Assessment of Earthquake Evacuation Shelter Capacity in Seoul: A GIS-Based Analysis of Transient Population Accommodation in Critical Infrastructure

Hyun Soo Park 01, Seol A Kwon 02

01 National Crisisonomy Institute (NCI), Chungbuk National University, 1 Chungdae-ro, Seowon-Gu, Cheongju, Chungbuk, Korea, chaos51@hanmail.net

02 National Crisisonomy Institute (NCI), Chungbuk National University, 1 Chungdae-ro, Seowon-Gu, Cheongju, Chungbuk, Korea, seolakwon@chungbuk.ac.kr

Abstract

This study evaluates the capacity of earthquake evacuation shelters in Seoul, South Korea, a city considered part of the national critical infrastructure. Using GIS-based spatial analysis, we account for transient population fluctuations across different times of the day, weekdays versus weekends, and seasons. The analysis, conducted on a output area, highlights significant inadequacies in current shelter infrastructure, with many areas consistently unable to accommodate populations effectively. Our findings indicate that shelters with larger capacities can accommodate a greater number of people from nearby areas, while shelters with smaller capacities result in many areas being only partially accommodated or not accommodated at all. This consistency in shelter capacity, regardless of time and population movements, suggests the need for a comprehensive approach to disaster preparedness. Key recommendations include the strategic expansion and optimal placement of shelters, the integration of advanced technologies for real-time population tracking, enhancement of public awareness and preparedness through regular drills, the development of comprehensive urban planning policies, and fostering collaboration among various stakeholders. By addressing these gaps, Seoul can enhance its resilience and ensure the safety of its residents during major seismic events. This study underscores the critical need for innovative strategies and policies to improve disaster preparedness in urban environments.

Key words: Earthquake evacuation, Shelter capacity, Critical infrastructure, GIS-based analysis, Urban resilience

I. Introduction

Global trends have underscored the increasing concern regarding natural disasters, particularly in the context of earthquake preparedness and response strategies, which have emerged as critical social issues. Seoul, being a densely populated urban center, faces significant risks of extensive casualties and property damage in the event of a major earthquake. Consequently, accurately assessing the capacity of earthquake evacuation shelters and formulating effective response measures in Seoul is of paramount importance (Kazeminia, 2020; Choo & Yoon, 2022; Hong & Feng, 2024).

The global recognition of earthquake hazards extends to South Korea, which was traditionally perceived as a seismically safe region. However, recent seismic events, notably the Gyeongju earthquake in 2016 and the Pohang earthquake in 2017, have fundamentally altered this perception (Han, et al., 2021). The Gyeongju earthquake, with a magnitude of 5.8, stands as the strongest recorded seismic event in Korea, prompting heightened awareness and urgency in earthquake preparedness. These incidents highlight the imperative for readiness, especially in densely populated areas such as Seoul (Lee, et al., 2022).

Earthquake preparedness is crucial for mitigating large-scale human and property losses during seismic events. The efficient operation and management of evacuation shelters, coupled with precise capacity assessments, are vital for enhancing disaster response capabilities. This is particularly pertinent for metropolitan areas like Seoul, where leveraging advanced technologies such as Geographic Information Systems (GIS) is essential for the continuous evaluation and improvement of shelter capacity and spatial distribution (Kazeminia, 2020).

GIS (Geographic Information System) is a powerful tool for visualizing and analyzing spatial data, integrating various geographic information to address complex problems effectively (Jiao & Feng, 2024; Kazeminia, 2020; Lee, et. al, 2020). This study aims to utilize GIS to analyze the population capacity of earthquake evacuation shelters in Seoul. Specifically, it will assess the shelters' capacity considering the fluctuating population based on seasonal and temporal variations (Kim, et. Al.,, 2022).

Seoul experiences significant fluctuations in its transient population depending on the time of day and season. Therefore, an in-depth analysis that accounts for these variables is essential (Xu, et. Al., 2016; Hong & Feng, 2024). For instance, population densities can vary drastically during commuting hours, weekends, and holidays. Thus, this research will evaluate the capacity of earthquake shelters in Seoul using transient population data across different seasons and times of the day, aiming to develop effective evacuation plans (Kim, et. Al.,, 2022; Kazeminia, 2020).

The objectives of this study are threefold. First, to analyze the distribution and capacity of earthquake shelters in Seoul using GIS (Hong & Feng, 2024). Second, to evaluate the shelters' capacity considering seasonal and temporal population fluctuations (Lee, et. al, 2020; Kim, et. Al.,, 2022). Third, to provide practical recommendations for enhancing Seoul's earthquake preparedness policies and evacuation planning based on these findings (Xu, et. Al., 2016; Kazeminia, 2020).

Such research provides crucial foundational data for creating safer urban environments capable of withstanding major natural disasters. Moreover, by demonstrating the applicability of GIS and transient population data in disaster response research, this study aims to offer a universal research model that can be applied to other urban contexts (Hong & Feng, 2024; Kim, et. Al.,, 2022; Xu, et. Al., 2016).

II.. Material and Methods

2.1 Study Area and Data

This study aims to examine the capacity of earthquake shelters over time, taking into account the floating population. For this purpose, data from the 'Seoul Living Population' provided by the Seoul Open Data Plaza (https://data.seoul.go.kr/) were utilized. This dataset aggregates population data for output areas, which are smaller than administrative units such as towns and neighborhoods, considering factors like population size (approximately 500 people), socioeconomic homogeneity (housing types, land prices), and the spatial shape of the output area.

The population in each output area was estimated using information from mobile communication base stations. Seoul has a total of 19,153 output areas, and the dataset provides hourly population data for each area, enabling an analysis of population changes over time.

For data on earthquake shelters in Seoul, information from the 'Earthquake Shelter Status' provided by the Public Data Portal (https://www.data.go.kr/) was used. This dataset includes various details such as shelter facility names, facility areas, and coordinates. Using this information, the capacity range of shelters in nearby regions was determined. The capacity of earthquake shelters was calculated based on the facility area, with the standard of 1.43㎡ per person.

