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Allocating Evacuation Shelters in Kumamoto Compact City under the Population Estimation

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Abstract Evacuation shelters provide shelter and basic living facilities for affected people after disasters. They are an essential part of the urban disaster emergency response system. In this study, a spatialization distribution model of the population in Kumamoto City was constructed using land use data. The P-median model was used to analyze the service areas and the supply and demand of evacuation shelters, the distance of demand points to the corresponding shelters. The results show that the ratio of shelters that met the demand in Kumamoto City is only 41.2%, which is less than half. This ratio increased more in the Urbanization Area. In the Residential Promotion Area and the Urbanization Function Promotion Area with higher population density, the ratio of evacuation shelters with insufficient capacity is higher than that in the Urbanization Area. Among the 15 local hubs in the Urbanization Function Promotion Area, only three shelters have a supply-demand ratio greater than 1. About half of the people can reach the shelter within a distance of 0-1000 meters in terms of evacuation distance. The spatial population estimation model using land use data constructed in this study can simulate the spatial distribution of demand points in evacuation. The supply and demand of shelters were evaluated concerning their capacity. It can be used as a reference for the optimal allocation of evacuation shelters in Kumamoto City and future disaster prevention planning in the Kumamoto compact city.

Keywords: *evacuation shelter, Kumamoto compact city, P-median, population estimation*

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1. Introduction

With high economic development and urbanization, the hazards and losses caused by natural disasters are increasing. The importance of disaster prevention and mitigation in urban planning is also receiving more and more attention. As an important component of the urban disaster response system, evacuation shelters have been increasingly emphasized in many countries and regions, such as Japan [1], United States [2] and China [3], and have been incorporated into urban planning. An evacuation shelter is an area or site that provides shelter and basic living facilities for evacuees after a disaster occurred. The suitable location of the shelter, which effectively reduces the evacuation time of evacuees [4], is essential for the safety of the residents' lives and to avoid secondary damage from secondary disasters.

After a disaster, people's instinct is to evacuate to the nearest evacuation shelter or open area. However, as shelters are not evenly distributed and their capacity varies, it is easy for some shelters to have more people than they can carry, making them unable to provide adequate primary living conditions for the evacuees. Other shelters are located at relatively long distances, resulting in sparse populations, unused shelters and waste of social resources [5]. Therefore, it is necessary to explore the division of the service areas of shelters according to scientific methods and to plan the location of shelters in a more reasonable way.

For assessment and optimal allocation of shelter locations, various modelling approaches have been used to solve such problems, such as the P-median model [6,7,8], the P-center model [9], the maximum coverage model [10,11], etc. Many researchers have developed improved or hybrid models based on the above models with multi-objective constraints [12,13], etc. Such as Xu et al. construct a multi-criteria constrained location model for earthquake shelters and analyze the spatial coverage of selecting candidate shelters to determine the location [14]. Jin et al. developed a minimum-cost-maximum-flow solution for the location selection of underground emergency shelters in urban communities [15]. The P-median model determines both the location and the service area of a facility, with the objective of minimizing the total weighted distance. The P-median model is an efficient and rapid allocation method for a limited number of public facilities and has the advantages of simplicity, fewer control variables and faster operations [5]. It is widely used in shelter location evaluation and optimal allocation.

To plan evacuation shelters properly, it is necessary to grasp the spatial distribution of the population. Many methods have been applied for estimating the spatial population distribution, such as the estimation using land use [16,17], buildings [18,19], remote sensing night light data [20], etc. Bian et al. used a modified dasymetric mapping method to estimate population distribution with 30 m × 30 m land use data while estimating the vulnerable population based on census data [16]. Lívia et al. estimated the urban population using the volume of single buildings and high-rise residential buildings obtained from remote sensing (lidar) data [21]. Related studies have shown that land use is a crucial factor in the spatial distribution of population [22]. Using land use data for population estimation is an effective way. Therefore, this study will use the linear relationship between land use and population distribution to analyze the population distribution within each land use.

As a country prone to natural disasters, Japan has designated 48,014 evacuation shelters in 944 municipalities as of October 1, 2014. [1]. Evacuation shelters in Japan are usually set up according to school districts, and in the event of a disaster, people usually seek refuge preferentially at the shelters within their school district. However, as many of the main shelters are not located in the center of the school district, they may not be the closest shelters for residents [23]. In addition, with Japan's aging and declining birthrate and the impact of compact urban development policies, urban land use and population distribution will undergo major changes.

This study aims to examine the supply and demand of evacuation facilities and the evacuation distance at each demand point. A spatialized population distribution model of Kumamoto City was constructed from land use data, and population data of census areas were mapped to the corresponding land use types. The P-median model was used to analyze the service area and supply and demand of evacuation shelters and the distance from the demand point to the corresponding evacuation shelter. This study will contribute to the optimal allocation of evacuation centers in Kumamoto City. It will also provide a reference for future disaster prevention planning in the Kumamoto compact city.

