Study on the Emergency Shelter Spatial Accessibility Based on Simulation of Evacuation Process

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Abstract. Urban emergency shelters are very important public safety facilities. This paper analyses the spatial accessibility of emergency shelters in urban Tianjin by simulating the evacuation process. This process is divided into stages by using GIS spatial analysis techniques based on shelter data and house data. A big difference or ascendancy is that this method can find out the discrimination in the service supply and service demand. The difference can reveal the competition among them. The experience results show that, except for Hebei District, which needs to increase the construction of evacuation sites, the spatial distribution of emergency evacuation sites in other districts and counties in Tianjin is reasonable, but there is a need to improve the utility rate of large and medium-sized evacuation sites in terms of planning, construction and management.

Keywords: spatial accessibility · emergency shelter · Simulation of evacuation process · spatial analysis

1 Introduction

Emergency shelters are very important public facilities for people living in cities when the disaster happens. They are used for evacuation and resettlement of refugees, with some basic living facilities. Parks, green spaces, school playgrounds, squares in the city are often used as emergency shelters. With the development of urbanization, most of cities in China have built emergency shelters for resettlement, evacuation and rescue of disaster victims. Both the service supply and demand have spatial and non-spatial dimensions feature, and the emergency shelters still compete with others near around them, so the spatial accessibility of emergency shelters is a vital indicator to measure the emergency shelters service.

Spatial accessibility refers to availability and convenience to the public supplies [1, 2]. In recent years, various methods have been proposed to calculate the spatial accessibility, such as two-step floating catchment area method (2SFCA) [3, 4], network model method [5], the nearest facility method [6]. And those methods have been used to access various infrastructures, such as healthcare services [7, 8], fire stations [9], public transport stations [10], and other public facilities. The methods mentioned above usually used in those kinds of uncompetitive or less uncompetitive condition. The big

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difference from emergency shelters to other public facilities is competitive, or in other words, when using emergency shelters, the status of society is unnormal and urgent. This issue has been overlooked in studying spatial accessibility of emergency shelters. Wei used proposed method to access the spatial distribution and service efficiency [11]. The extended 2SFCA method has been used for measuring spatial accessibility and crowdedness of the emergency shelters in Beijing by Zhou [12]. Tang combined 2SFCA method and origin-destination matrix to calculate the spatial accessibility of shelters in Guangzhou [13]. The spatial unit of population used in the study of spatial accessibility of emergency shelters is another important factor. The census tract size used in the study of mention above is the basic administrative unit, such as county [11], block unit [12]. The spatial scale of them is usually bigger than the service threshold travel distance. This can lead to errors and uncertainty in calculating spatial accessibility.

This paper proposes a simulation method that fully consider the spatial and nonspatial aspect of the supply and demand of public service. And the competitive relation among the service supply or demand is also in the consideration. The proposed method is used to measure the spatial accessibility of shelters in the urban area of Tianjin, China.

2 Study Area and Data Resource

The study area in this paper is the urban area of Tianjin, China, which include 6 counties (Fig. 1). Its total area is 194.22 square kilometers with 4.057 million people. The average density of population is 20888 people per square kilometer. There are various active faults located in Tianjin. In 1976, the 7.8 magnitude Tangshan earthquake caused the urban area