2.2 Research Methodology

This study aims to investigate the spatial capacity of earthquake shelters and identify areas that cannot be accommodated by considering the floating population at different times of the day. This approach is expected to facilitate the effective allocation of earthquake shelters.

To achieve this research objective, the distance from the centroid of each output area to the nearest earthquake shelter was calculated. The analysis used road travel distances rather than straight-line distances due to obstacles such as buildings that may impede direct travel in real-world scenarios. Additionally, the three closest shelters were identified for each output area to account for situations where the nearest shelter exceeds its capacity, allowing residents to seek alternative nearby shelters.

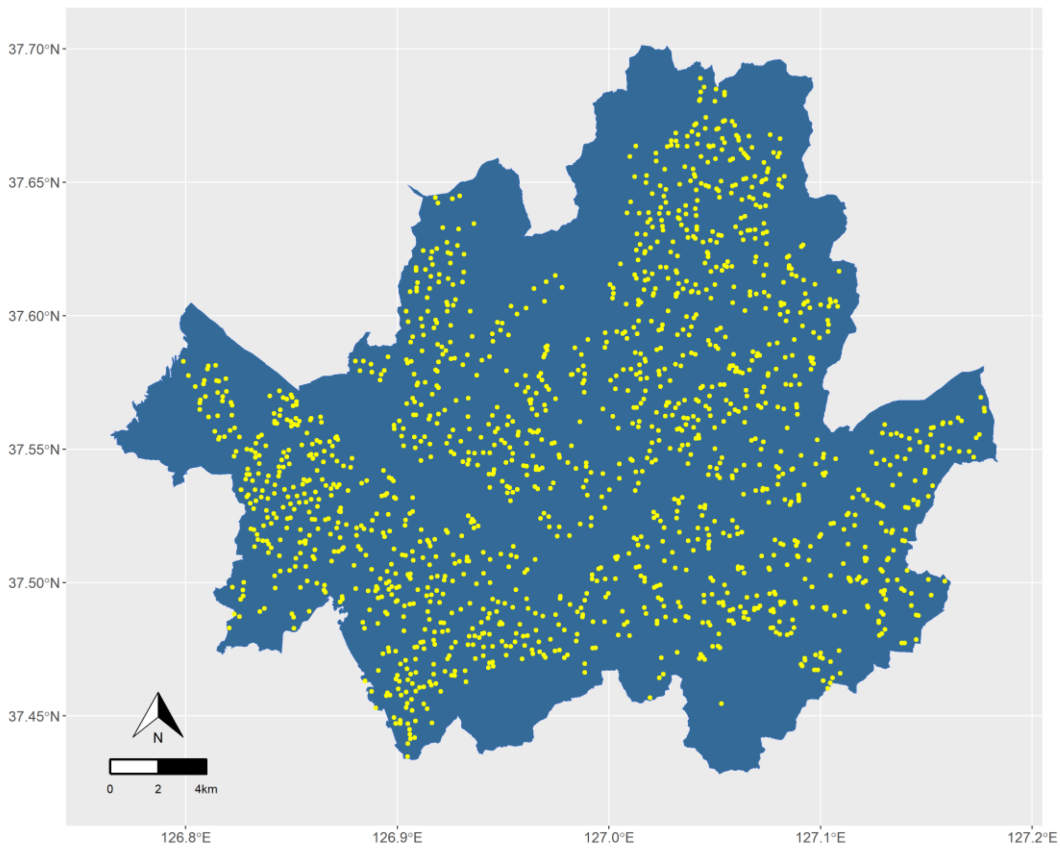
The capacity range of each shelter was determined by calculating the number of people that could be accommodated starting from the closest output areas, based on road travel distance. Each output area was categorized as "fully accommodated" if all its population could be sheltered, "partially accommodated" if only a portion could be sheltered, or "not accommodated" if none could be sheltered. If a shelter had excess capacity after accommodating the population of its nearest output areas, it would accommodate people from the second and third closest output areas that were classified as "partially accommodated" or "not accommodated."

Data on the floating population were provided on an hourly basis, making it impractical to calculate shelter capacity for every hour of every day. Therefore, two days per month (one weekday and one weekend day) were selected, specifically the second Thursday and Saturday of each month, to compare weekday and weekend scenarios. The time was divided into "daytime" (8:00 AM to 6:00 PM), "evening" (7:00 PM to 10:00 PM), and "night" (11:00 PM to 7:00 AM the following day). Seasonal distinctions were made as follows: "spring" (March to May), "summer" (June to August), "autumn" (September to November), and "winter" (January, February, December).

III. Results

3.1 Status of Earthquake Shelters in Seoul

There are a total of 1,564 earthquake shelters in Seoul, and their spatial distribution is shown in Figure 1. Excluding the Han River and the mountains located on the outskirts of Seoul, the shelters are generally evenly distributed.



<Figure.1> Spatial Distribution of Earthquake Shelter

The types of facilities designated as earthquake shelters in Seoul are shown in Table 1. Schools make up the majority with 1,020 shelters (65.2%), followed by parks with 493 shelters (31.5%). Together, schools and parks account for over 95% of the earthquake shelters in the city.

<Table.1> Facility type of earthquake shelter

Type	Frequancy	%
School	1,020	65.2
Park	493	31.5
Shelter	12	.8
Parking Lot	10	.6
sports facility	9	.6
public square	6	.4
Others	14	.9
Total	1,564	100.0

The facility areas of earthquake shelters in Seoul are shown in Table 2. The most common earthquake shelters have an area of 1,000-3,000㎡, with 538 shelters (34.4%). Following this, shelters with an area of 3,000-5,000㎡ number 395 (25.3%), and those with an area of 5,000-10,000㎡ number 248 (15.9%). There are 36 shelters (2.3%) with a smaller area of 500㎡, while relatively larger shelters with an area exceeding 10,000㎡ number 167 (10.7%).

