Research Paper

An open data-driven investigation method for urban emergency shelter planning

Wanqing SU, School of Architecture, Harbin Institute of Technology, China

Zhichong ZOU, School of Architecture, Harbin Institute of Technology, China

Xinpeng LIN, School of Architecture, Harbin Institute of Technology; Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology， Ministry of Industry and Information Technology, China

Zhongze LI, School of Architecture, Harbin Institute of Technology; Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology， Ministry of Industry and Information Technology, China

Abstract

Climate change increases urban risk relative to natural and man-made disasters. The distribution of emergency shelters is an important part of the urban disaster prevention and mitigation system. In China, a National Disaster Prevention and Mitigation Plan (2016-2020) and a National Standard of Urban Disaster Prevention Planning (GB/T51327-2018) was published in 202017 and019 respectively. A new town and rural emergency shelter planning and construction standard which relates to future risk increases were proposed. To better understand the current urban emergency shelter status with the respect to the long city history and complex urban conditions, it is necessary to develop a data-driven investigation method with high accuracy but low cost. By focusing on identifying the insufficiency of serviceability of the current in-use emergency shelters under the new standards, an effective open data-driven investigation method is proposed. Open data was collected from online map services (points of interest, road networks, and building footprints), census yearbooks (population), and sectors' official websites. With a case study of Shenzhen, this paper introduces data-driven modeling framework and parameter optimization strategies. Spatial patterns discovered by the proposed method are significantly important to urban emergency shelters planning for future risk increasing with population dynamics. All data collection, modeling and computation are performed with QGIS.

Key word:

emergency shelter, *spatial optimization*, *evacuation simulation*, *network analysis*

1. Introduction

In recent years, with the accelerated urbanization in China, the impact of natural disasters on cities has been increasing. According to the Ministry of Emergency Management of China, in 2021, a total of 107 million people were affected by disasters, 867 people died or went missing due to disasters, and 5,738,000 people were relocated in emergencies. Emergency shelters can effectively enhance urban resilience and protect people’s safety in case of disasters. The spatial layout and optimization of emergency shelters have been the focus of disaster science and geography research in recent years. China has released new plans and standards for disaster prevention and mitigation in recent years. Under the new standards, it is an urgent problem to reasonably start the planning related to emergency shelters to guide the reasonable evacuation of evacuees and improve the efficiency of post-disaster evacuation, because of China’s large population.

In recent decades, many scholars have done a lot of research on the rationality of the spatial layout of shelters, because this is directly related to whether the city can effectively provide shelter services for the refugee population in the event of a disaster(Masuya et al., 2015)Various methods can be used to evaluate the spatial layout of emergency shelters, such as accessibility models, coverage models, and P-median models. The concept of spatial accessibility was first introduced in 1959 and defined as the potential opportunities for nodes in a transportation system to interact with each other(Hansen, 1959). In 1974, based on accessibility, the theory of location factors and human factors on layout optimization was proposed to promote the development of theories related to facility layout and location selection(Austin, 1974). Subsequently, the raster model and the Gaussian two-part moving search method (2SFCA) were added to the methodology for evaluating the accessibility and effectiveness of emergency shelters (Gall, 2004; Li et al., 2020). Some scholars have also improved the search radius based on the 2SFCA method while integrating network analysis methods and population high-resolution grid data(Zhu et al., 2018) or using the bivariate Moran's I to determine the spatial relationship between the accessibility of emergency shelters and population density(Su et al., 2022) to propose a location for the future planning and construction of emergency shelters. In addition, the Location-Allocation model is also used in the planning of shelter sites(Kocatepe et al., 2018; ReVelle and Swain, 1970; Sherali et al., 1991). Hakimi first proposed the P-median model and the P-center model in 1964 to solve the siting problem in networks (Hakimi, 1964). The facility coverage location model (SCLM) and the maximum coverage model (MCLM) are also widely used in solving emergency shelter planning problems (Roth, 1969; Toregas et al., 1971).

The prerequisite for the effective functioning of emergency shelters is that their supply and demand should be balanced in each district of the city(Zhang et al., 2020). Analyzing the evacuation needs of a city before conducting evacuation simulations has proven to be a viable approach (Chen et al., 2020). In the planning of emergency evacuation sites, the relationship between evacuation sites and evacuation activities should be established, and models should be created under the objective function, such as the shortest path model and minimum-cost functions (Yamada, 1996; Zhou et al., 2012). Understanding the siting of emergency shelters requires an analysis of the spatial and temporal distribution of housing needs; the difficulty here is to figure out the size and distribution of the city's population (Bayram and Yaman, 2018). Traditionally, population distribution relies on land cover data, land use data, night light data, etc (Briggs et al., 2007; Mao et al., 2012). With the development of big data, however, many new ways have emerged to determine the population distribution. Chen et al. used POI to analyze whether the service capacity of evacuation sites meets the evacuation demand(Chen et al., 2020). Yu and Wen used high-resolution remote sensing image data, census data, and land use data to assess the supply and demand for shelter under different diurnal scenarios(Yu and Wen, 2016). In short-term to long-term evacuation scenarios, the demand can be the number of people that are present at night, because sufficient disaster relief operations can be carried out at this time(Chen et al., 2013).