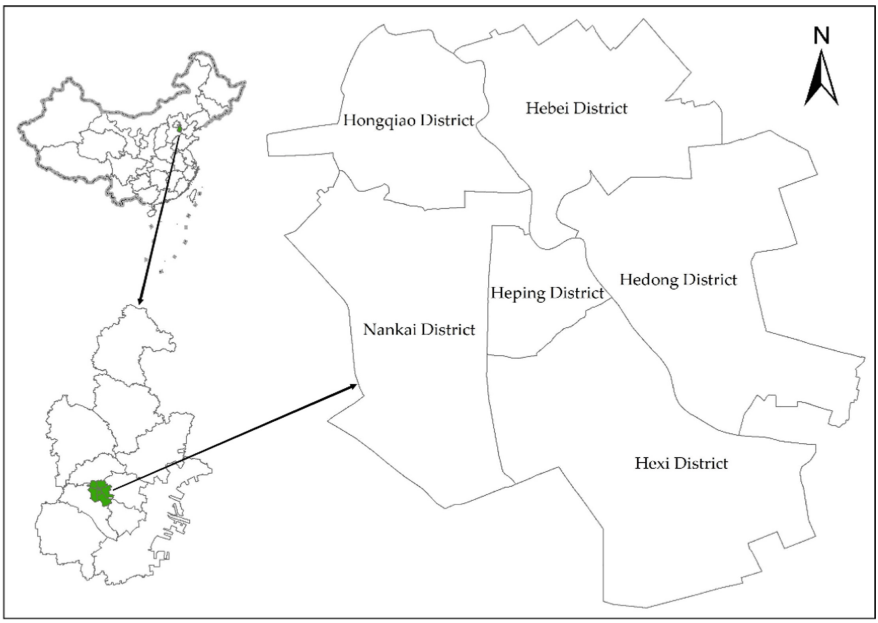

Fig. 1. The spatial distribution of study area in China [self-made figure]

to be damaged seriously. In addition, natural disasters or public safety accidents (such as rainstorms, fires, explosions, chemical leaks, etc.) also seriously threat the public safety of Tianjin. Therefore, Tianjin has a greater demand for emergency shelters.

The data of emergency shelters was obtained from bureau of emergency management of Tianjin. The population data was got from the seventh national census data published on the website of the Tianjin municipal bureau of statistics. The buildings data was from Tianjin institute of surveying and mapping Co. Ltd.

3 Method

3.1 The Census Tract Unit

The population distribution is a basic data of the service demand. The spatial scale of census tract is connected with the accuracy of spatial calculating. In this paper, the buildings are taken as the basic census tract, which is more reasonable and accurate.

This method based on the follow hypothesis that population distribution is positively correlated with buildings, and population is proportional to building area [14–16]. The calculation equation of population density per square meter of building area is as follows.

$$\overline{P_k} = \frac{N_k}{\sum_{j=1}^{m} (L_j \times A_j)} \tag{1}$$

$$p_j = \overline{P_k} \times \left(L_j \times A_j\right) \tag{2}$$

where $\overline{P_k}$ represents the population density of building k in a certain county, N_k is the total population of county k, L_j is the number of floors of building j, A_j is the floor area of building j. p_j represents the population in building j.

3.2 The Emergency Shelters

According to industry construction standards, emergency shelters are divided into 3 categories. They are temporary emergency shelter, fixed emergency shelter and center emergency shelter. The serve distance of temporary emergency shelter is 500 m, and the serve distance of the rest two is 1500 m.

As for the capacity of every emergency shelter is provided in the original data. In this paper, the emergency shelters are divided into four types: micro, small, medium, large, and their corresponding population is listed in Table 1. There are 77 emergency shelters whose capacity are bigger than 10000, which are parks or green lands. These 77 emergency shelters were given a threshold travel distance of 1,500 m and the rest were given a threshold travel distance of 500 m.

3.3 Evacuation Process Simulation

When natural disaster happens, the evacuation process is affected by various factors, such as the size of the disaster, the distribution and capacity of emergency shelters, and the distribution of population density, and it is a dynamic and random process. As for

Table 1. The population of different types [self-made table]

types	Macro	Small	Medium	Large
Capacity range	0–1000	1000–5000	5000–10000	>10000

the emergency shelters, the evacuation process is a changing population from zero to the biggest capacity or a certain number below it.

Because there are a big number of emergency shelters in downtown area of Tianjin, usually people in certain buildings can have several emergency shelters to choose. We assume that people choose emergency shelters randomly in the set providing evacuation service. The technical route is as follows.

1. The people in the buildings are divided into n groups, and every time one group go to the shelters. The whole process includes n stage. If the number of people in a building is less than n, then there is only one person in a group and then number of groups is less than n.
2. If the number of people in an emergency shelter is lower its the capacity, then search the buildings that are covered by the catchment area.
3. If the people in a building is more than n person, then each time there is one group go to the shelter.
4. Perform step 2 and 3 in a loop for n times.

In the actual disaster evacuation process, a small number of people will stay due to various reasons. In this paper, it is assumed that one group people stay in their original places.

3.4 Spatial Accessibility of Emergency Shelters

There are 3 parameters that are used to access emergency shelters. They are the spatial accessibility, crowdedness, and the number of stayers. The spatial accessibility is the ratio of the number of people who went to the shelters and the total number who wanted to. The crowdedness is the ratio of number of refugee and the capacity of emergency shelter. The stayers are the people who want to find an emergency shelter, but there is no emergency shelter can provide service.