<Table.2> Facility area of earthquake shelter

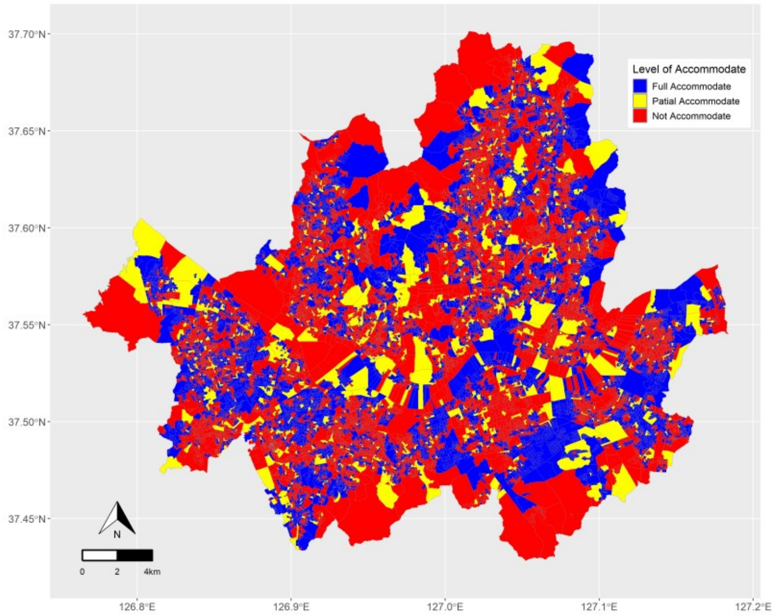
Area	Frequancy	%
Under 500㎡	36	2.3
500~1,000㎡	180	11.5
1,000~3,000㎡	538	34.4
3,000~5,000㎡	395	25.3
5,000~10,000㎡	248	15.9
Over 10,000㎡	167	10.7
Total	1,564	100.0

3.2 Shelter Capacity by Time

The analysis of earthquake shelter capacity during the daytime on weekdays in spring is shown in Figure 2. Among the output areas in Seoul, only 8,262 areas (43.7%) were fully accommodated by the earthquake shelters, while 9,849 areas (51.4%) were not fully accommodated. The global spatial autocorrelation of these areas, indicated by Moran's I value, was 0.41 ($p < .001$), demonstrating a significant spatial clustering.

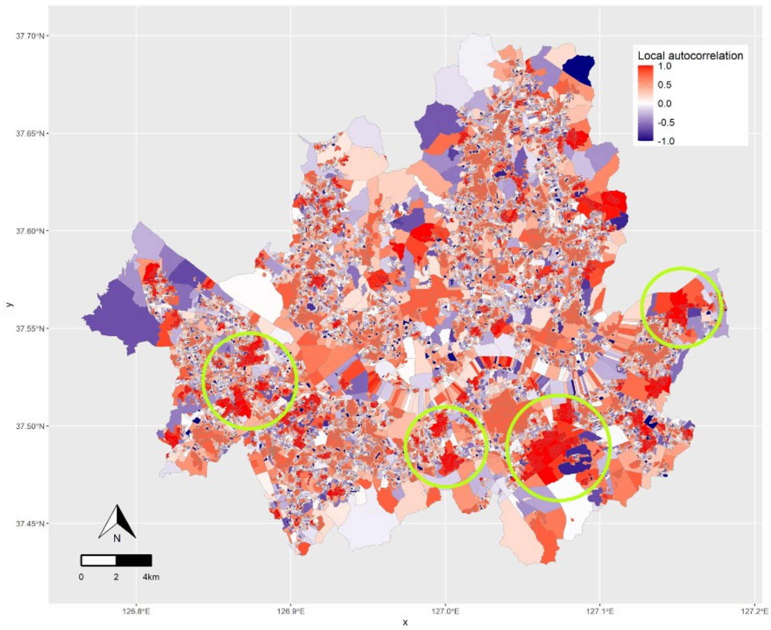
<Table.3 > Degree of accommodation(spring, weekday, daytime)

Degree of accommodation	Frequancy	%
Full accommodation	8,362	43.7
Partial accommodation	942	4.9
Not Accommodation	9,849	51.4
Total	19,153	100.0