According to the current situation of emergency shelter construction in China, the new planning standard approach is to allocate emergency shelters to the available land as much as possible based on the city's existing land resources and population distribution, the per capita index and a certain service radius standard. However, because urban planning often lags behind urban construction and because the population is dynamic and mobile, the planning of evacuation sites cannot effectively meet evacuation needs.

Aiming to apply open data to investigate whether the number and capacity of emergency shelters meet the specifications, this study constructs a set of assessment processes based on the QGIS platform, and carry out empirical research in Shenzhen, Guangdong Province. The demand for emergency shelters after a disaster is explored through evacuation simulations and relevant optimization strategies are proposed for the improvement of emergency shelters against the new normative standards proposed by the Chinese government.

2. Data and Methods

2.1. Data

The open data used in this study are mainly road network data and population count data, which are collected from Open Street Map and World Pop data platform respectively. Since there are many categories, by referring to the classification in the article How to classify roads in OSM map, the author classifies them into elevated and expressways, urban trunk roads, urban secondary roads, urban feeder roads, internal roads, pedestrian roads, bicycle paths, and suburban rural roads, as shown in Table 1. (1) More accurate outputs than top-down approaches where census data are outdated and/or census projections from these are highly uncertain. projections from these are highly uncertain; (2) Measurement and mapping of uncertainty highlights where caution in using the data should be exercised and where further data collection could be prioritized. Shenzhen Statistical Yearbook and POI data were used as auxiliary data.

Table 1 Road classification table

id	OSM Classification	Classification
1	tertiary	Urban Secondary Roads
2	tertiary_link	Urban Secondary Roads
3	residential	Urban Bypass
4	unclassified	Urban Bypass
5	secondary	Urban Trunk Roads
6	secondary_link	Urban Trunk Road
7	primary	Urban Trunk Road
8	primary_link	Urban Trunk Roads
9	motorway	Elevated and Expressway
10	motorway_link	Elevated and Expressway
11	trunk	Elevated and Expressway
12	trunk_link	Elevated and Expressway
13	track	Suburban Rural Roads
14	track_grade1	Suburban Rural Roads
15	track_grade2	Suburban Rural Roads
16	track_grade3	Suburban Rural Roads
17	track_grade4	Suburban Rural Roads
18	track_grade5	Suburban Rural Roads
19	bridleway	Internal Roads

20	living_street	Internal Roads
21	path	Internal roads
22	service	Internal Roads
23	footway	Pedestrian Roads
24	pedestrian	Pavement
25	steps	Pedestrian paths
26	cycleway	Bicycle paths
27	unknown	Other

2.2. Methods

Through the network analysis of QIGS, this study analyzes whether the capacity and service capability of the emergency shelter can meet the city's evacuation demand. It mainly consists of the following three steps. The first is the spatial distribution analysis of the evacuation population, the second is the simulation of people's evacuation, and the third is the spatial analysis and statistics of the results.

Clarifying the spatial distribution characteristics of the evacuation population is the key to evaluating the service capacity of emergency evacuation sites. The analysis is carried out by World pop data and statistical yearbook data. In urban planning, the traditional practice is to balance the macroscopic supply and demand quantities. However, the service of emergency shelters in a certain area of the city may not meet the evacuation demand. So it is necessary to establish an evaluation process based on evacuation simulation to do an assessment of the spatial pattern of emergency shelters in the city. Based on the results of the previous assessment step, an analysis is conducted to explore the problems of emergency shelters under the new standards. This will lead to strategies for optimizing the size and spatial distribution of emergency shelters.

