Evaluating the Crowdedness of Urban Emergency Shelters Based on the Improved Gravity Model

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Abstract. The evaluation of the crowdedness of urban emergency shelters is highly important for the evacuation and advance planning of emergency shelters. Given the urgency of evacuation following a disaster, this study assesses the buildings in a residential area, and attempts to improve the existing gravity model of emergency shelter evaluation through the introduction of population-scale influence factor, emergency shelter service capacity and travel limit distance. The study considers parts of the Chengguan District of Lanzhou City as an example. Based on the attraction of emergency shelters to the residential area, the residents are allocated to each emergency shelter for quantitative analysis of urban emergency shelter crowdedness under different travel limits distances. The results show that the crowdedness differs greatly depending on the distance to the shelter, and becomes worse due to the small number of emergency shelters in the Southwest region. With the increase of the travel limit distance, the number of emergency shelters that can be reached by the residents increases; consequently, the crowdedness decreases, which shows a trend of increasing from northeast to southwest. The improved gravity model considers the travel distance, population size and service capacity of emergency shelter. The model allows us to evaluate the impact of the travel distance on the crowdedness of emergency shelters when the travel distance is short, and assess the service capacity of emergency shelters when the travel distance is long. The use of this model can reasonably and reliably reflect the crowdedness of emergency shelters and provide a scientific basis for the planning and decision-making of relevant government departments.

1. Introduction

With the acceleration of urbanization disaster risks are rising. In urban areas with the high concentration of population and property, a disaster can often result in a large loss of life and property. Emergency shelters have a great importance for disaster victims providing rescue and resettlement when sudden disasters such as earthquakes strike. Emergency shelters are also an important part of the urban disaster prevention and mitigation system. The planning and construction of emergency shelters have started to attract the attention of governments at all levels.

A rational spatial distribution of emergency shelters can ensure urban disaster resistance. At present, the evaluation of the rationality of the spatial layout of emergency shelters focuses mainly on their accessibility. The accessibility of emergency shelters reflects the distance from the residential areas to emergency shelters. Various methods have been used to evaluate the accessibility of emergency shelters. Dou and Zhan [1] compared the resulting emergency shelters accessibility using Gravity Model and Space Syntax. Anhorn and Khazai [2] evaluated the accessibility of emergency shelters following an earthquake using Maximize Capacitated Coverage analysis. Tang et al. [3] evaluated the emergency shelter accessibility in urban communities using a two-step floating catchment area (2SFCA) method. Zhu et al. [4] evaluated the emergency shelter accessibility using variable catchment sizes for 2SFCA.

The important aim of the accessibility evaluation of urban emergency shelters is determining whether the layout of emergency shelters is reasonable, as well as identifying the service scope gap. Following this, measures can be taken to minimize non-rational distribution. However, a simple analysis of the accessibility of emergency shelters only reflects the of the residential areas to emergency shelters but cannot directly evaluate their use. To solve this problem, the inverted two-step...
floating catchment area (i2SFCA) method was introduced to evaluate the "Crowdedness" (resource scarcity or competition intensity) of public facilities [5]. So far, this method has been applied in studies of the crowdedness of public facilities such as medical facilities [6] and fire facilities [7]. However, the i2SFCA ignores the influence of population competition and travel limit distance on the probability of choosing an emergency shelter.

In this study, we introduced a population-scale influence factor, emergency shelter service ability and travel limit distance to improve the gravity model. Following this, the crowdedness of emergency shelters in some areas of Chengguan District, Lanzhou City, Gansu Province was evaluated, based the attraction of an emergency shelter to the residential area. Finally, we quantitatively evaluated the rationality of the spatial distribution of emergency shelters in the study area according to the crowdedness.

2. Study area and data
Figure 2. Distribution of population in the study area

Lanzhou City is the capital of Gansu Province, located in the north-western part of China. The study area is located in the southwest of the Chengguan District of Lanzhou City, mainly including seven streets such as Donggang West Road and Jiujian Road (Figure 1). The residential population of the study area was 350475 at the end of 2015, comprising roughly a quarter of the permanent population of Chengguan District, which belongs to the high-density population gathering area.

Emergency shelters mainly include playgrounds, parks, parking lots, green spaces and large areas of spaces between buildings [4]. The distribution of emergency shelters in the study area was obtained from Google Earth, with each of them being larger than 2000 m². The population data were collected from the Statistics Bureau of Lanzhou, and the population distribution data were obtained based on the vertical projection area and the floor number of the buildings (Figure 2).

3. Methods

3.1. Improved Gravity Model

The gravity model was proposed by Hansen [8] in 1959, and is one of the methods based on the spatial interaction in accessibility measurement of public facilities. It considers the scale, spatial barrier and distance decay between supply and demand. The gravity model is generally presented as follows (1):

$$A_i = \sum_{j=1}^{n} \frac{M_j}{d_{ij}^\beta}$$

where $A_i$ is the gravity accessibility index, $n$ is the total number of emergency shelters, $S_j$ is the service capability of emergency shelter at location $j$, $d_{ij}$ is the distance between the locations $i$ and $j$, $\beta$ is the distance friction coefficient ($\beta = 2$ when the travel distance is short, otherwise 1).