<Figure.2 > Capacity of earthquake shelters by spring, weekday, daytime

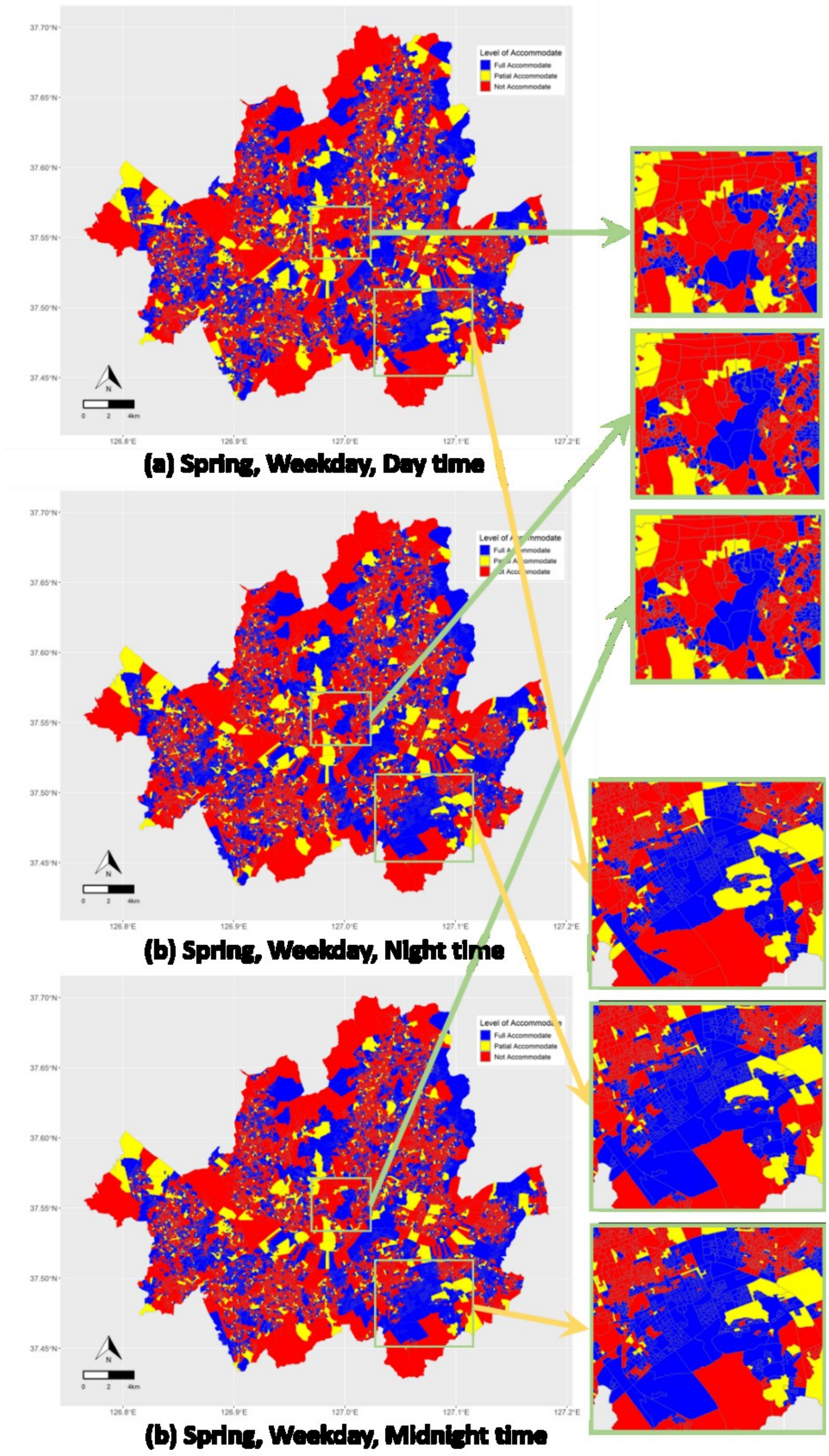
To examine the local spatial autocorrelation of areas where the population can be fully accommodated by earthquake shelters, Figure 3 was analyzed. The regions indicated by circles in the figure show a relatively higher number of areas fully accommodated by earthquake shelters compared to other regions.



<Figure. 3> Local autocorrelation of Capacity of earthquake shelters(spring, weekday, daytime)

Next, examining the shelter capacity across different times of the day, as shown in Figure 5, reveals the following.

When comparing the daytime, evening, and nighttime on weekdays in spring, there are no significant differences in most regions, except for a few areas highlighted in the figure.



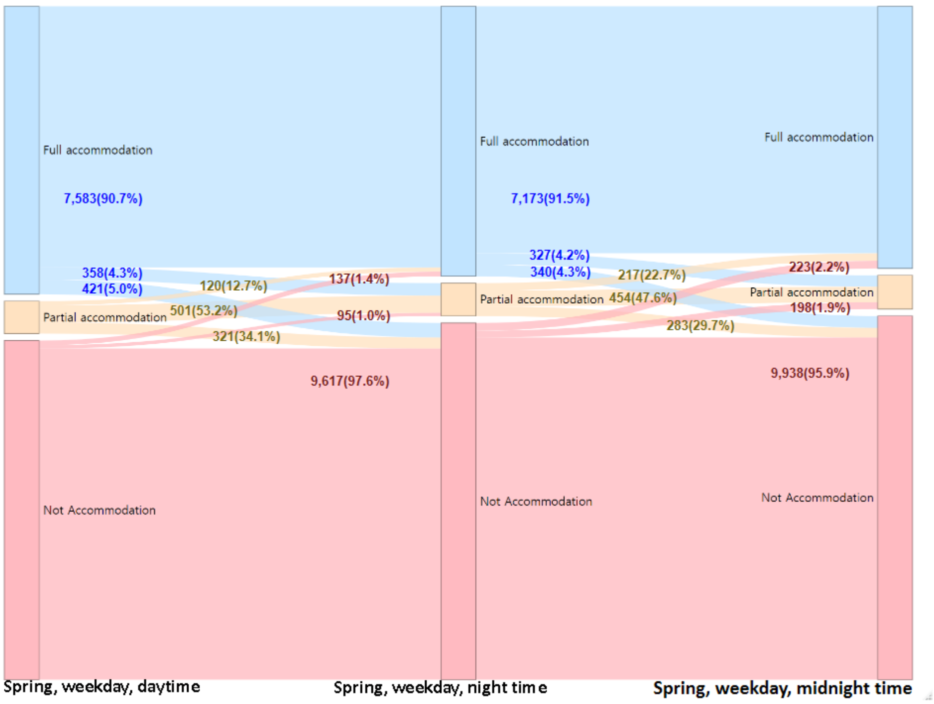
<Figure. 4> Capacity of earthquake shelters by time during spring weekdays

The capacity analysis of earthquake shelters for each time period is shown in Figure 4. During the daytime on weekdays in spring, 8,262 output areas (43.7%) were fully accommodated, 7,840 areas (40.9%) in the evening, and 7,613 areas (39.7%) at nighttime, showing a slight decrease but not a significant difference.

Among the output areas fully accommodated during the daytime, 7,583 areas (90.7%) remained fully accommodated in the evening. Of the areas partially accommodated during the daytime, 501 areas (53.2%) were still partially accommodated in the evening, 321 areas (34.1%) were not accommodated, and 120 areas (12.7%) became fully accommodated. Of the output areas not accommodated during the daytime, 9,617 areas (97.6%) were also not accommodated in the evening, with only a small number becoming fully accommodated (137 areas) or partially accommodated (95 areas).