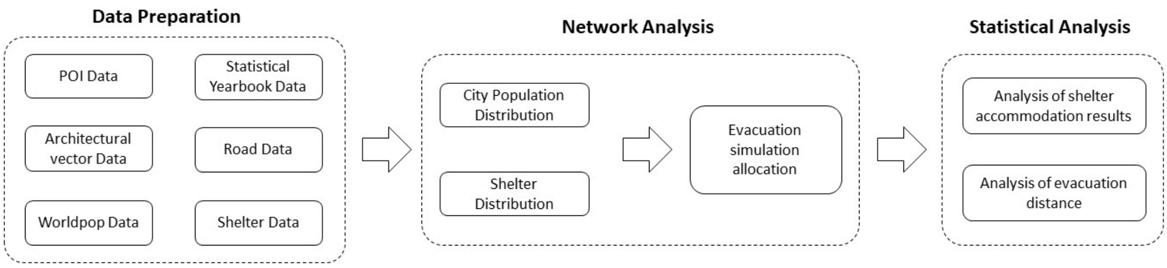

Figure 1. Research Flow Chart

2.2.1. Starting point of the evacuation population

The population distribution of a city is a key factor in emergency shelter planning, as it directly affects the location and size of emergency shelters in the city. The size and distribution of the population vary greatly in cities while emergency shelters in cities should cover as many areas as possible. Therefore, determining the starting point of citizens in case of a disaster is a key part of emergency shelter planning.

The OSM road data is used to filter out the city's main roads, secondary roads and branch roads from them, and to divide the city so as to get the plots of land, which are used as the starting points for the citizens to escape. Using the World pop population count data, combined with the data from the statistical yearbook for its auxiliary correction in the total population of the city and the number of permanent residents of each administrative person, the value of the population count is assigned to the divided plots, and the center of mass of the plots is extracted to obtain the spatial location of the citizens' escape departure point and the number of escape population at that point.

Table 2 Shenzhen citizens escape from the starting point and the number of escape

Id	Population size	Plot size (m)	Lon	Lat
1	48333	35039808.61	113.9102362	22.82414732
2	12157	3928961.485	113.9518048	22.80926736
3	42400	33380362.15	113.9738489	22.76985764
4	1537	409411.331	114.0309122	22.76090475
5	6359	2966196.895	114.0406278	22.7606021
6	160	47556.0692	114.0586072	22.75746674
7	17091	6865270.985	114.0696545	22.74128493
8	1949	510162.1059	114.0943878	22.74105823
9	18638	3033658.698	114.1077638	22.71978857
10	1823	228025.54	114.1334735	22.71597685
11	27111	1929278.378	114.1383332	22.70388245
12	825	90187.96372	114.1532671	22.68917537
13	6173	755569.4674	114.1585374	22.67897422
14	14265	1597052.723	114.1521513	22.66840061
15	1321	571253.3603	114.1634161	22.66057613
16	295	227729.2515	114.1776188	22.65999683
17	8918	4910757.127	114.1920379	22.68254232
18	2747	810339.5854	114.1968184	22.71399075
19	1631	61529.90649	114.2042085	22.72385054
20	1361	130699.0204	114.2040482	22.72895192
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2.2.2. Evacuation Simulation Using Network Analysis in QGIS

This paper uses network analysis in QIGS to perform evacuation simulations. This study aims to find the gap between the emergency shelter and the current norms, so the simulation simplifies influencing factors such as psychological, cognitive, and road congestion, and retains the relevant indicators from the norms to build the model. The plot where the citizen is located is the starting point of escape in this study, and the emergency shelter is the end point.

The hypothetical conditions of the simulation are as follows.

(1) When a disaster occurs, citizens will evacuate along urban roads, so OSM road data is used as the road network data set.

(2) In the selection of target evacuation sites, citizens will choose according to the principle of proximity,

no matter how complicated the route is.

(3) Roads after a disaster will not be blocked due to building collapse, earthquake, etc. All roads are passable without considering the blockage factor.

The main steps of the evacuation simulation are as follows.

(1) Using the network analysis plug-in in QGIS, the data includes the escape starting point, emergency shelter, and OSM road data.By inputting the starting point, end point and road network data, the distance (in meters) of the road network from each starting point to each end point is calculated using the OD matrix and finally recorded in the "total_cost". This step shows the straight line path between the starting point and the end point in QGIS.

(2) According to the evacuation simulation hypothesis of this study, we only need to filter out the route with the shortest evacuation distance, so we select the destination with the least "total_cost" among all destinations by SQL query.

(3) The processed results are imported into QGIS for spatial visualization, showing the connection between each starting point and the nearest evacuation site.

3. Case Study

The study area is Shenzhen, Guangdong Province, including Futian, Luohu, Nanshan, Bao’an and other 10 administrative districts. The Shenzhen-Shantou Cooperation Zone is not included in this study because it is an enclave, not bordering other administrative districts of Shenzhen. Shenzhen is the first special economic zone in China. After 40 years of development after the reform and opening up, it has developed from a small fishing village to an international city with a land area of 1997.47 square kilometers and an urbanization rate of 100%. According to the data of the seventh national census, the resident population of Shenzhen is about 17.56 million.

