Assessing Water Shortages and Spatial Accessibility in Large-Scale Earthquakes: A Supply-Demand Analysis for Emergency Preparedness

Azuki SUEHIRO [a], Mustafa MUTAHARI [b], Nao SUGIKI [c], Kojiro MATSUO [d]

[a,b,c,d] *Architecture and Civil Engineering Department, Toyohashi University of Technology, Aichi, 441-8580, Japan*
[a] *E-mail: suehiro.azuki.ah@tut.jp*
[b] *E-mail: mutahari.mustafa.dj@tut.jp*
[c] *E-mail: sugiki@ace.tut.ac.jp*
[d] *E-mail: k-matsuo@ace.tut.ac.jp*

Abstract: Large-scale disasters can cause prolonged water supply disruptions, severely impacting households and evacuation centers. This study evaluates household preparedness for drinking water shortages and assesses emergency water reserves in Gifu City, Japan. A questionnaire survey was conducted to estimate household water stockpiles, and municipal reserves at evacuation centers and school pools were analyzed. Spatial accessibility to water sources was examined by integrating stockpile distribution with the distance to evacuation centers, highlighting disparities in water availability. Scenario-based modeling assessed shortages under varying levels of water supply shortage, revealing critical gaps in both household and municipal preparedness. The findings of the study emphasize the importance of equitable water access and the need for improved stockpiling strategies that consider spatial accessibility challenges. This research contributes to disaster mitigation policies by providing insights into strengthening water supply resilience and ensuring efficient emergency distribution, ultimately enhancing community disaster preparedness and response.

Keywords: Urban Disaster Mitigation, Large-scale Earthquake, Supply-demand Analysis, Water Shortage, Water Stockpile, Disaster Resilience

1. INTRODUCTION

The likelihood of a Nankai Trough earthquake occurring has been steadily increasing, with the Earthquake Research Promotion Committee estimating a 70–80% probability of a magnitude 8–9 earthquake within the next 30 years (as of January 24, 2020). According to the Cabinet Office's 2012 report on the "Tsunami Height and Seismic Intensity Distribution of a Nankai Trough Earthquake," parts of Shizuoka and Miyazaki prefectures could experience a magnitude 7 earthquake, while widespread areas surrounding these regions are expected to endure strong tremors ranging from magnitude 6- to 6+. The devastation from such an event is projected to surpass that of the Great East Japan Earthquake, leading to severe and prolonged disruptions. Given the widespread impact, external assistance from unaffected regions is likely to be significantly constrained, further complicating recovery efforts.

In the event of a large-scale, multi-regional disaster such as the Nankai Trough Earthquake, catastrophic damage is anticipated, including widespread lifeline disruptions and structural collapses. With only approximately 1,200 water trucks available nationwide, the capacity to provide emergency water supply is expected to fall short of demand. According to the Status of Earthquake Resistance in Waterworks Projects (2021) by the Ministry of Health, Labor, and Welfare, only 41.2% of Japan's main water pipelines have been upgraded to earthquake-resistant standards, highlighting the vulnerability of the water supply infrastructure in times of crisis.

The extended recovery period for water infrastructure following past disasters further underscores this vulnerability. According to the Great East Japan Earthquake Damage Survey Report for Water Supply Facilities (Disaster Assessment Material, 2011) by the Ministry of Health, Labor, and Welfare, electricity was restored to 98.6% of its capacity within one week of the disaster, while water supply restoration lagged significantly, reaching 99% only after three weeks. This demonstrates that water supply systems take considerably longer to recover than electricity, exacerbating the challenges of post-disaster survival and recovery.

In preparation for such emergencies, per capita daily water supply targets have been established, along with emergency water provision standards. However, there remains a critical gap in defining the amount of drinking water that should be stockpiled at evacuation centers. While structural (hard) disaster countermeasures such as infrastructure upgrades require long-term investment and implementation, enhancing preparedness through efficient resource allocation and supply readiness (soft countermeasures) can provide immediate and effective support for disaster response and recovery. Strengthening both aspects is essential to mitigating the impact of future large-scale disasters.

The 2024 Noto Peninsula Earthquake severely impacted transportation infrastructure, rendering many roads impassable due to cracks, fallen trees, and other obstructions. According to the 2024 Noto Peninsula Earthquake Emergency Recovery (Road Reopening) Status report by the Ministry of Land, Infrastructure, Transport and Tourism (as of July 9, 2024), approximately 90% of major trunk roads were restored within two weeks. However, immediately after the disaster, not only residential roads but also key transportation arteries were unusable, significantly restricting mobility and accessibility. In the aftermath, walking and cycling became the primary mode of transportation, making the delivery of relief supplies extremely difficult. Additionally, evacuees were forced to rely on walking to reach evacuation centers and secure drinking water, a task made even more challenging by road damage. Even when roads remained intact, confusion and congestion often prevented people from using cars. Carrying water over long distances is physically demanding, making it critical to ensure that essential resources are accessible within a manageable walking distance.