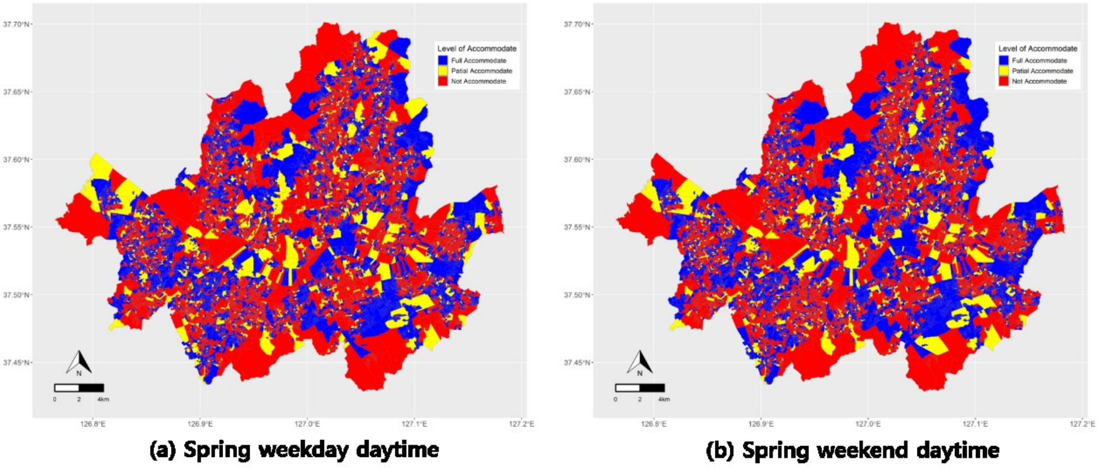
Comparing evening to nighttime, 7,173 output areas (91.5%) that were fully accommodated in the evening remained so at nighttime. A portion of the areas were partially accommodated (327 areas) or not accommodated (340 areas). Of the areas partially accommodated in the evening, 454 areas (47.6%) remained partially accommodated at nighttime. The number of fully accommodated areas (217 areas) or not accommodated areas (283 areas) was relatively small. Of the areas not accommodated in the evening, 9,938 areas (95.9%) continued to be not accommodated at nighttime, with only a few becoming fully accommodated (223 areas) or partially accommodated (198 areas).

The analysis results across different time periods showed no significant differences compared to the daytime. In other words, output areas that were fully accommodated tended to remain fully accommodated regardless of the time of day, while those that were not accommodated continued to be not accommodated.

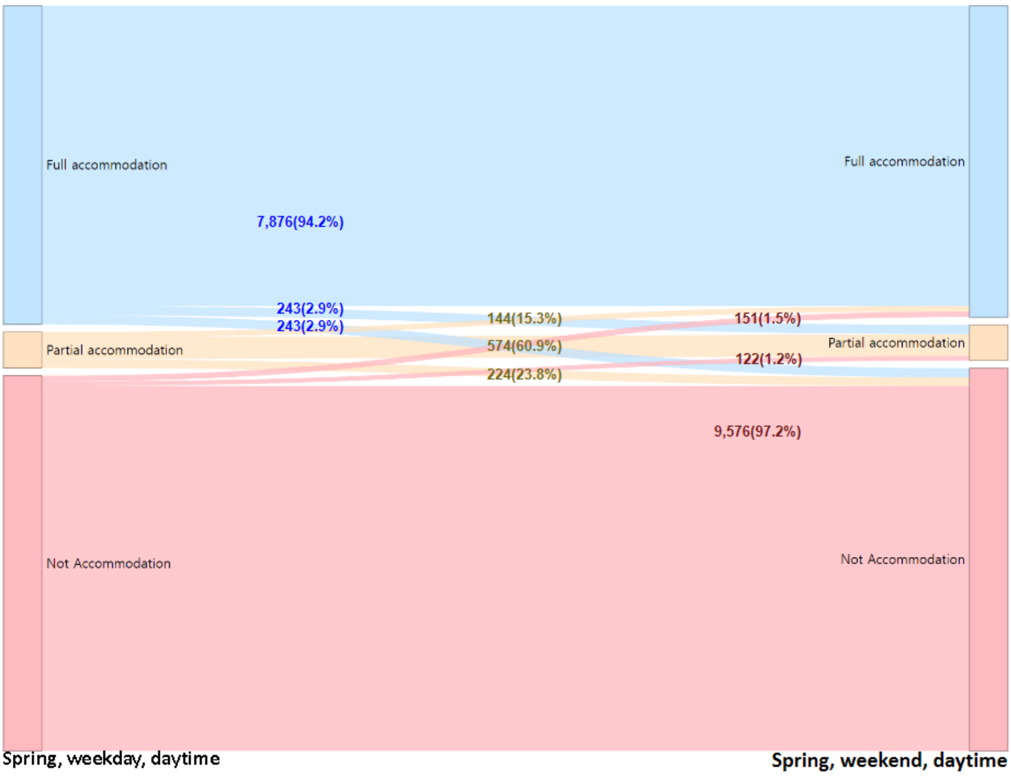


<Figure. 5> Degree of accommodation(spring, weekday)

To compare the capacity range of earthquake shelters between weekdays and weekends during the spring season, Figure 6 was analyzed. When comparing the daytime on weekdays with the daytime on weekends in spring, no significant differences were observed.