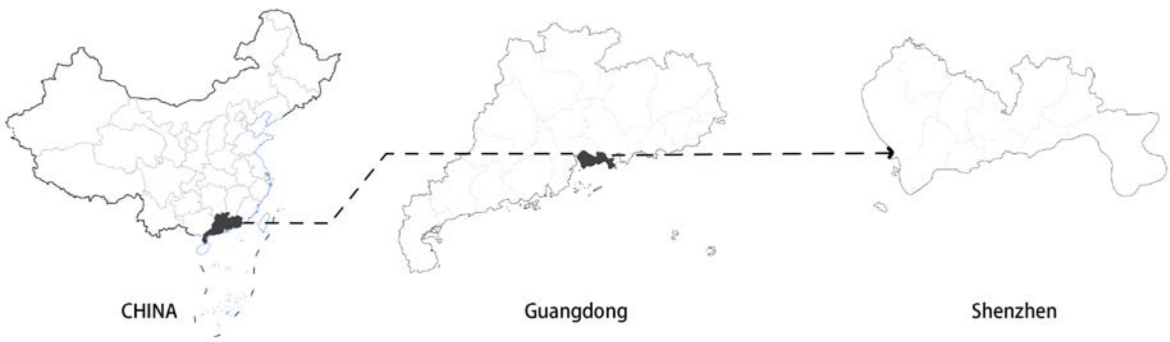

Figure 2. Shenzhen District Map

Since Shenzhen is located in a low hilly coastal area, the rainy season may last as long as 6 months every year and catastrophic weather such as typhoons and heavy rains are frequent. From January 1970 to August 2019, there have been 41 earthquakes with magnitude 2-3 and five earthquakes with magnitude 3-4 in Shenzhen. The severest one was a magnitude 3.7 in 1999. The most recent one occurred on November 19, 2010, when an earthquake with a magnitude of 2.8 on the Richter scale was felt between

Nanshan and Bao'an District. In addition, Shenzhen's undulating terrain makes it easy for geological disasters to happen in the case of heavy rainfall. Two larger landslides occurred on December 20, 2015 and July 18, 2017, the former of which resulted in 73 deaths and four missing people. The main types of disasters and calamities in Shenzhen are shown in Table 3.

Table 3 Types of disasters and their names

Type	Natural disaster disaster name
Meteorological disaster	Flood, typhoon, rainstorm, cold wave, drought, high temperature, etc.
Geological hazards	Earthquakes, landslides, mudslides, fissures, ground subsidence, soil erosion, etc.

With the economic and social development, the population becomes more concentrated in the city. In the event of a disaster, if there is no clear evacuation guideline or safe shelter, it is very easy to cause significant casualties and property damage. Urban emergency shelters play an important role in responding to sudden disaster events. At present, China has introduced targeted standards, and most cities are gradually building and reconstructing emergency shelters. Shenzhen, as one of the most developed cities in China, is also actively promoting the construction of emergency shelters.

4. Results

4.1. Population distribution and the need for shelters

In this study, the plots are formed by enclosing the OSM road network, and the urban green areas are removed by POI and basic ecological control line data to obtain the plots representing the built-up area of the city. The population of each plot is then calculated to obtain the departure points of evacuees in the study area and the number of evacuees at each point.

Figure 3 shows the population density of each parcel. The population of Shenzhen is mainly concentrated in Futian and Luohu District, followed by Nanshan, Bao'an and Longgang District, so the planning of evacuation sites in these areas should take population distribution into greater account and should be targeted.