2. Study Area

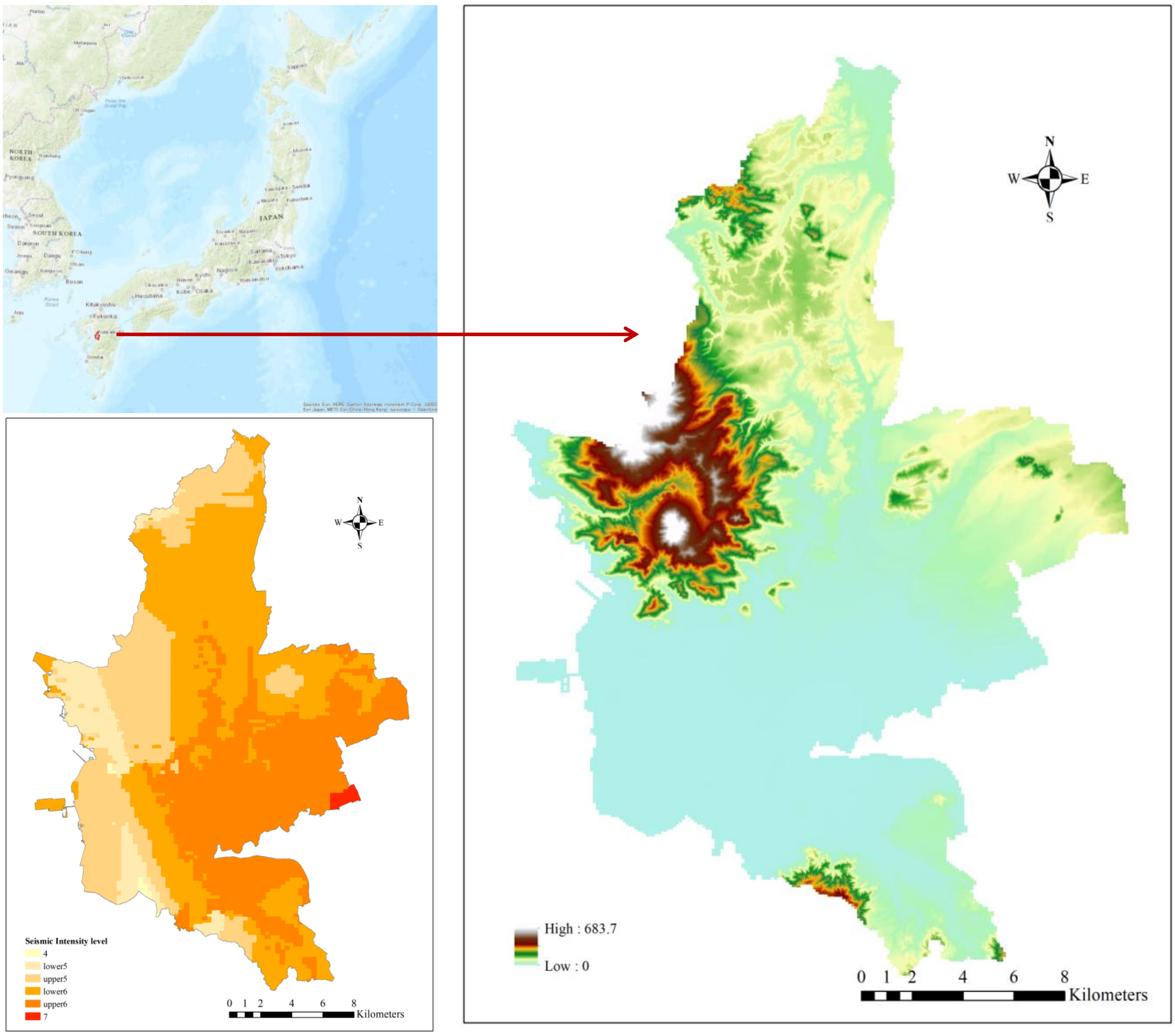

Figure 1. Location of Kumamoto City and its terrain, 2016 Kumamoto main quake intensity map

Kumamoto City, facing the Ariake Sea, located in the center of Kumamoto Prefecture, Japan. It is surrounded by the Kinpu Mountains in the northwest, the highland in the north, and the distant Aso Mountains in the east, with the most plains in the south. In the center of the city, the Shirakawa River originates from the Aso Volcano, and the Tsuboi and Iseri Rivers, which originate in the northern part of the city, flow through the city and into the city Ariake Sea in the west (Figure 1).

In April 2016, for the first time in recorded history, Kumamoto City was hit by two earthquakes of intensity 7 in the same area in just 28 hours, causing great damage. The earthquake that occurred at 9:26 pm on Thursday, April 14, later referred to as the "foreshock", had its epicenter at a depth of 11km in the Kumamoto Prefecture (32°44.5'N, 130°48.5'E) and measured 6.5 on the Richter scale. The earthquake that occurred at 1:25 am on Saturday, April 16, which is considered to be the "main quake", had its epicenter at a depth of 12 km in the Kumamoto Prefecture (32°45.2'N, 130°45.7'E) and measured 7.3 on the Richter scale. The main quake intensity [24] is shown in Figure 1. The earthquake caused extensive damage to roads, bridges, and other infrastructure, schools, community centers, and other public facilities that serve as evacuation centers in times of disaster, as well as to riverbanks and retaining walls on steep slopes. Furthermore, flooding, landslides, and liquefaction also occurred over a wide area following the earthquake, resulting in extensive damage.