The challenges posed by disrupted transportation and water supply systems align with broader research on disaster resilience. Several studies have examined the vulnerability of water infrastructure to natural disasters, categorizing key resilience issues into environmental, social, and systemic factors. Research by Pamidimukkala et al. (2021) identified climate change, aging infrastructure, and population growth as primary contributors to prolonged recovery periods. Furthermore, studies on infrastructure interdependence have revealed that failures in one sector can trigger cascading effects in others. Rahimi-Golkhandan et al. (2022) analyzed such interdependencies in Tampa, Florida, demonstrating that regions with higher social vulnerability are more susceptible to compounding infrastructure failures. Similarly, an assessment of water supply disruptions in Texas following a major outage (Tiedmann et al. 2021) underscored the need for government intervention and sustained investment in resilient infrastructure. These findings highlight the necessity of proactive measures to strengthen disaster resilience, not only through immediate emergency response efforts but also through long-term policy and infrastructure planning.

Existing studies on water distribution during large-scale earthquakes has revealed significant discrepancies between demand and supply, particularly in densely populated residential areas. A study by Matsumoto et al. (2016) found that in the event of a major earthquake, three districts experienced water demand exceeding stored water supplies, all of which were highly populated housing complexes. Similarly, Watanabe (2009) analyzed water shortages in Miyagi Prefecture by overlaying emergency water supply facility locations with projected demand based on population distribution and ground conditions. The findings showed that areas with high water demand faced shortages of approximately 50%, while areas with lower demand experienced shortages exceeding 85%. Further analysis by Komura et al. (2022) assessed the resilience of public elementary schools in Toyohashi City, particularly focusing on earthquake-resistant water storage tanks. While some level of preparedness was observed, significant disparities existed between different school districts. In certain districts, the minimum emergency water supply standard of 7.5 liters per capita per day, as defined by the Sphere Standard, was not met. This highlights critical gaps in emergency water provisioning.

A key issue identified in previous studies is the lack of household preparedness in securing drinking water, whether through bottled water or home water servers. Additionally, as discussed earlier, evacuation centers often do not have a standardized provision of drinking water, with significant variations in supply from one shelter to another. Most existing studies assess water sufficiency during disasters based on municipal infrastructure, such as earthquake-resistant water tanks and distribution reservoirs. However, these assessments overlook the role of individual household preparedness, which is a crucial factor in disaster resilience. To develop more effective mitigation strategies, it is essential to improve the accuracy of water shortage estimations by considering both government-provided resources and household stockpiles.

Building on this need, the objective of this study is to evaluate residents' preparedness for drinking water shortages during large-scale disasters by analyzing household water stockpiles through a questionnaire survey. Recognizing the critical role of water accessibility in post-disaster recovery, this study estimates potential water shortages by integrating stockpile levels at both evacuation shelters and individual households. Furthermore, it examines regional water accessibility by factoring in the distance to evacuation sites, providing a comprehensive assessment of water availability and identifying gaps in disaster preparedness. By addressing both municipal infrastructure and household resilience, this research aims to contribute to more effective emergency water supply strategies, ultimately enhancing disaster response capabilities and community resilience.

To enhance realism, this study analyzes scenarios in which different proportions of Gifu City's population—ranging from half to the entire population—lose access to water supply, reflecting actual disaster conditions. This approach not only provides a more accurate assessment of water availability and accessibility but also informs strategies to strengthen disaster resilience and emergency response planning. By addressing both governmental and household preparedness, this research contributes to improving disaster mitigation policies and ensuring a more resilient water supply system in future emergencies.

The remaining part of this paper is divided into the following sections: after the introductory section, section 2 briefly presents the reviewed existing studies, and is followed by section 3. The third section discloses the data acquisition, data analysis methods, and survey results. Subsequently, section 4 discloses the study`s results. Lastly, in section 5, the conclusion section summarizes this study and presents ideas for future research prospects.