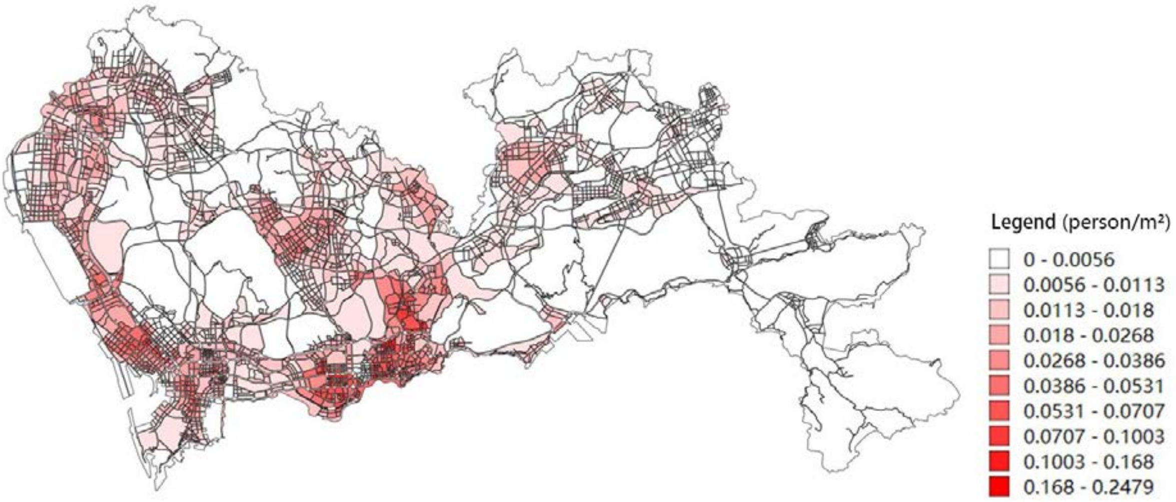

Figure 3. Population density of each block in Shenzhen

In the current normative standards, the capacity of emergency shelters is calculated based on the population size of the city. In this study, statistics on the resident population, evacuation population, and emergency shelter capacity of each administrative district were conducted (see Table 4). By obtaining the resident population of each administrative district through the statistical yearbook and following the requirement of the planning standard that the number of fixed evacuation population should not be less than 15% of the resident population within the area of responsibility for emergency shelter services, the number of population that should be served by emergency shelters in the whole city and each administrative district can be calculated. By comparing it with the capacity of shelters, the supply and demand of shelters in each administrative district can be obtained.

Table 4 Macro refuge supply and demand

Administrative District Name	Number of resident population	Number of the shelter population	Capacity of shelter sites
Dapeng New District	15690	2354	9761
Yantian District	21430	3214	4287
Ping Shan District	55430	8314	23769
Guangming District	110350	16553	18373
Luohu District	114750	17213	12780
Futian District	155410	23312	91467
Nanshan District	180420	27063	50924
Longhua District	254320	38148	73199
Longgang District	399900	59985	43813
Baoan District	449110	67367	51744

The supply of emergency shelters in Luohu, Longgang, and Baoan Districts could not meet their demand. Among the administrative districts where the supply of shelter capacity meets the demand for shelter, Futian, Longhua and Nanshan District have the largest surpluses, while the supply and demand of the remaining administrative districts basically match.

4.2. Evacuation simulation results

4.2.1. Evacuation distance of evacuation sites

Using OD cost matrix analysis in QGIS, the distance of the road network between two points can be calculated based on the origin, destination and road network datasets (see Figure 4).

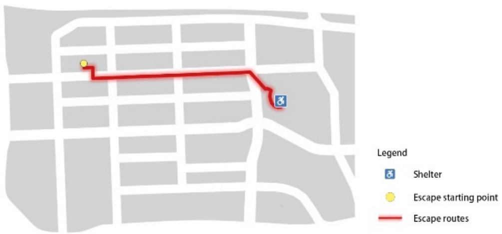

Figure 4. Brief schematic diagram

The first step is to generate an attribute table of evacuation route information, including starting point number, ending point number, and distance traveled based on the starting point, ending point, and road network data set. The result covers the simulation calculation results for all routes from each starting point to end point (see Table 5).

Table 5 Simulation results

origin_id	destinatio_id	entry_cost(m)	network_cost(m)	exit_cost(m)	total_cost(m)
1	43	287.0776066	18355.6984	63.1080368	18705.88404
1	44	287.0776066	18977.53861	5.4177279	19270.03395
1	1121	287.0776066	18355.6984	63.1080368	18705.88404
1	416	287.0776066	38253.81292	23.2183297	38564.10885
1	445	287.0776066	40781.91964	10.881052	41079.8783
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In this study, it is assumed that the evacuees will go to the evacuation site with the shortest distance on the road network. Further filtering of the data, therefore, is needed. The second step is to run an SQL query in QGIS to select the distance with the lowest "total_cost" from the starting point to all destinations. The figure only shows the connection between each starting point and the nearest destination, expressing the relationship between the escapees and their nearest evacuation sites in a certain area.

According to China's National Standard for Urban Disaster Prevention Planning (GB/T51327-2018), the evacuation distance of short-term fixed evacuation sites should be within 1 km. The blue line indicates that the evacuation distance is within 1km, while the red line indicates that the evacuation distance exceeds the requirement of 1km specified in the standard. It can be seen that in the central area of the built-up area of the city, most of them can meet the standard for evacuation distance, with Futian District doing the best job in this regard. Most of the evacuation distance of evacuation places can meet this requirement.