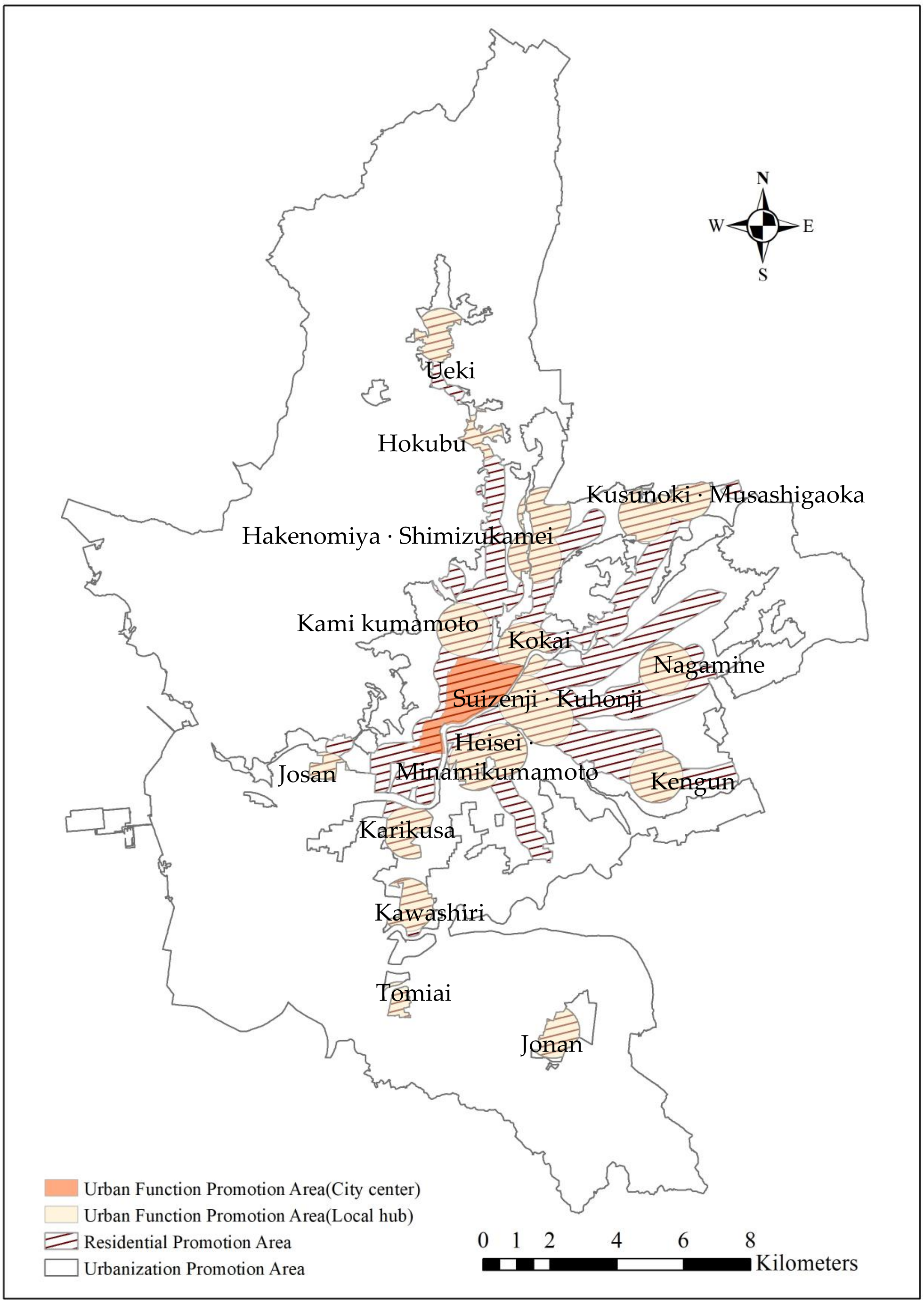

Figure 2. Kumamoto City urban planning areas

Kumamoto City proposed a compact city development strategy in its master plan formulated in 2014. Kumamoto Compact City has planned corresponding areas (Figure 2) to achieve compact city goals, such as the Residential Promotion Area. The goal is to maintain the population density at 60.8 people/ha under the anticipation of population reduction [25]; the Urbanization Function Promotion Area is to induce and improve facilities necessary for urban residents' living, such as hospitals, commerce, finance, etc. Before and after the earthquake, the urban planning concepts were different, i.e., before the earthquake, compact city planning aimed at centralization to cope with urban problems such as sprawl or depopulation. In contrast, after the earthquake, the effects of natural disasters such as earthquakes and floods were taken into account.

After the Kumamoto earthquake, many people chose to evacuate in their cars. In addition to worrying about aftershocks, the lack of shelter near their homes was also an important reason [26]. It indicates that there are certain problems in the allocation of evacuation shelters in Kumamoto City, and a study on the supply and demand of evacuation facilities and the allocation of the location is necessary.