2. LITERATURE REVIEW

2.1 Disaster Evacuation and Evacuation Modeling

Disaster evacuation, regardless of its cause, either natural or human-made events, requires comprehensive research due to its complex and multidimensional nature. Several studies have been conducted to simulate and analyze different aspects of disaster evacuation, including evacuation plans, evacuation behaviors, route selection, transportation mode preferences, and shelter choices. For example studies by Margrethe et al. (2010), Winnie et al. (2010), Daniel et al. (2010), Choi et al. (2021), and Ellen et al. (2010) focus on building disaster evacuation such as exit choices, behavioral responses, impact of width of doors, population type, exit choice optimization, and their simulations during building disaster evacuations.

Similarly, natural disaster evacuations have also been studied by several existing studies. For example, studies by Michael and Sally (2010) and Alsnih et al. (2004) focused on bushfire evacuations, in which they reviewed bushfire evacuation strategies and investigated household evacuation behaviors in Australia, respectively. Pablo et al. (2013) developed hybrid structural models for predicting evacuee behavior, Karam et al. (2013) used multi-agent simulation to simulate human interactions during disaster, and Duan et al. (2019) focused on estimating behavioral choices during evacuations. Other existing studies by Jumadi et al. (2016) and Grajdura et al. (2022) developed agent-based models to assess population risk during volcanic eruptions and to simulate wildfire evacuations, respectively.

Natural disaster evacuation choices, evacuation shelter distribution, and evacuation shelter capacities are the other major factors affecting disaster risk mitigation and are widely studied in existing studies. For instance, Honda et al. (2020) assessed evacuation shelter capacities in Japan. Kongsomsaksakul et al. (2005) highlighted the importance of optimal evacuee distribution across shelters, while Yamada and Yamasaki (2021) studied evacuation direction choices during tsunamis. Ma. Bernadeth et al. (2021) examined how sociodemographic characteristics influence shelter selection. Mamoru et al. (2018) investigated location choices in the 2016 Kumamoto Earthquake. Similarly, Mami et al. (2000) and Reio et al. (1999) studied evacuation location choices, and the findings confirm the diversity of evacuation location choices rather than only designated evacuation shelters, emphasizing the importance of diversified shelter planning. A study by Noda et al. (2024) also confirms the diversity of evacuation locations, rather than designated evacuation shelters, but also evacuating to private cars, hotels, acquaintance houses, or remaining at home.

Through this literature review, it was found that highly infectious disease such as COVID-19 also affects evacuation location choices. Several studies have investigated evacuation behaviors during the COVID-19 pandemic. For instance, Masashi et al. (2020) conducted a systematic literature review focusing on the complex disasters under the condition of the COVID-19 pandemic and suggested a dispersed evacuation approach considering COVID-19. Hisao et al. (2021) have developed a tsunami evacuation placement model that considers the physical distancing guidelines for infection control and living space per person while assessing the evacuation shelter capacities. Kinichi et al. (2021) utilized the 2019 East Japan Typhoon data to investigate the flood evacuation amid the COVID-19 pandemic. Shrabani et al. (2021) developed a multi-objective optimization model to minimize the total number of new infections in the evacuation shelter and maximize the total number of evacuees amid COVID-19 during flood evacuation. Yuto et al. (2022) used the 2016 Kumamoto Earthquake to analyze evacuation challenges that may arise during the COVID-19 situation. Noda et al (2024) also studied the evacuation choice behavior of individuals and households under compound risk of natural disasters such as earthquakes and floods amid the COVID-19 pandemic in Japan and confirmed that disaster-affected people may not necessarily evacuate to designated evacuation shelters but to other places such as their own private cars, friends or family`s house, hotels, or may not evacuate at all but may move to upper floors of their apartments, fearing the widespread of the disease.

Transportation and evacuation modeling are the other critical components of disaster response planning that need to be studied widely while aiming at disaster risk mitigation precautions, and during and post-disaster risk mitigation. Existing studies have developed various methods to investigate and analyze evacuation dynamics, with a particular emphasis on traffic demand estimation, damage to transportation systems, evacuation choice behavior, driving behavior, and congestion during evacuation. For example, Huizhao et al. (2010) examined driving behaviors during floods, Murray-Tuite and Wolshon (2013) did a comprehensive review of highway-based evacuation modeling, addressing the key factors involved in evacuation processes, such as route selection, congestion, and the behavior of evacuees. Similarly, studies by Fu and Wilmot (2004), Zhang et al. (2013), Antonio and Antonino (2014), and Zhua et al. (2018) focus on model developments to estimate traffic demand, predict departure time, analyze the impact of large scale evacuation on the transportation system, and analyze evacuation behaviors, respectively. Elisa et al. (2021), have explored the impact of the COVID-19 pandemic on evacuation behaviors, particularly the tendency for ridesharing among strangers during flood evacuations.