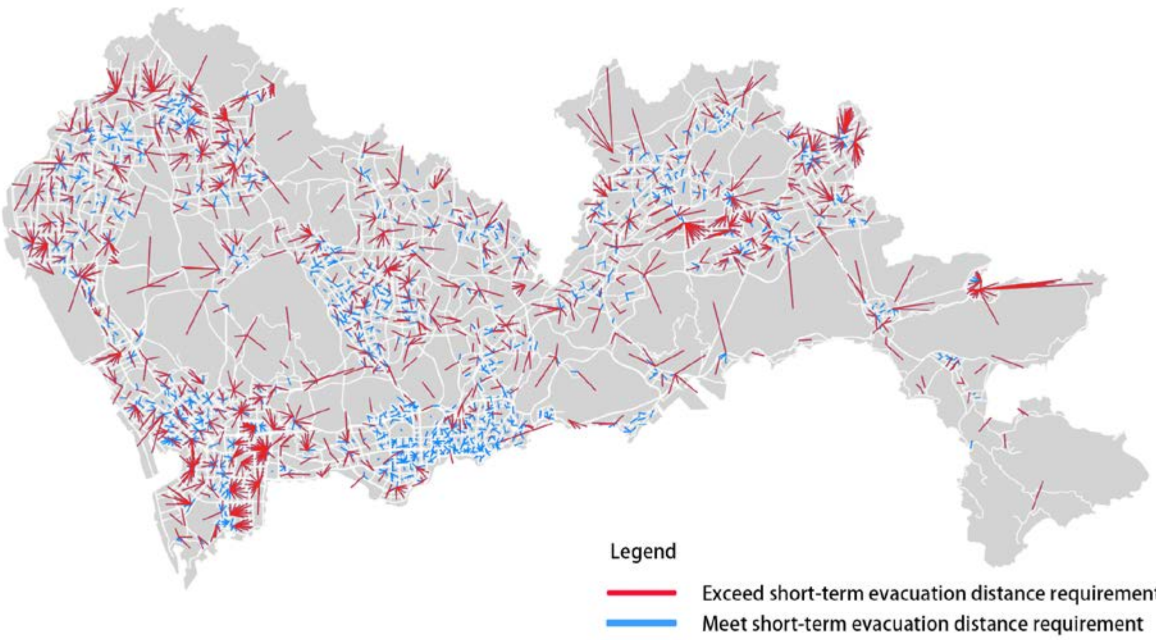

Figure 5. Diagram of evacuation simulation results

According to the statistics in Figure 6, among all 2939 evacuation routes, the shortest evacuation distance is within 100m. A total of 1500 routes have an evacuation distance of less than 1km, which meets the requirements of short-term evacuation places for evacuation distance. The average evacuation distance in Shenzhen is 1.16km. According to the requirement that the evacuation distance of long-term fixed evacuation sites should be within 2.5km, a total of 95% of all evacuation routes meet it. Generally speaking, the evacuation distance of most evacuees is within 2km.