3. Materials and Methods

3.1. Data Collection

The data used in this study are land use data, population data, and evacuation shelters data. The details are shown in Table 1. The land use data (Figure 3) was obtained from the Kumamoto City Basic Survey. It includes non-urban land, water, low-rise residential, medium high-rise residential, commercial, etc. The land use metadata type was vector, and the data was converted to 100m×100m raster data by ArcGIS's polygon to raster tool.

Table 1. Date sources

Data	Year	Sources
Land use	2018	Kumamoto City Basic Survey
Population census data	2018	Basic Resident Register population of Kumamoto City
Evacuation shelter	-	Kumamoto City homepage

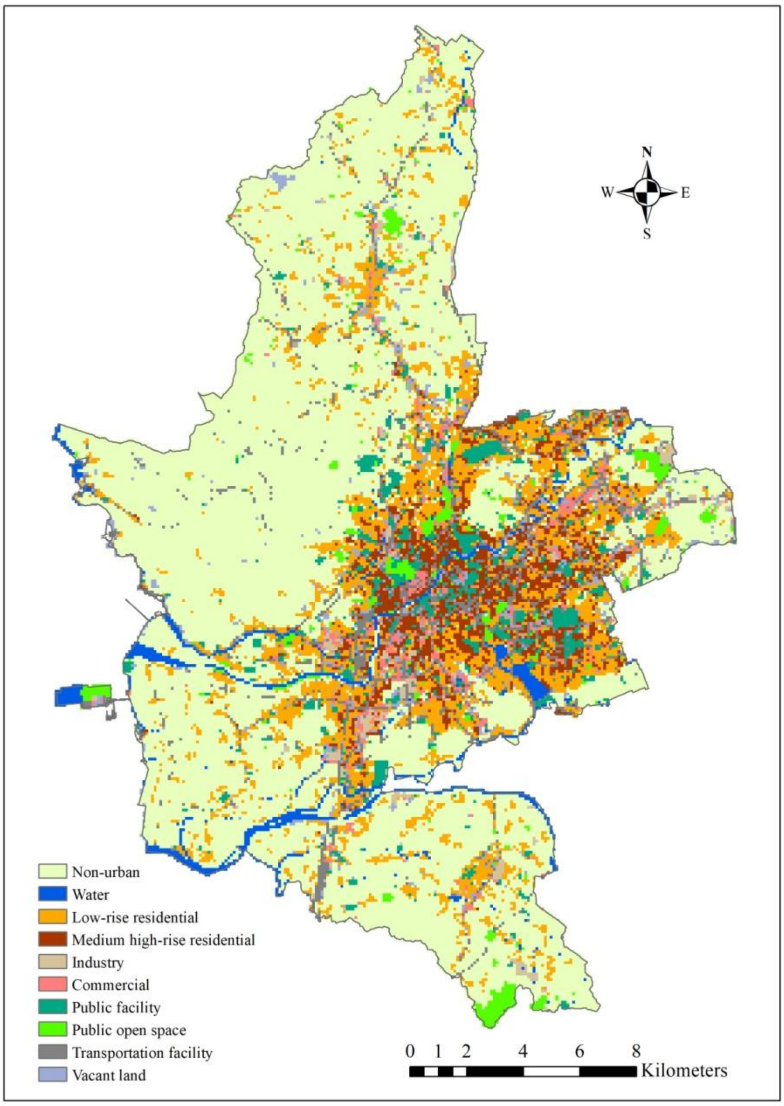

Figure 3. Land use

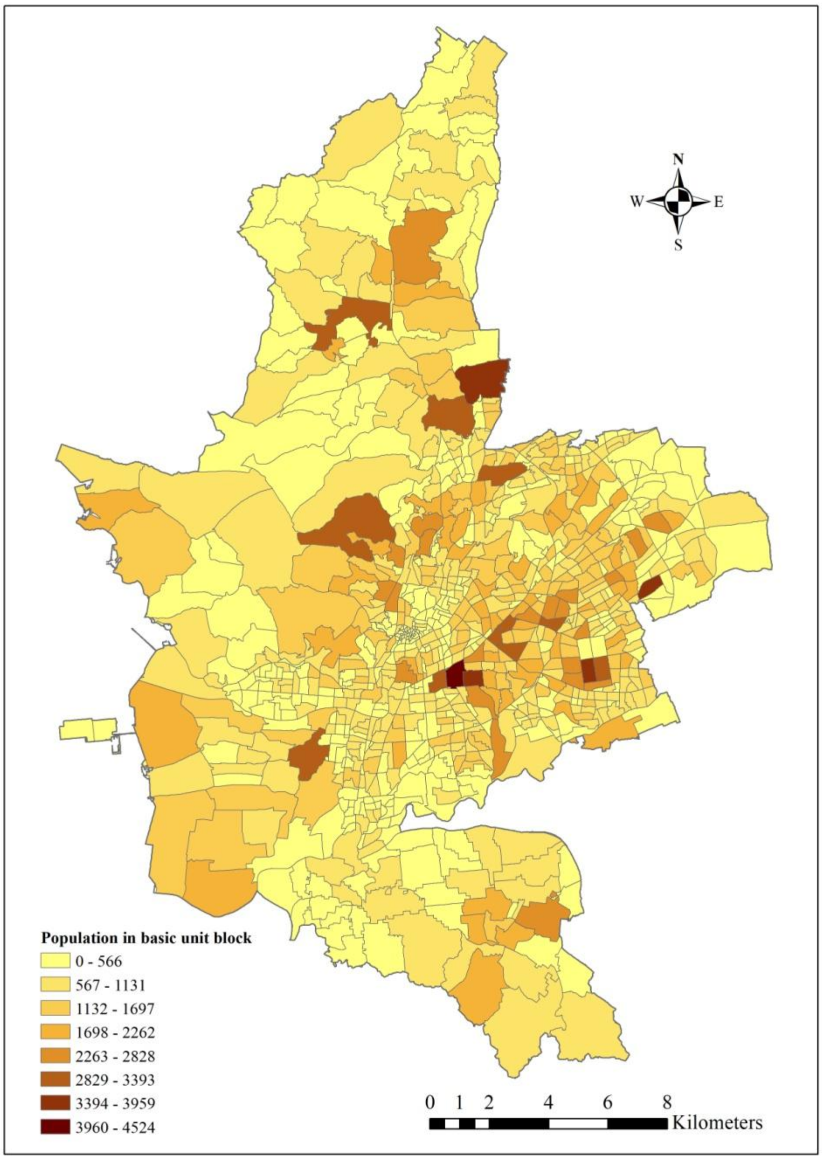

Figure 4. Population distribution in the basic unit block

Population data (Figure 4) is from the Basic Resident Register population of Kumamoto City [27], which details the number of people in each basic unit block. The evacuation shelter data come from the homepage of Kumamoto City [28], and the latitude and longitude of each shelter were extracted with the given address to be loaded into ArcGIS for subsequent calculations. Most of the evacuation facilities in Kumamoto City are school buildings, gyms, parks, etc.

3.2. Methods

It is assumed that only residential land uses, i.e. low-rise residential and medium high-rise residential, have a population distribution. As the distribution of population should be different between low-rise residential and mid-rise residential, in this study, the association between land use and the population is quantified by the population within the geographical unit (i.e. the basic unit block) and the area of the different land use types, using regression analysis [16]. The population within each land use was estimated using the following equation (1).

$$Pop_m = Pop_n \times \frac{con_k \cdot area_m}{\sum_{m \in n} con_k \cdot area_m} \tag{1}$$

Where Pop_m is the estimated number of populations in the intersected polygon grid m. The intersected polygon grid results from the intersection of the base unit block and the land use polygon grid. Pop_n is the number of populations within the basic unit block n. con_k is the parameter for the land use type k estimated in the regression equation. $area_m$ is the area of the intersecting polygon grid.