Through this literature review, it was found that existing studies have widely covered different dimensions of evacuation planning, and little attention has been given to accessing and supplying the needs of the non-designated evacuation shelter evacuees. Hence, the study emphasizes the comprehensive evaluation of transportation networks by analyzing the accessibility of individuals and households to evacuation shelters and other resources during and post-disaster. Additionally, considering the diversity in the evacuation location choices, this literature review suggests a need for studies to consider not only the accessibility of evacuees in the evacuation shelters to different resources and supplies but also individuals who did not evacuate to the designated evacuation shelters. It is believed, this effort can provide evacuation planners and decision-makers with an evaluation tool to further minimize the disaster risk and contribute to sustainable and resilient urban developments.

2.2 Water Supply and Demand in Disaster Response

As discussed above, significant studies have been carried out on evacuation dynamics during large-scale disasters; however, there is a gap in the investigation of water supply and demand in post-earthquake scenarios. Natural disasters often disrupt water infrastructure, leading to severe water shortages (Fan et al., 2024). For example, the 1995 Kobe earthquake resulted in extensive damage to water pipelines, with over 30,000 casualties and more than 25,000 homes destroyed (Kuraoka and Rainer, 1996). Despite the significant importance of water access, there is a gap in the existing studies in integrating water demand analysis into evacuation model evaluation. This integration is crucial for improving the efficiency and effectiveness of disaster response strategies.

Water shortages during disasters are caused by several factors, such as infrastructure damage, population displacement, and disruptions in supply chains. While previous studies have focused on optimizing evacuation strategies (Ekaputra et al., 2024; Bakhshian and Martinez-Pastor, 2023; Sun et al., 2017), relatively few studies have examined how water shortage affects evacuee behavior and resource allocation. For instance, existing studies have highlighted the challenges associated with water supply management during a disaster, but they have not addressed how water access affects the movement of evacuees and how resources need to be allocated. To this end, Miao et al. (2024) introduced a method for estimating water demand post-earthquake; however, not only water demands but also evacuation strategies need to be incorporated into the water estimation models. Such models could enable more effective coordination between water supply management and evacuation efforts, ensuring resources are allocated optimally.

Furthermore, Research by Pamidimukkala et al. (2021) highlights factors like climate change, aging infrastructure, and population growth as major contributors to prolonged recovery periods. Additionally, studies by Rahimi-Golkhandan et al. (2022) and Tiedmann et al. (2021), show that failures in one sector, like water or transportation, can trigger cascading effects in others. These findings emphasize the need for effective measures, such as government intervention and investment in sustainable and resilient urban infrastructures, to reduce the impact of future disruptions. Strengthening resilience requires not only effective emergency response efforts but also long-term policy and infrastructure planning that addresses vulnerabilities in both water supply and other critical sectors.

2.3 Addressing Water Shortages in Large-Scale Earthquake Disasters

One of the disasters that largely affects water supply chains is large-scale earthquakes. Water shortages following large-scale earthquakes pose critical challenges for disaster response and recovery. Several studies have examined the impacts of earthquakes on water supply infrastructure (Endo et al., 2022; Barfal et al., 2022; Kato and Endo, 2017) which highlight significant disruptions due to pipeline damage and infrastructure failures. Past disasters, such as the 2024 Noto Peninsula Earthquake and the Great East Japan Earthquake, have proved that water system recovery often lags behind electricity restoration, prolonging the crisis and complicating evacuation situations. Furthermore, studies by Komura et al. (2022), Matsumoto et al. (2016), and Watanabe (2009) investigate disparities in water supply between different regions and underscore the need for improved resilience planning.

As discussed above, some studies have already developed methods to estimate water demand during and after earthquakes (Miao et al., 2024; Tolan and Wein, 2021). Ide et al. (2025) developed a method to model the water supply system recovery after an earthquake. Considering the frequency and intensity of disasters, it seems crucial to integrate water demand analysis, infrastructure resilience analysis, and supply chain disruptions into existing evacuation models. In addition, Research on cascading failures and long-term resilience (Rahimi-Golkhandan et al., 2022; Tiedmann et al., 2021) also confirms that water accessibility is interconnected with broader socio-environmental factors, making it crucial to incorporate these dynamics into disaster response planning.