<Figure. 6> Comparison of spring weekday and weekend daytime

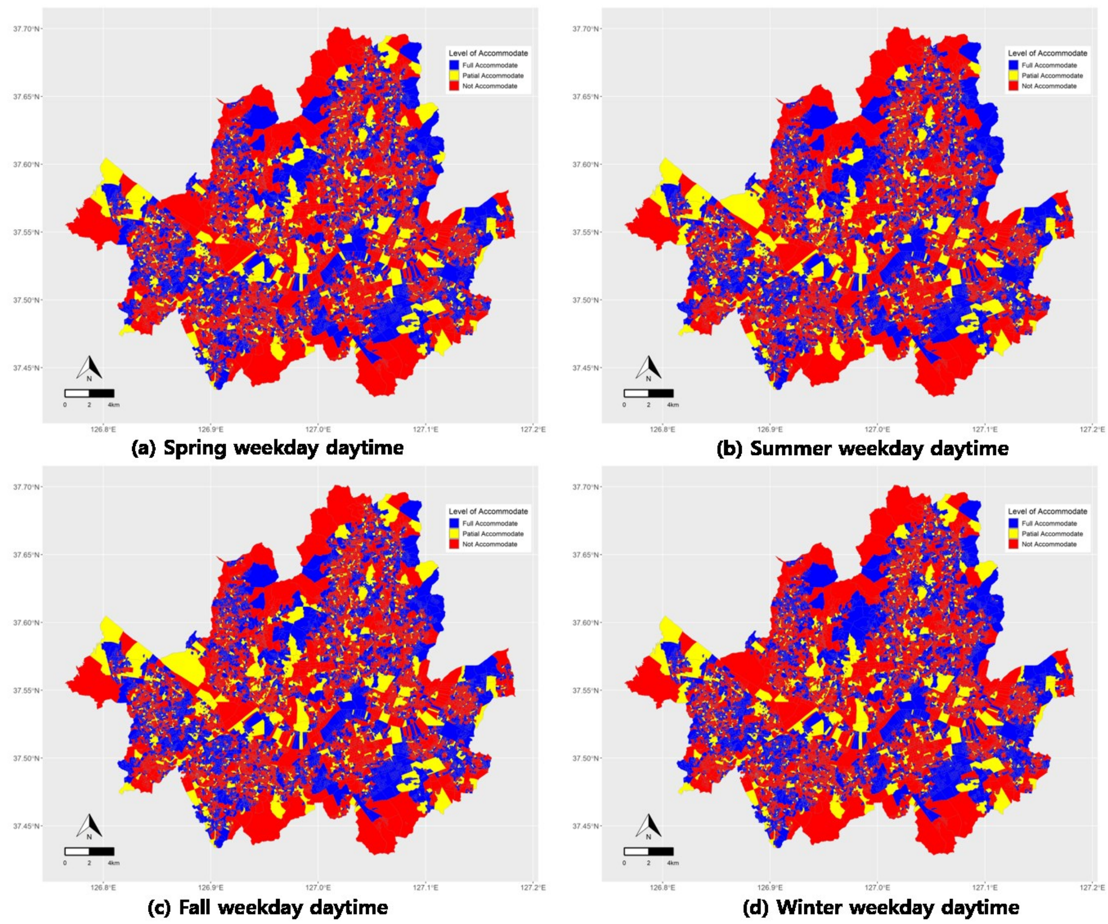


<Figure. 7> Degree of accommodation(spring, weekday/weekend, daytime)

The analysis of earthquake shelter capacity between weekdays and weekends in spring is shown in Figure 7. During the daytime on weekdays in spring, 8,262 output areas were fully accommodated by earthquake shelters. Of these, 7,876 areas (94.2%) remained fully accommodated during the daytime on weekends. The differences between weekday and weekend for areas that were partially accommodated or not accommodated were not significant, with 243 areas in each category showing little change.

For the output areas that were partially accommodated on weekdays, 574 areas (60.9%) remained partially accommodated on weekends, while some areas became fully accommodated (144 areas) or not accommodated (224 areas) on weekends. Among the areas not accommodated on weekdays, 9,576 areas (97.2%) continued to be not accommodated on weekends, with a small number becoming fully accommodated (151 areas) or partially accommodated (122 areas).

These results indicate that the capacity of earthquake shelters during the daytime on weekdays and weekends in spring shows minimal variation.



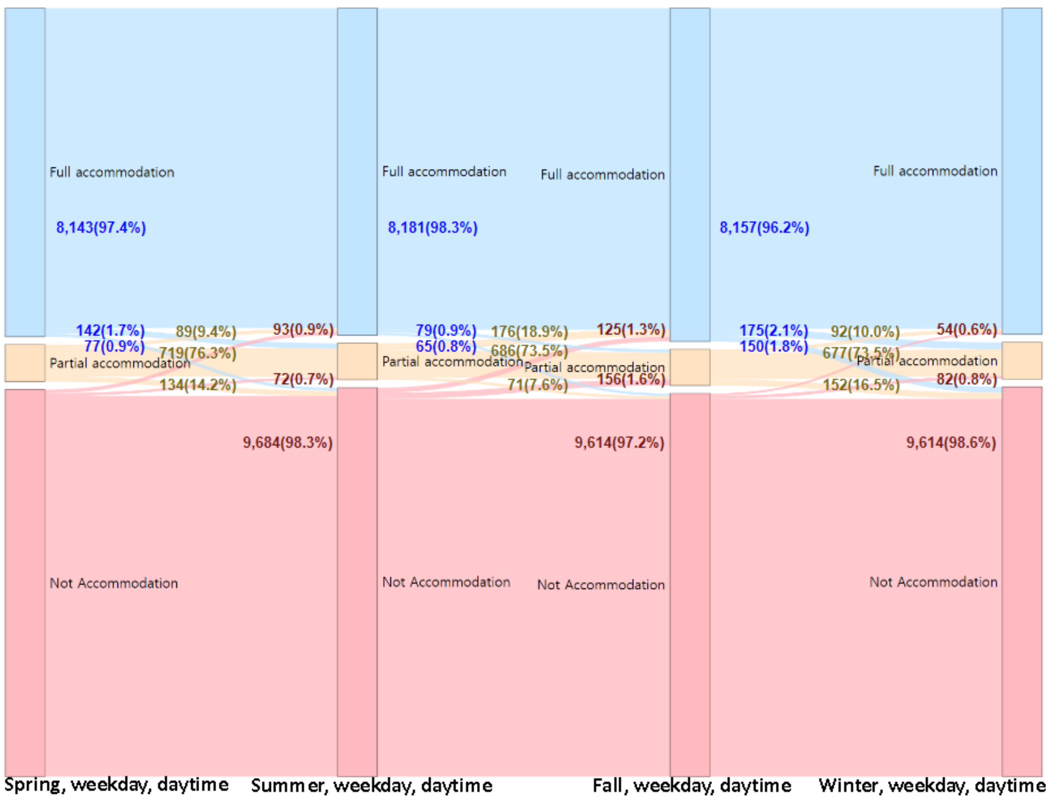
<Figure. 8> Seasonal Comparison of weekday daytime

The capacity range of earthquake shelters was then compared across different seasons. For this purpose, the weekday daytime shelter capacity was analysed for each season, as shown in Figure 8. While there were minor differences in the capacity range of earthquake shelters across seasons, the overall results indicated that there were no significant differences.

