prioritize efficiency, resulting

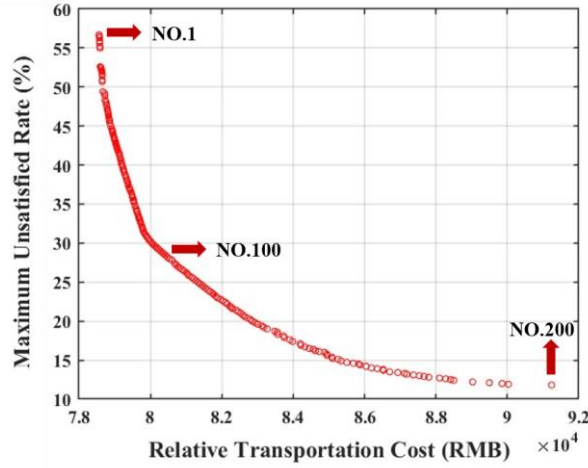
422   in lower relative transportation costs, correspond to solutions that are plotted ~~plot~~ close to the y-axis. The results

423   indicate~~provide~~ a variety of strategies for~~to the~~ ~~decision-~~decision-makers~~,~~; the choice of~~and which~~ solution~~to~~

424   ~~choose~~ depends on the decision-maker's preference between the relative transportation cost and the degree of

425   demand satisfaction.

426

427

428   Figure 4. ~~The PP~~areto front for relative transportation cost and maximum rate of unsatisfied demand in the

429   1000-year flood scenario.

430

431   Fig. 4 also shows the objective values for three representative solutions (i.e., No. 1, No. 100, and No. 200). These

432   solutions demonstrate different trade-offs between the relative transportation cost and the maximum rate of

433   unsatisfied demand. Solution No. 1 yields the lowest relative transportation cost and the highest maximum rate of

434   unsatisfied demand, totalling 56.7%. Solution No. 200 achieves the lowest maximum rate of unsatisfied demand

435   (11.8%), and the relative transportation cost is the highest of all values in the solution set. However, solution No.

436   200 increases the relative transportation cost by 16% compared with that for solution No. 1 but achieves a 44.9%

437   reduction in the maximum rate of unsatisfied demand. The objective value of solution No. 100 is between the

438   values of the other two solutions, with a moderate transportation cost and a maximum rate of unsatisfied demand

439   of 29.8%.

440

441   As mentioned above, the choice of resource allocation scheme depends on the decision-maker's priorities. If the

442   decision maker emphasizes efficiency, solution No. 1 may be adopted, with ~~a~~ its low transportation cost~~, may be~~

443   ~~adopted~~. Conversely, ~~a if the decision~~ decision-maker that prioritizes equity can employ, solution No. 200, with a

444   low maximum rate of unsatisfied demand~~, can be employed~~. Moreover, for a balanced consideration of both

445   efficiency and equity, a middle-ground solution between No. 1 and No. 200 can be selected, such as efficient

446   solution No. 100.

447

448   Figure 3b and Table ~~2~~ 3 present the spatial patterns of the resource allocation scheme and the service capacity of

449   the activated ERWs for solution No. 100 in the 1000-year flood scenario. All available supplies are distributed

450   (Table ~~2~~3). The branch ERW (No. 25) provides services to a large number (34) of EFSs, serving 56% of all

451   activated EFSs. Moreover, Figure 3b reveals that there are relatively few ERWs and that they cannot meet the

452   large demand ~~of~~ for EFSs in the central areas of Shanghai. Furthermore, the results show~~result shows~~ three cross-