The evaluation of shelter allocation in this study used the location-allocation model in the network analysis of ArcGIS10.6. The population capacity of each evacuation shelter is limited by its effective area [4]. Therefore, the number of the population accommodated in a shelter should not exceed its capacity. The goal of the P-median model in the location-allocation model is to select a certain number of facilities from all candidate facilities, and to maximize the total distance between the demand points and their closest facilities. We use this model to evaluate each demand point's evacuation distance during evacuation and investigate whether the supply and demand balance of the evacuation shelters.

4. Results and Discussion

4.1. Population Estimation Results

Intersecting the land use and basic unit block of Kumamoto City, with population within the basic unit block as the dependent variable and the area of each land use counted within the basic unit block as the independent variables, the regression results are shown in Table 2. The resulting regression coefficients were substituted into population estimation method mentioned in the previous section to obtain the number of people within each grid polygon, and the results are shown in Figure 5.

Intersecting the estimated grid population data with the intensity of the main shock of the 2016 Kumamoto earthquake, the proportion of the population within each intensity range is obtained. The results are shown in Table 3. Among them, the proportion of the population in seismic intensity 4 and 7 is the smallest. The upper 6 has the largest proportion, accounting for 65.17%, followed by the lower 6, accounting for 29.99%.

Table 2. Regression analysis results

Land use(m^2)	con	t-value
Low-rise residential	0.0048	29.7915
Medium high-rise residential	0.0147	39.8853
R^2	0.73	

Table 3. Population proportion in each seismic intensity

Seismic intensity	Population (%)
4	0.01
Lower5	0.69
Upper5	4.13
Lower6	29.99
Upper6	65.17
7	0.01