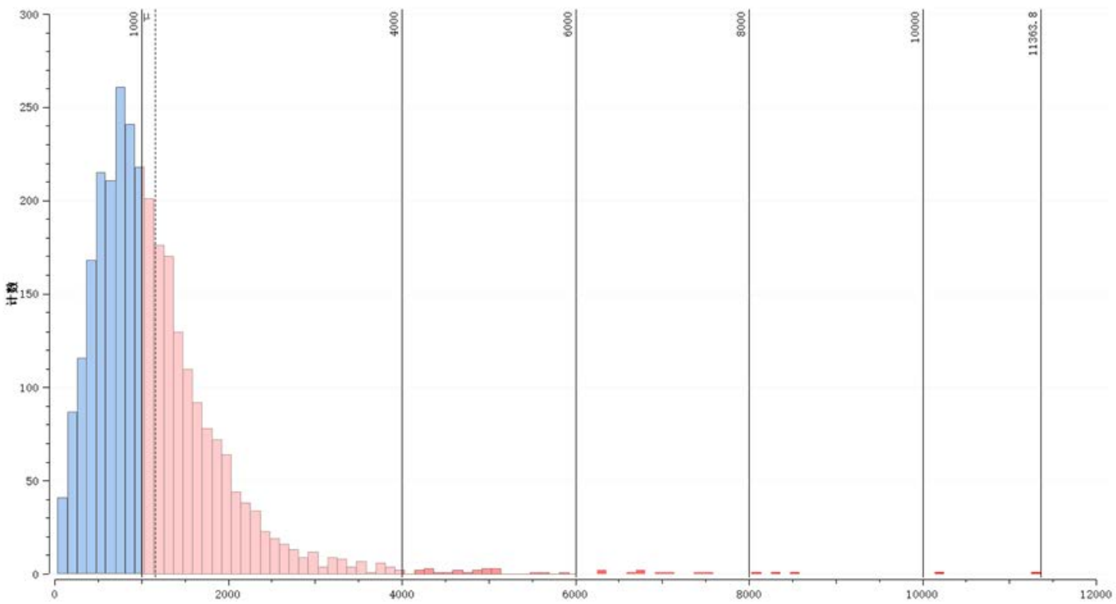

Figure 6. Evacuation distance histogram

As can be seen through Figure 7, for the plots that have the evacuation distance of more than 2.5km, most of them are in the urban fringe areas as well as the mountainous areas in the city, overlapping with the urban ecological control area. Only 25 of the 146 plots are outside the urban ecological control area, and basically adjacent to the ecological control area. The escape distance of the western coastal area of Baoan and Nanshan District mostly does not meet the evacuation distance standards, indicating that the region's refuge resources are scarce.

4.2.2. Shelter capacity

The capacity of the evacuation site after the completion of the evacuation simulation is obtained by subtracting the number of evacuees evacuated to the site from the capacity of the evacuation site. The capacity of each evacuation site is obtained from the public documents released by the Shenzhen government. The capacity of the evacuation site is shown in Figure 8. A red dot indicates that the site has a surplus capacity after accepting the nearest evacuees and can accommodate more people while a blue dot indicates that the site has insufficient capacity and cannot meet the evacuation demand of the nearest evacuees. The size of the dot indicates the size of the surplus or shortage of capacity. Among all the places of refuge, only 39.1% of them have the capacity to meet the evacuation needs of the nearest evacuees, with red dots mainly concentrating in Futian, Luohu and Nanshan District, and blue dots mainly in Bao'an, Longhua and Longgang District. The results indicate that the construction of places of refuge is better in the better developed districts, while the places of refuge adjacent to ecological green areas mostly show the situation of insufficient capacity. In general, there are many places of refuge in each administrative district that cannot meet the evacuation needs of evacuees, indicating that there is an imbalance between supply and demand. In the future, these shelters with insufficient capacity should be renovated to increase the capacity of evacuees, or new shelters should be added in their surrounding areas.

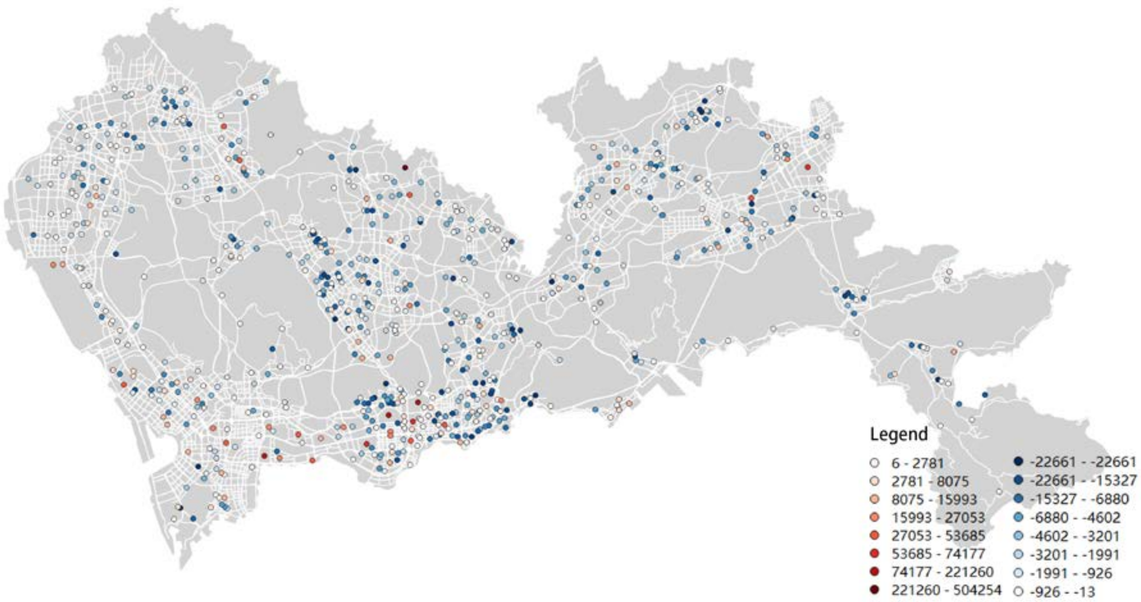

Figure 8. Accommodation of evacuation sites after evacuation simulation

5. Discussion

According to the analysis results, urban emergency shelters show different problems in different areas of Shenzhen. This is related to the development time sequence of the city, the tightness of land and the distribution of urban population. The discussed solutions should also differ for the central urban areas and other areas of the city.