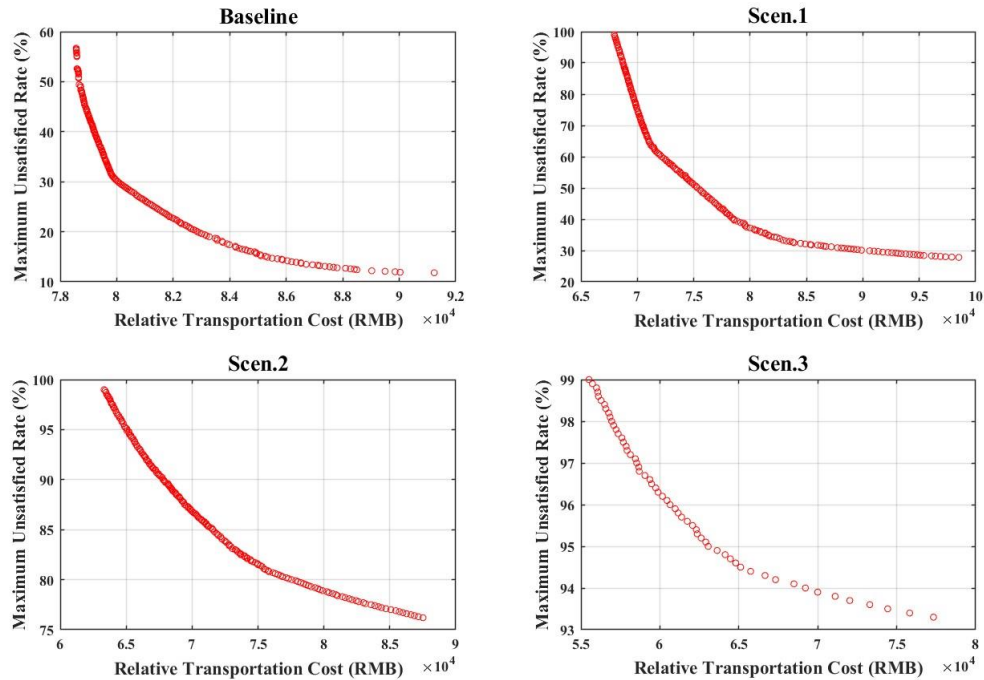
453   river supply routes from the city-level ERW (No. 24) to EFS No. 26 and from the branch ERW to EFSs No. 26

454   and No. 39. The former is also the longest ~~of the~~ route~~s~~ in this scheme. In addition, the results suggest ~~s~~ that the

455   resource demands of 79% of EFSs are met in ~~the~~ solution No. 100. Among the remaining EFSs with unmet

456 demand~~s~~, EFS No. 36, located in the urban cent~~er~~e, shows~~displays~~ the maximum rate of unsatisfied demand,
457 totalling 29.8%.
458

3.3.3. Analysis of demand variability in the 1000-year flood scenarios

460 Given the capacity limitations of each EFS, it is impossible to accommodate all affected elderly people in the
461 1000-year flood scenario. As a result, the activated EFS demand (Q_j) in the optimization model includes only the
462 number of elderly people assigned to EFSs in Section 3.3.2. To investigate the results of demand variability, it is
463 assumed that the capacity of each EFS can be moderately adjusted to accommodate more elderly people and that
464 each EFS's demand is increased by 10%, 50%, and 100% (~~,~~ scenario 1, ~~Scen.~~scenario 2, and ~~Scen.~~scenario 3, ~~Scen.~~
465 ~~1, Scen. 2, and Scen. 3~~respectively)~~, respectively~~. The other parameters in the bi-objective optimization model
466 and in the NSGA-II algorithm are consistent with those in Section 3.3.2 (baseline scenario). The Pareto front for
467 the four scenarios is obtained, and the results are presented in Figure 5. Table 5 ~~illustrates t~~lists the objective
468 values of the endpoint solutions of the Pareto frontiers.

470 Figure 5. ~~The PP~~Pareto fronts for the relative transportation cost and maximum rate of unsatisfied demand in the
471 four scenarios.
472

473 Table 5. ~~The o~~Objective values of the endpoint solutions of the Pareto fronts in the four scenarios.

The efficient solution		Relative transportation cost (RMB)	Maximum unsatisfied rate (%)
Top point	Baseline	78563.8	56.7
	Scen.1	67961.0	99
	Scen.2	63324.5	99
	Scen.3	55510.5	99
Bottom point	Baseline	91237.4	11.8
	Scen.1	98501.0	27.8
	Scen.2	87516.5	76.2

	Scen.3	77328.8	93.3

474

475 In a comparison of~~Comparing~~ the results ~~of~~for the four scenarios, Figure 5 shows that the baseline scenario yields

476 the highest satisfaction rate, with maximum rates of unsatisfied demand ranging from 11.8% to 56.7% (Table 5).

477 Scenario 3 results in~~exhibits~~ a significantly higher rate of unsatisfied demand, falling between 93.3% and 99%.

478 This indicates that a fair allocation scheme can be achieved by reducing the gap between supply and demand.

479 Furthermore, the results demonstrate that Scenario 3 yields a better solution than the other scenarios do~~others~~ in

480 terms of relative transportation costs, i.e., a lower value. Moreover, the relative transportation cost declines

481 gradually from the baseline scenario to Scenario 3, potentially due to the expanding gap between supply and

482 demand, which presents challenges for optimizing the maximum rate of unsatisfied demand. Therefore, the

483 relative transportation cost can be further optimized~~there is more room for optimization in terms of relative~~

484 ~~transportation cost~~.