4 Results and Analysis

4.1 Emergency Shelters Data

By the end of 2020, there were 682 emergency shelters in the urban area of Tianjin, which total area is 4.0572 million square meters (Fig. 2). The detail information about each district in urban area of Tianjin is shown in Table 2.

Table 2. The emergency shelters in the urban area of Tianjin [self-made table]

County	Shelters number	Total area (m^2)	Capacity
Heping district	55	310210	355000
Hedong district	134	361540	858787
Hexi district	214	1056684	822174
Nankai district	163	692392	890422
Hebei district	2	224000	647702
Hongqiao district	114	744039	483130

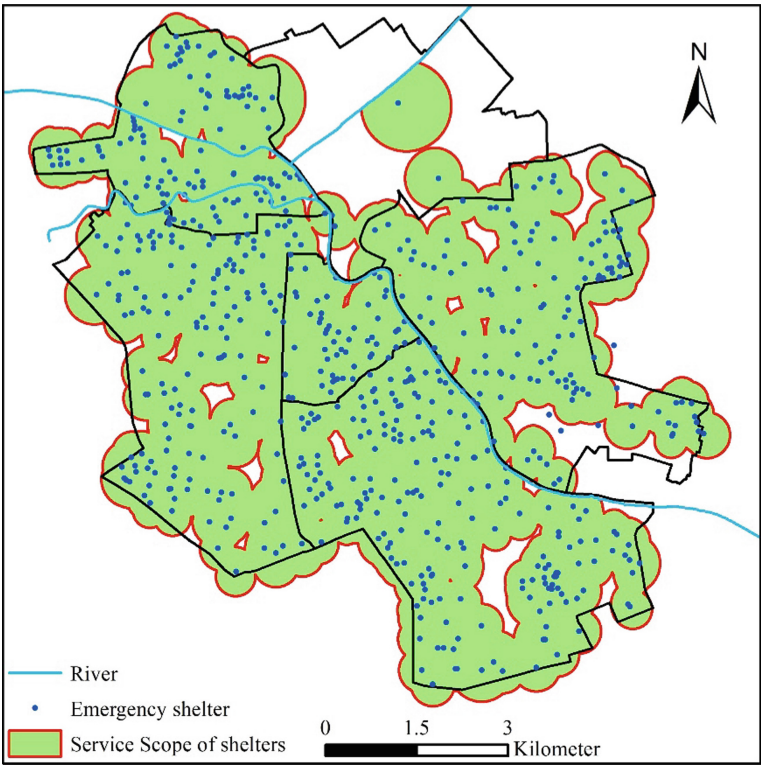

Fig. 2. The distribution of emergency shelters and its service scope [self-made figure]

4.2 Population Density Distribution

The Eq. (1) and (2) are used to calculate Tianjin's building data and the seventh national population census to get the population per building. By using the kernel density analysis in ArcGIS 10.5, we have the population distribution map (Fig. 3).

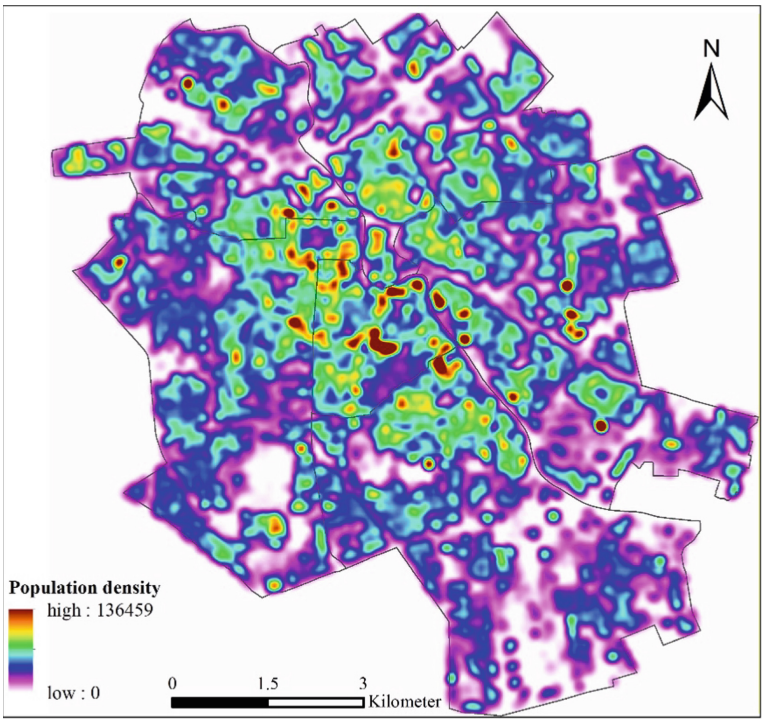

Fig. 3. Population density distribution in Tianjin urban area [self-made figure]

In Fig. 3, it can be seen that areas with high population density include the entire Heping district, the area along Haihe river, part of area in Nankai district near Heping district.