In the central urban areas, there is a big difference in the service situation of refuge places. As Futian and Luohu Districts are the early development and construction areas in Shenzhen, their urban built environment and facilities are more complete compared with other areas. The evacuation distance of the refuge places in these areas can meet the standard requirements, except for Futian port area. Because of its closeness to Hong Kong, this area's development is more special. At the same time, a large number of people are distributed in the central city, resulting in a serious shortage of capacity supply of some places of refuge, which are mostly concentrated in residential areas or near urban villages. As for Nanshan District, as it is a newly built area, the distance between plots is too long due to highly concentrated construction. There are mainly residential, commercial and office buildings, with little common resources to be used as emergency shelters. Therefore, the evacuation distance of the area is too long, with the evacuation distance of most of the plots exceeding 1 km. In the future planning, the capacity of existing urban emergency shelters should be expanded to meet the needs of evacuees. As for in Nanshan District, priority should be given to finding new vacant land or stock renewal of existing land to build new shelters.

In addition to the central city of Shenzhen shelter places basically meet the requirements of the normative standards. In Longgang District, Baoan District, Longhua District and other areas, due to the late development of the city, there are large shortcomings in the number and capacity of places of refuge, and the capacity of most places of refuge can not meet the evacuation needs of the surrounding evacuees. Only some of the places of refuge located in the center of these regions can meet the demand for shelter. At the same time, many local urban development is not very compact and the land is relatively loose compared to the central city, so there are many evacuation distances in excess of the short-term emergency shelter standards. Even at the edge of the built-up area, there are many plots with evacuation distances exceeding 2.5km, which does not meet the standard requirements for long-term shelters. However, considering that there are still more open spaces in these areas, the subsequent planning can be flexible to add new emergency shelters so as to meet the requirements of the normative standards.

The results of the urban emergency shelter survey in this study can find the gap between the current situation and the normative standards, and thus guide the planning practice for better implementation. It can solve the problem that traditional planning tools cannot investigate whether the capacity and number of traditional shelters meet the normative standards in the context of the increasing disaster risk and the introduction of new disaster prevention normative standards in China.

6. Conclusion

After the Chinese government releasing the relevant normative standards for urban disaster prevention and mitigation and emergency shelters in recent years, a survey method that can understand the gap between the current situation of urban emergency shelters and the normative standards is needed. This study evaluates the service capacity of emergency shelters in Shenzhen with the aim of developing a high-precision and low-cost data-driven survey method to guide the planning and construction of emergency shelters.

The results show that most of the emergency shelters can meet the requirements of the normative standards in terms of evacuation distance; As for capacity, although the total capacity of shelters in most administrative districts is greater than the number of evacuees, thus meeting the requirements of macro indicators, there is an imbalance in the supply and demand of shelters in space within the city because of the differences in the population distribution. The capacity of many shelters is not difficult to meet the demand of evacuees in the surrounding area. Simulating the escape situation when a disaster occurs can guide the resource allocation of emergency shelters in urban planning. In areas with high population density, especially in old urban areas, the number of facilities that can be used as evacuation sites is insufficient, the evacuation demand gap is large, and the problem of insufficient capacity of evacuation sites is prominent. In areas with low population density, most of them face the problem of long evacuation distance. In the central areas of cities, the stock of land resources can be tapped to build evacuation sites through stock renewal and other means. In other areas, the emergency evacuation service capacity can be improved by building facilities that can be used as evacuation sites, such as schools, gymnasiums, and parks.

Based on urban big data, this study can provide quantitative research data for the spatial optimization of emergency evacuation places in urban planning and reference for improving the construction of urban evacuation places. In this study, some conditions and modeling environments (such as road disruption, behavior and psychology) are simplified in evacuation simulation and spatial optimization, which may affect simulation results. More detailed simulation studies are needed in the next level of micro or meso-scale research.

7. Funding

This work was jointly supported by the Fundamental Research Funds for Central Universities under Grant No.HIT.HSS.202108 and Grant No.AUEA5750000120; Graduate Education and Teaching Reform Project of Harbin Institute of Technology under Grant 21HX0303; and Education and Teaching reform research project of Heilongjiang Education Department under Grant SJGY20190208.

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