485

486 Overall, the results show that significant gaps between supply and demand indicate resource shortages, resulting

487 in a high degree of ~~unfairness~~inequity in the allocation plan. The implication is that solely relying on optimal

488 allocation strategies is inadequate to address the inequity~~unfairness~~ issue. Increasing resource inputs is a crucial

489 fundamental approach to alleviate the unfairness related to resource allocation. These findings aid in

490 understanding the level of equity~~fairness~~ involved in resource allocation decisions.

491

492 **4. Conclusions**

493 Flood relief logistics planning is a critical component of flood management that directly impacts the livelihood

494 and security of affected populations. In this study, we presented a comprehensive framework for flood relief

495 logistics planning using a combination of GIS network analysis and resource allocation optimization models. By

496 integrating these methodologies, we achieved a synergistic outcome that leverages the strengths of both

497 approaches. The framework was implemented in Shanghai, China, to explore the availability of ERWs and EFSs

498 as well as the flood relief logistics plans in future coastal flood scenarios.

499

500

501 ~~Such flood relief logistics planning could contribute to enhancing the efficiency and fairness of emergency~~

502 ~~management strategies.~~Our work can assist emergency managers in better understanding the inadequacies of

503 existing emergency facilities and ~~The framework proposed in this study can also be adopted for applications in~~

504 ~~other coastal cities worldwide.~~ highlights the importance of incorporating climate risk information into exhaustive

505 government flood relief logistics plans. ~~Such flood relief logistics planning could contribute to enhancing the~~

506 ~~efficiency and fairness of emergency management strategies.~~ The framework in this study can also be adopted for

507 applications in other coastal cities worldwide. However, to arrive at more robust conclusions, future studies could

508 focus on~~be directed to~~ the following aspects: 1) Demand estimation: Given issue of agei~~i~~ng in Shanghai, the

509 elderly population is likely to increase significantly by 2030, which is highly likely to lead~~leading~~ to ~~a high~~

510 ~~probability of~~ greater scarcity ~~in~~of shelter resources and supplies. Therefore, future research should focus on

511 obtaining more detailed data on the elderly population to better understand the spatial distribution and temporal

512 changes in the affected elderly population. 2) Traffic scenarios: Currently, the model assumes that roads are closed

when the water level reaches 30 cm. Future work should incorporate more complex traffic scenarios, such as variable speeds at which vehicles can safely navigate flooded areas, to better simulate real-world conditions. 3) Model validation: This study has not yet incorporated a formal validation of the proposed models. Comparing model outputs with historical flood event data or established decision models would provide a more comprehensive validation and enhance the robustness of the framework. Future work should prioritize these comparisons to improve the model. ~~1) our demand estimation of supplies relies entirely on the affected elderly population and is biased to some extent. A more accurate approach would consider the willingness of various individuals impacted by flooding to reside in shelters at varying flood levels. 2) it is assumed that roads are closed when the water limit of 30 cm is reached, and the speed at which vehicles can safely navigate a flooded road network is not considered. More complex traffic scenarios should be considered in future work. 3) our research predominantly presents a static perspective of the supply-demand relationship. Recognizing that disaster situations are dynamic and evolve over time, there is a pressing need for the development of multiphase emergency resource allocation models. These models should capture the continuous and multistage nature of emergency response decisions, ensuring a holistic approach.~~

Furthermore, in this study, the disaster situation ~~is~~ was explored in ArcGIS, and the resource allocation models ~~are~~ was developed in MATLAB. Therefore, future efforts could focus on developing ~~accessible,~~ comprehensive decision-support systems and large models that integrate disaster assessment with relief resource allocation models. Such systems can offer predictive analytics and scenario-based simulations, enabling proactive decision-making. ~~These systems have the potential to provide decision-makers with predictive analytics and scenario-based simulations, thus enabling proactive decision-making rather than reactive response.~~ By filling these research gaps, researchers can contribute to optimizing ~~the future of~~ effective flood relief logistics planning in the future ~~can be ensured~~, providing more resilient and adaptive emergency responses in coastal cities worldwide.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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