4.3 Evacuation Process Simulation and Analysis

The evacuation process in the Tianjin urban area is divided into 9 steps. One tenth people in the building go to the emergency shelters in every step. If the number of people is a floating-point number, then drop the fractional part and add 1 to the integer part. In the end of process, some key parameters are calculated. In this experience, it is assumed that there are one in ten people staying where they were. The choice of evacuation site for the evacuation population in each building is randomly made among the evacuation sites that can serve them.

The Usage of Different Type Emergency Shelters

During the evacuation simulation of emergency shelters classified according to different volumes, (as shown in Fig. 4), the variation of utilization rate of different shelters was obvious. Among them, the utilization rate of micro shelters quickly reached 90% in the first three stages, and the utilization rate of small and medium shelters reached 80% in the 6th stage. The utilization rate of large shelters reached only about 30% even in the last stage.

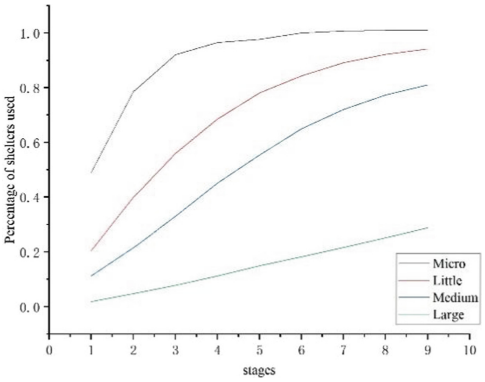

Fig. 4. The usage of different type shelters [self-made figure]

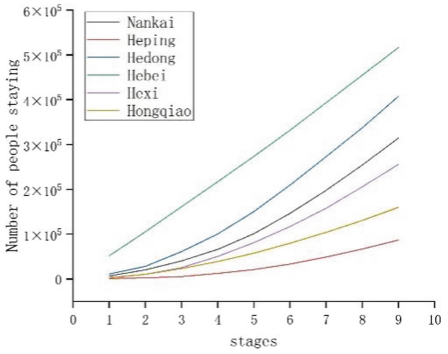

Fig. 5. Map of changes in the number of evacuees by district [self-made figure]

The Stayers' Distribution of Buildings

The distribution of the number of stranded people was made based on the data of the buildings, as shown in Fig. 5, which shows the change of the density of the geographic distribution of stranded people in the urban area of Tianjin from stage 1 to stage 9.

After calculation and simulation, the number of people staying in the buildings at each stage was obtained. Based on the definition of the number of stranded people and the simulation data above, the curves of the change of crowd stranding and the change of the capacity of each shelter in six districts of Tianjin are shown in Fig. 5. It can be seen that the number of stranded people in Hebei District increases the most significantly; the number of stranded people in Heping District is the least and the curve changes the most gently; the curve changes in Hongqiao District are also relatively gentle; while the curves of stranded people in Hedong District and Nankai District rise faster after the 5th stage and in Hexi District after the 7th stage. This indicates that the spatial distribution of evacuation places, in areas where the density distribution of the population is not consistent, the evacuation places do not play their proper role.

From Fig. 4, it can be seen that there was no serious detention in the areas except Hebei District from the 1st to the 3rd stage of the evacuation process; in the 5th to the

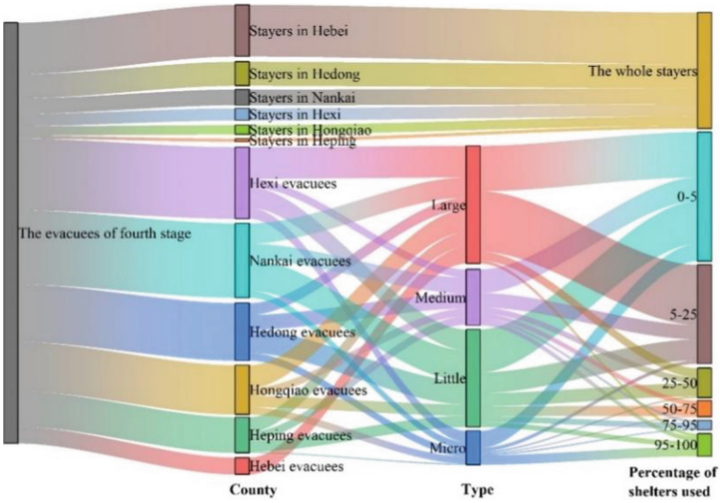

Fig. 6. Flow chart of the evacuees in the fourth phase [self-made figure]