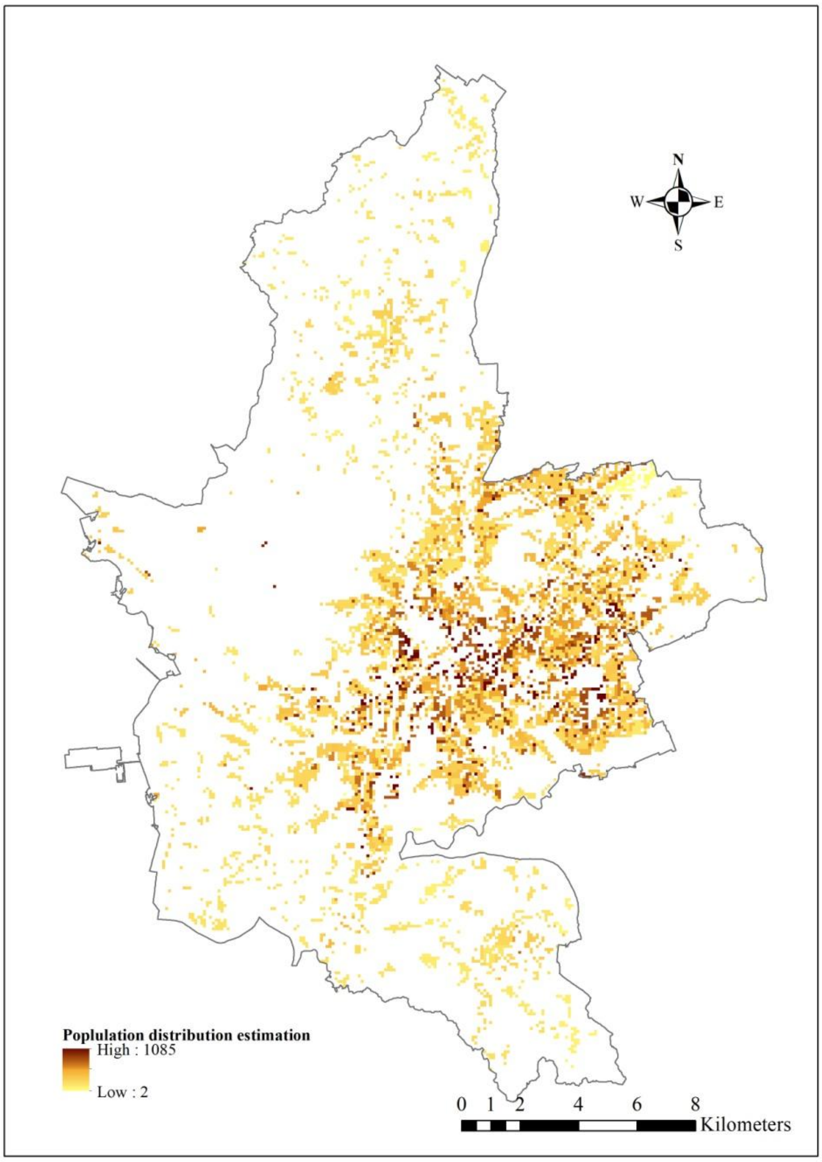

Figure 5. Population estimation result

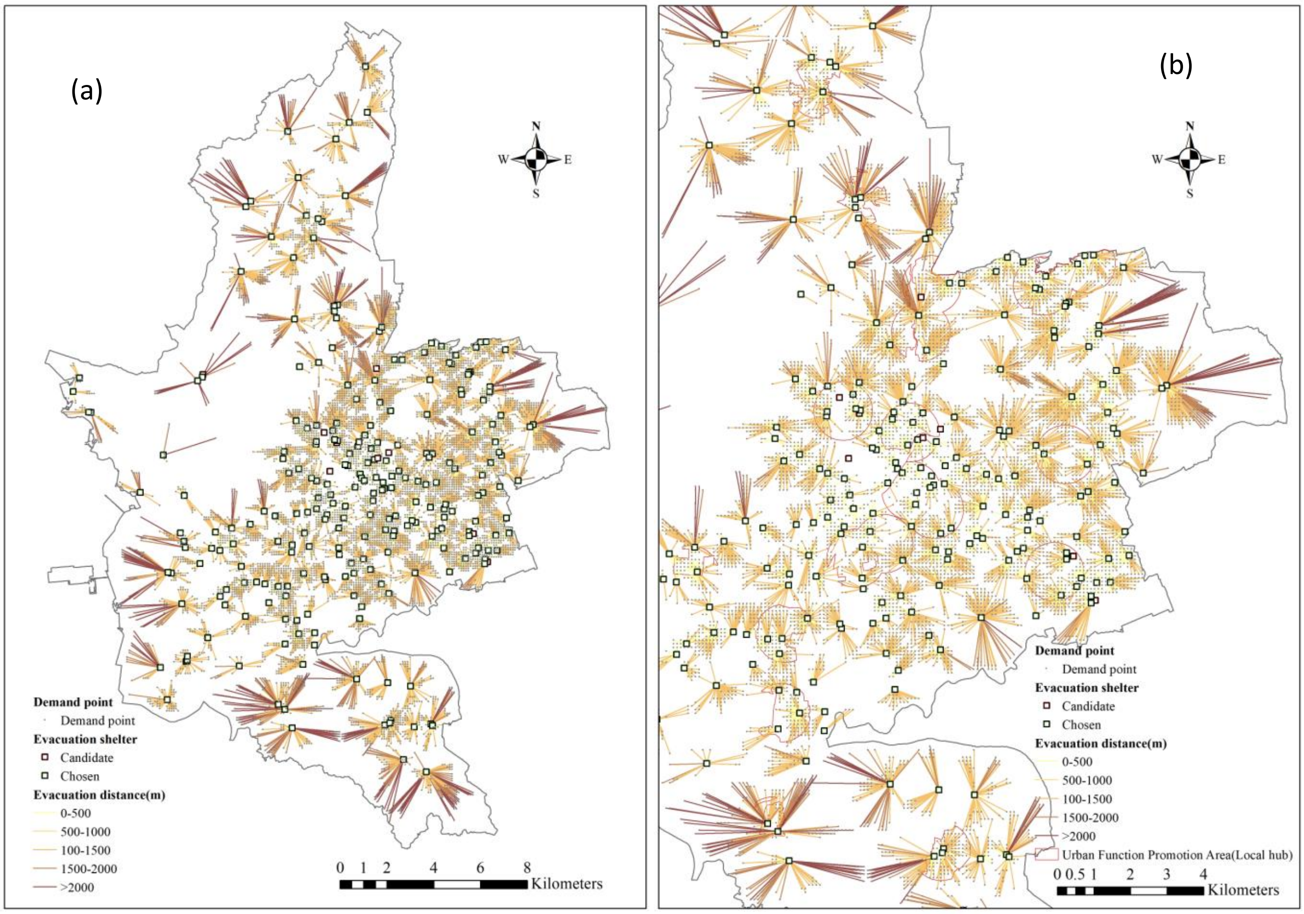

Figure 6. P median model results: (a) Map of the location of evacuation shelters and allocation of demand points, (b) Enlarged view of the allocation of the Urbanization Function Promotion Area shelters

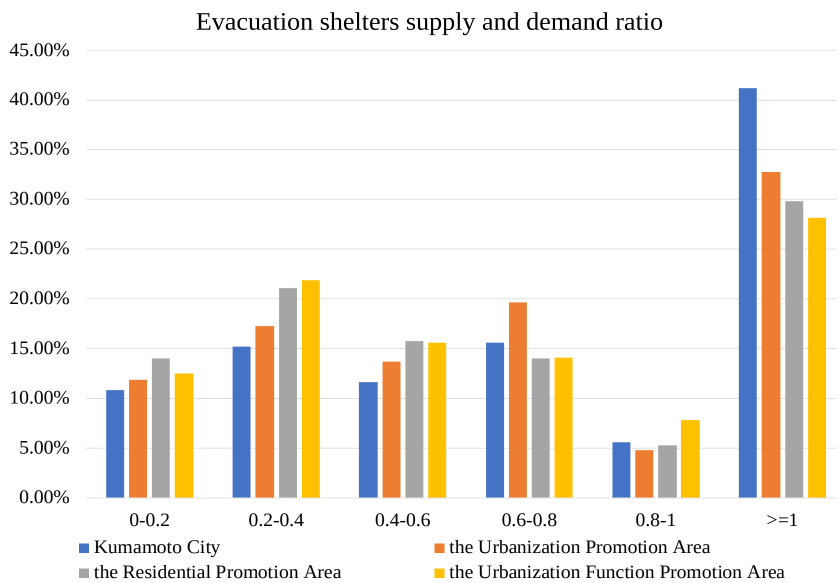

Figure 7. Evacuation shelters supply and demand ratio in each urban planning area

4.2. Evacuation Shelters Supply and Demand Analysis

According to the P-median model, we obtained the results of shelter allocation for each demand point at the time of evacuation. The results are shown in Figure 6.

Overall, we found that the total capacity of evacuation shelters in Kumamoto City can meet the evacuation needs. However, within the service area of each shelter, only 41.2% of shelters meet the shelter requirement (Figure 7), which is less than half. It indicates that there are problems with the current layout of shelters in Kumamoto City, and there is an imbalance between the supply and demand of shelters. Figure 7 shows that the ratio of shelters where the supply is less than the demand has increased further in the Urbanization Promotion Area, and the proportion of shelters that meet demand is only 32.74%. The Residential Promotion Area is where Kumamoto City induces population and has a high density of medium high-rise residential, so the population density is relatively high. The ratio of shelters with insufficient supply is higher than that of the Urbanization Promotion Area, especially the ratio of shelters with a supply to demand ratio of 0-0.6 is more than half, reaching 50.88%. As an urban area with relatively complete facilities, the Urbanization Function Promotion Area has the lowest proportion of shelters where supply exceeds demand, which is only 28.13%. In response to the development requirements of a compact city for disaster prevention after the Kumamoto earthquake, in addition to continuing to improve basic living facilities such as medical care, commerce, and finance, it is also necessary to strengthen the guidance and construction of disaster relief facilities such as shelters. Spatially, the supply and demand of evacuation facilities in Kumamoto City show a decreasing ratio of evacuation facilities to meet the demand, from the whole city to the Urbanization Function Promotion Area. It is related to the construction of Kumamoto compact city, with higher population density in areas close to the city center.

Specifically, we calculated the total capacity of shelters in each local hub (Table 4). We found that only three shelters had a supply-demand ratio greater than 1: Kokai (1.47), Hokubu (1.26), and Jonan (1.24), which are located in the central, northern, and southern parts of Kumamoto City, respectively. Among them, the supply of shelters in Nagamine is severely less than the demand, with a supply-demand ratio of only 0.26. The distribution of evacuation centers in Kumamoto is unbalanced among local hubs.