Although the general gravity model considers emergency shelters service capacity and travel distance, it ignores the impact of population size on the competition and travel limit distance of emergency shelters. To improve the gravity model, this study introduces the population-scale influence factor and travel limit distance. The specific formula is as follows:

$$A_i = \sum_{j=1}^{n} \frac{M_jS_{ij}}{d_{ij}^\beta V_j}, V_j = \sum_{k=1}^{m} \frac{P_kS_{kj}}{d_{kj}^\beta S_{ij}}$$

where, $P_k$ is the population of the residential area at location $k$, $m$ is the total number of residential areas, $V_j$ is the population-scale influence factor, $D_j$ is the travel limit distance, $d_{kj}$ is the distance between the locations $k$ and $j$, $S_{ij}$ is the factor influencing the selection of an emergency shelter (i.e. when the travel distance exceeds $D_j$, the emergency shelter will not be selected).

3.2. Crowdedness

Crowdedness can be used to measure the impact of residential areas on emergency shelters. In the latest study, Wang [5] proposed i2SFCA to evaluate the "Crowdedness" (resource scarcity or competition intensity) of public facilities. The result is the ratio of service population to public facilities, which can directly reflect the utilization degree of public facilities. The calculation method is as follows:

$$C_j = \frac{P_j}{M_j} = \sum_{k} P_k f(d_{kj}) (\sum_{i} M_i f(d_{ij}))^{-1}$$
where, $C_j$ is the crowdedness of facility $j$, $P_j$ is the total number of people may attracted by facility $j$, $P_k$ is the population of residential area at location $k$, $M_j$ is Service capability of facility $j$, $D_j$ is the travel limit distance, $f(d_{kj})$ is the distance decay function between the locations $k$ and $j$.

i2SFCA is an extension of the classical Huff model, which allocates the population to each public facility according to the probability of choosing public facilities in residential areas, so as to obtain the total population that a public facility may attract. In this study, the improved gravity model is used to optimize the Huff model, and then the optimized Huff model is used to improve the i2SFCA. Specific formulas are as follows:

$$C_j = \left( \sum_{k=1}^{m} P_k P_{kj} \right) M_j^{-1}, P_{kj} = \frac{M_j S_{kj} A_k^{-1}}{d^{2} J_{j}}$$

(4)

where, $P_{kj}$ is the probability of residential area $k$ choosing facility $j$.

4. Results

As shown in Figure 3, the crowdedness of emergency shelters was separately calculated at 500 m, 1000 m, and 2000 m travel limit distance scenarios. In the 500 m scenario, the crowdedness of emergency shelters varied greatly, being higher than 0.5 person per m², and partly higher than 1 person per m² in the southwestern region due to the small number of emergency shelters. However, the crowdedness of emergency shelters was low in the southwestern region as a result of the small number of people arriving. In the 1000 m scenario, the number of emergency shelters that could be reached from the residential area increased, and the whole crowdedness decreased. The crowdedness of emergency shelters with a higher service capacity in the central region increased with the increase in the arriving population, however, all of these were less than 0.5 person per m². In the 2000 m scenario, the service capacity of emergency shelters is the main influencing factor. The crowdedness increased from northeast to southwest, being less than 0.1 person per m² in the northeast and between 0.2 person per m² and 0.4 person per m² in the southwest. The standard for urban planning for earthquake resistance and disaster prevention [11] advises that the effective shelter area for people in emergency
evacuation places should not be less than 1 m². According to the results of this study, in the 500 m scenario, the emergency shelters in southwest and south of Gaolan Road Street exceeded the standard of effective shelter area per capita, and the crowdedness was larger. In the 1000 m scenario, only the emergency shelters in Gaolan Road Street exceeded the standard. In the 2000 m scenario, the overall crowdedness was low and met the standard requirement of effective shelter area per capita.

5. Conclusions
An important goal of emergency shelter planning and construction is to promote a rational use of resources. In this paper, we calculated the crowdedness using the improved gravity model that considers the population-scale influence factor, emergency shelter service ability and travel limit distance. Compared with accessibility, the emergency shelter crowdedness can more intuitively reflect the degree of resource utilization to a certain extent, as well as the rationality of the spatial layout. Our results show that the crowdedness of the emergency shelters in the study area is mostly high when the travel distance is short, although the crowdedness meets the standard requirement of effective shelter area per capita when the travel distance increases. Hence, it is important to measure whether the spatial distribution of shelters is balanced and reasonable in densely populated urban areas based on the crowdedness, which can also provide suggestions for the planning and management of emergency shelters in the future.

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