6th stage, there was detention in some areas; and in the 7th stage, there was serious detention in some areas of Tianjin. In the distribution of stranded people from stage 7 to stage 9, it is obvious that there is no or only a small number of stranded people in the service areas of some large and medium-sized evacuation sites with circular areas.

From the Sankey diagram of the flow of the evacuation crowd in stage 4 shown in Fig. 6, it can be seen that: at this time, the capacity of most of the micro evacuation places used has reached saturation, and small evacuation places play a greater role. And large and medium-sized evacuation sites are not fully utilized. From the perspective of different districts and counties, the number of people stranded in refuge is much larger in Hebei District than in other districts and counties because of the smaller service coverage of refuge places. Heping district, Hongqiao district, Hexi district, Hedong district, the number of stranded people is relatively small.

The Crowdedness and Spatial Accessibility of Emergency Shelters

The detail results can be seen from experience because the buildings are calculated as the basic census tract. In the Fig. 7, buildings with high spatial accessibility and buildings with low spatial accessibility are intersecting in their geographical distribution. This phenomenon is associated with the number of people in the building, which means that buildings with less people can have more chance of shelter service. On a larger scale, spatial accessibility differs from neighborhood to neighborhood for the different capacity in their neighborhood. An obvious example is that there are only two emergency shelters in Hebei district, which leads most areas of Hebei district not being covered by shelter services with a spatial accessibility of zero. In the areas adjacent to Hedong district, Nankai district and Hebei district, the accessibility is also low, which is mainly because the service capacity of refuge places in these areas cannot meet the demand. Although the population density of Heping District, Hexi District and Hongqiao District is higher,

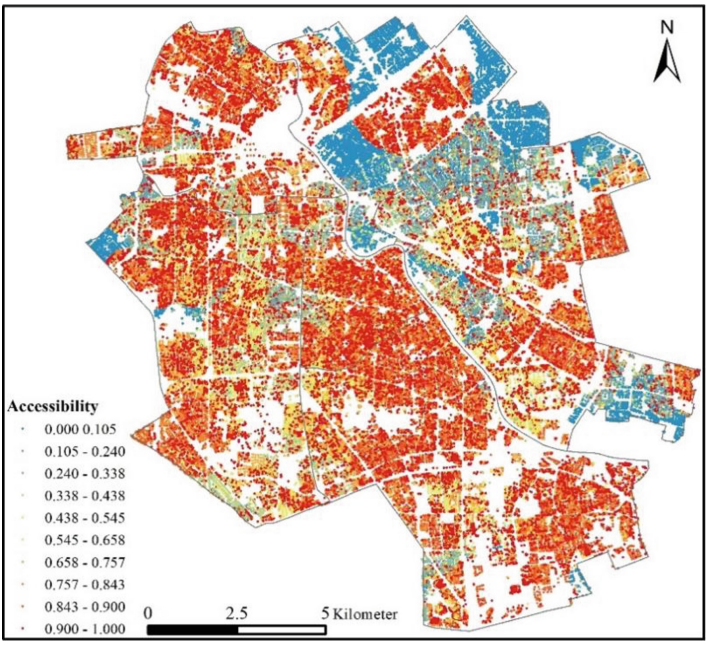

Fig. 7. The spatial accessibility of every building to emergency shelters [self-made figure]

the accessibility values of the shelters in these three districts are higher due to their reasonable capacity distribution of shelters.

5 Conclusion

The main purpose of this study was to evaluate the spatial accessibility of emergency shelters in Tianjin urban area. This study has shown that use single building as basic census tract could improve the spatial accuracy. The second major finding was that the proposed method of calculating accessibility can find the utilization and crowding rates of different types of shelters during the evacuation process. A limitation of this study is that process simulation requires more computational resources and time than traditional methods. The spatial accessibility of buildings to evacuation services was calculated for each region of Tianjin in an experiment in the urban area of Tianjin. The results have implications for improving the efficiency of the use of evacuation sites, and the planning layout.

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