About half of the people can reach the shelter within a distance of 0-1000 meters. Whether from the whole city perspective, the Urbanization Promotion Area, or the Residential Promotion Area and the Urbanization Function Promotion Area, the proportion of demand points that can reach evacuation shelter within 500-1000 meters is highest. The Residential Promotion Area has the highest percentage of 500-1000 meters, reachable at 39.10%. The reachable demand points in the distance range of 1500-2000 meters also account for a large proportion. Within the Urbanization Promotion Area, 17.42% of residents can find refuge within 500 meters. However, in the Urbanization Function Promotion Area, this ratio is the lowest, at 15.87%. The proportion of demand points reachable from 1500-2000 meters is not much different within each region. Over 2000 meters, there is a spatially decreasing distance from the whole city to the Urbanization Promotion Area, the Residential Promotion Area, and the Urbanization Function Promotion Area. There is not much difference between the whole city, and the proportion of accessible points in the Residential Promotion Area and the Urbanization Function Promotion Area is also similar.

Table 4. Evacuation shelters supply and demand ratio in each local hub

No	Local hub	capacity	demand	Supply and demand ratio
1	Ueki	4241	7437	0.57
2	Hokubu	7441	5924	1.26
3	Kusunoki Musashigaoka	15021	17748	0.85
4	Hakenomiya Shimizukamei	18241	20523	0.89
5	Kami kumamoto	9413	11871	0.79
6	Kokai	16275	11034	1.47
7	Nagamine	3782	14440	0.26
8	Suizenji Kuhonji	17737	35570	0.50
9	Heisei Minamikumamoto	13826	24101	0.57
10	Kengun	14407	21250	0.68
11	Josan	4861	6794	0.72
12	Karikusa	10398	18459	0.56
13	Kawashiri	7858	11685	0.67
14	Tomiai	2723	6493	0.42
15	Jonan	4155	3362	1.24

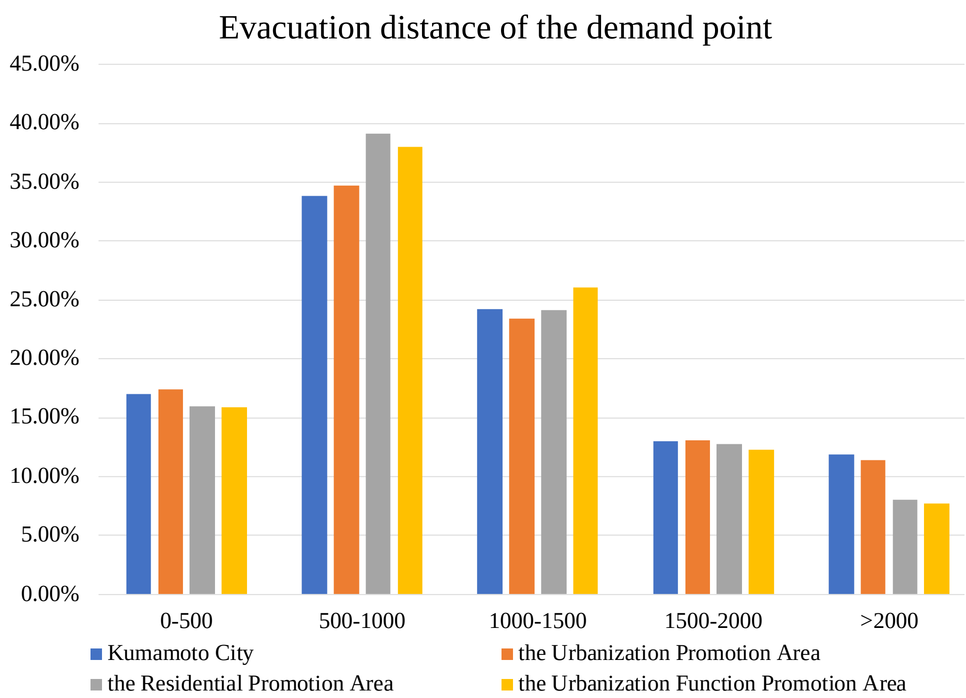

Figure 8. Evacuation distance of each urban planning area

Therefore, in the post-disaster construction of the compact city of Kumamoto, the optimal allocation of shelter facilities should be given attention, and areas with insufficient facilities should be induced and planned.

5. Conclusions

This study uses the linear relationship between land use and population distribution to spatialize the distribution of population in residential land within the statistical area of Kumamoto City. The obtained grid population data can effectively provide support for shelter analysis.

In the shelter analysis, the P-median model is used to divide the service area and obtain the number of evacuees within the service area, so that the relationship between shelter capacity and demand can be well analyzed. It is found that less than half of the evacuation shelters in Kumamoto City can meet the evacuation demand. Within each urban planning area, with the distance from the city center, the proportion of meeting refuge demand is lower. Among them, the lowest ratio is in the Urbanization Function Promotion Area, and there is also a great difference between the various local hubs within the Urbanization Function Promotion Area. In terms of the distance for evacuation, it is also found that the proportion of the Urbanization Function Promotion Area is lowest in the range of 0-500 m. This indicates that it is necessary to strengthen the planning and construction of evacuation facilities in the Urbanization Function Promotion Area in the process of building a compact city for disaster prevention.

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