To gain a more detailed understanding of the seasonal capacity range of earthquake shelters, the results of the seasonal comparison are shown in Figure 9. Among the output areas that were fully accommodated during the daytime on weekdays in spring, 8,143 areas (97.4%) remained fully accommodated during the daytime on weekdays in summer. Therefore, the majority of these areas were still fully accommodated in summer. A small number of these areas became partially accommodated (142 areas) or not accommodated (77 areas).

For the output areas partially accommodated during the daytime on weekdays in spring, 719 areas (76.3%) remained partially accommodated in summer, indicating a general continuation. Some areas became fully accommodated (89 areas) or not accommodated (134 areas), but these numbers were not significant.

Among the output areas not accommodated during the daytime on weekdays in spring, 9,684 areas (98.3%) continued to be not accommodated during the daytime on weekdays in summer, indicating minimal change. A few areas became fully accommodated (93 areas) or partially accommodated (72 areas), but these numbers were relatively small. This trend was consistent when comparing other seasons as well.



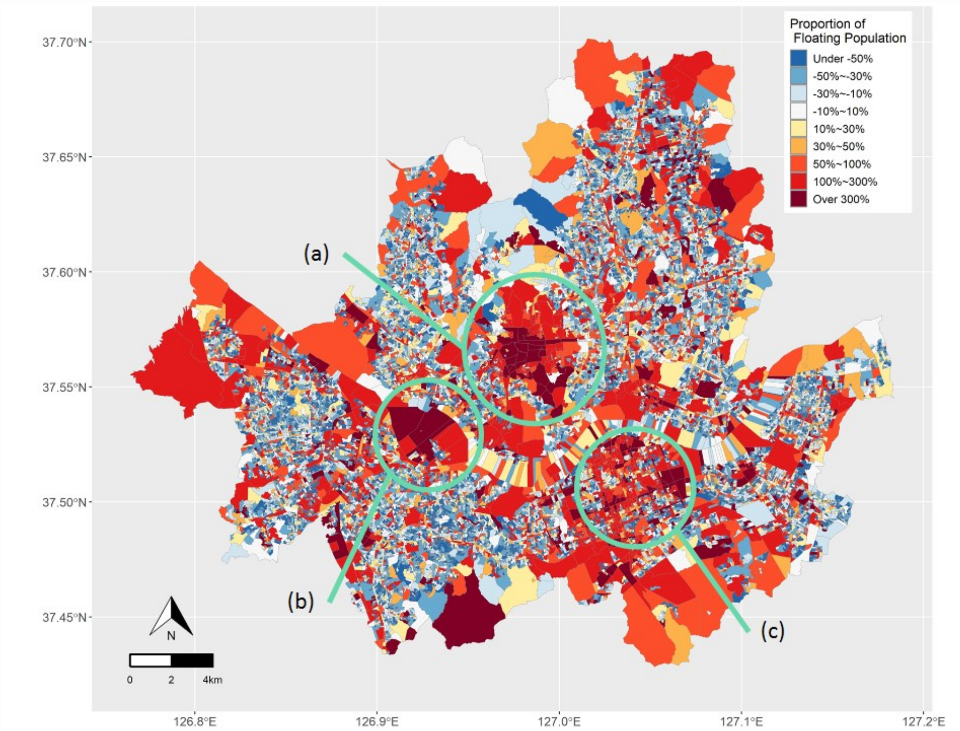
<Figure. 9> Degree of accommodation(seasonal, weekday, daytime)

Thus far, the capacity range of earthquake shelters has been compared based on different times of the day, weekdays versus weekends, and seasons. The overall number of output areas that were fully accommodated by earthquake shelters remained largely consistent regardless of time, weekday/weekend status, or season. This was also true for areas that were not accommodated. Nevertheless, it is important to note that population distrib ution varies continuously across different regions. Therefore, it is necessary to examine why the capacity range of earthquake shelters shows little variation.

One potential explanation for the absence of pronounced fluctuations in the capacity range of earthquake shelters is the methodology employed to aggregate the floating population. The floating population data were aggregated based on the output areas. As output areas are defined to include approximately 500 residents, they can encompass commercial or office buildings in close proximity to residential buildings where people do not reside. During the daytime, residents may be engaged in activities outside of their immediate residential area, such as commuting to workplaces or educational institutions. Others may be occupying commercial or office buildings within the same output area. This results in a substantial movement within the output area, yet the total population count remains largely unchanged.

To illustrate this point, Figure 10 compares the population changes from nighttime to daytime. The three regions marked with circles in the figure illustrate areas where the population concentration is significantly higher during the daytime, with a ratio of up to three times more than during nighttime. Conversely, in numerous outer areas, the population exhibits a decline during the daytime in comparison to nighttime. This observation suggests that the assumption that the capacity range of earthquake shelters remains unchanged due to population aggregation methods may not be valid.

These findings indicate that although the total population within an output area may not change significantly, significant intra-area movements can affect the demand on earthquake shelters.

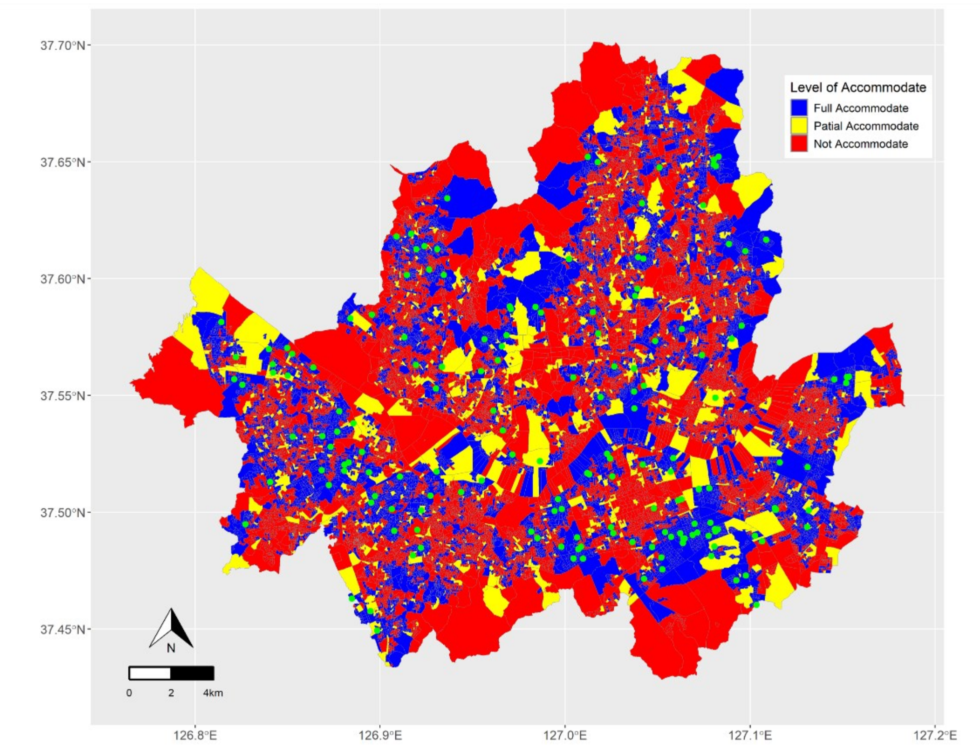


<Figure.10 > Proportion of floating population

Another hypothesis is that, as illustrated in Figure 1, the distribution of earthquake shelters is not concentrated in specific areas. However, the observed results may be due to the capacity of the shelters. The capacity of earthquake shelters varies considerably, as evidenced by the considerable differences in facility area as shown in Table 2. Shelters with a high capacity can accommodate a significant number of people from adjacent output areas, resulting in these areas being classified as fully accommodated. Conversely, shelters with lower capacity can only accommodate a limited number of output areas, which results in those areas being consistently partially accommodated or not accommodated at all, regardless of time, weekday/weekend status, or season.

To investigate this point, we conducted a study examining the capacity range of earthquake shelters during the daytime on weekdays in spring. Our analysis focused exclusively on shelters with a facility area of 10,000 ㎡ or more. The results are presented in Figure 11. As illustrated in Figure 11, the output areas that are fully accommodated by earthquake shelters are typically located in proximity to shelters with large capacities.

This observation lends support to the notion that the capacity of earthquake shelters plays a pivotal role in determining the extent to which output areas can be accommodated. Shelters with larger capacities are able to accommodate a greater number of people from nearby areas, which explains why certain output areas remain consistently fully accommodated. Conversely, shelters with smaller capacities exert a limited influence on the accommodation status of their surrounding output areas, resulting in greater variability in shelter usage. This insight emphasises the significance of incorporating considerations of shelter capacity into planning and optimising the allocation of earthquake shelters, in order to ensure effective coverage and accommodation for the population.



<Figure.11 > Accommodation of earthquake shelters and distribution of large earthquake shelters

IV. Conclusions

This study conducted a spatial analysis of earthquake evacuation shelters in Seoul, revealing critical inadequacies in the current infrastructure to effectively accommodate the transient population across various times and seasons. The results show that the capacity of earthquake shelters is largely consistent regardless of time, weekday/weekend status, or season, with certain areas consistently fully accommodated and others not accommodated.

The minimal variation in shelter capacity can be attributed to the varying capacity of shelters. shelters with larger capacities can accommodate more people from nearby areas, while those with smaller capacities can only serve limited output areas. As a result, in the case of a output area where an earthquake shelter with a very large capacity is adjacent, it can accommodate a large population. In contrast, in the case of shelters with low capacity, only a very limited number of output area are accommodated, so they may be classified as output area that are continuously accommodated only in part or not at all regardless of time.

First, there is a need to strategically expand existing facilities and establish new shelters, particularly in densely populated areas. This expansion should be guided by detailed spatial analysis to ensure optimal placement and accessibility.

Second, integrating advanced technologies such as real-time population tracking and GIS-based planning tools can significantly enhance the effectiveness of evacuation strategies. These technologies can provide dynamic insights into population movements and shelter capacities, facilitating more responsive and adaptive disaster management plans.

Third, enhancing public awareness and preparedness through regular drills and training programs is essential. Educating the public about the locations of evacuation shelters and the best routes to access them can improve response times and reduce panic during an actual earthquake.

Fourth, developing comprehensive policies that integrate disaster management with urban planning is crucial. This includes setting stringent building codes, ensuring that new developments include adequate evacuation provisions, and continuously updating emergency response plans based on the latest data and technological advancements.

Fifth, encouraging collaboration between governmental agencies, private sector stakeholders, and community organizations can lead to more robust and resilient disaster preparedness frameworks. Sharing resources and information can enhance the overall capacity to respond effectively to emergencies.

While this analysis highlights significant challenges, it also presents opportunities for innovation and improvement in disaster preparedness. By adopting a proactive and integrated approach, Seoul can enhance its resilience against earthquakes and ensure the safety and well-being of its residents.

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