In addition, existing studies have investigated the ability to carry water by hand, employing exercise physiology methods to calculate the relationship between the amount of water carried and the distance it can be transported. A study by Okumura et al. (1997) argues that the quantity of transportable water will become zero if the transport distance exceeds 1200 meters. Another study by Hosoi et al. (2003) adopted a model that accounts for personal attributes and the transport vehicle, setting the water carrying distance based on the energy consumed or metabolic rate for water transport. According to the study`s result, the relationship between water demand and distance, as water demand approaches zero, the transport distance approaches 2500 meters.

In response to the water shortage during disasters, Kobe City, located in Hyogo Prefecture, which was severely impacted by the Great Hanshin-Awaji Earthquake, has established detailed plans for emergency water supply in the event of a disaster. These plans include base locations capable of providing emergency water immediately following a disaster, with roughly one base per 2 km radius (Kobe City Resilience Plan - Safe City Development Promotion Plan, March 2022). Furthermore, the Ministry of Health, Labor and Welfare’s "Guidelines for Formulating Earthquake-Resistant Plans for Waterworks" (June 2015) stipulates that the distance over which residents should transport water within three days after an earthquake should generally be within 1 km in urban areas.

However, to the best of our knowledge, no study has been conducted to develop models to estimate water shortage considering the water stockpiling by households. Therefore, as a result of this study`s literature review, the study aims to bridge these research gaps by developing a comprehensive evaluation method that integrates water shortage analysis into a large-scale earthquake evacuation analysis method, considering the water stockpiling by households and water supply optimization. By considering both supply and accessibility challenges, the research will enhance disaster resilience planning for both urban and rural areas. Additionally, the study investigates how incorporating government-provided earthquake-resistant water storage alongside individual household preparedness refines water shortage estimations and improves emergency response strategies. The study contributes to the academic field by introducing an effective method for water shortage analysis in the case of an earthquake, incorporating water stockpiling by households and water supply optimization.

3. MATERIALS AND METHODS

3.1 Target area

The target study area of this study is Gifu City, located in Gifu Prefecture, Japan. As shown in Figure 1, Gifu City's population is unevenly distributed, with the majority residing in its central and southern parts. With a population of approximately 400,000, Gifu City is the most populous core city within the prefecture. Its strategic location in the south-central part of Gifu Prefecture positions it as a key urban center, making it a critical area for understanding the impacts of large-scale disaster scenarios on water supply and demand analysis.

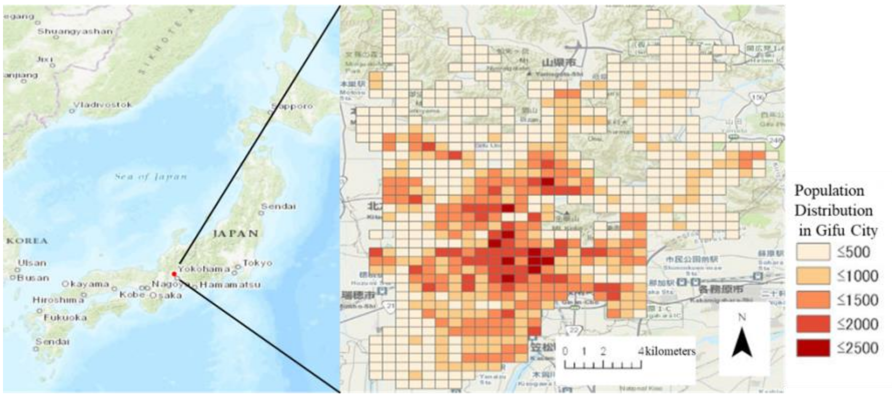

Figure 1. Population distribution in Gifu City

3.2 Analysis Framework

The analysis of water shortages is conducted over three days following a disaster. Water shortage estimates are calculated daily, based on two key water volume standards: (1) the Sphere Standard and (2) the emergency water supply target. Figure 2 presents the water shortage estimation framework used in this study. As shown in Figure 2, first, the study gathered household distribution data in Gifu City from the 2020 census data, and evacuation rate and water outage rate information from the 2023 Gifu City Disaster Damage Report. Utilizing the household distribution data, evacuation rate, and water outage data, the study estimated the distribution of Evacuated Households (HE), and Households affected by Water Outage (HWO). In this study, the HE refers to the households whose place of residents are damaged due to the earthquake and need to be evacuated to the designated evacuation shelter, whereas the HWO refers to the housholds whose place of residents are not damaged but they are affected by water outage due to damage to the water piplines. The HWO is estimated from the difference between the total number of households and the total number of evacuated households (HE). The households that have faced a 100% water outage are referred to as 100%_HWO, whereas the households that have faced a partial water outage are referred to as 50%_HWO, which is half of 100%_HWO.

In this study, the water requirement refers to the amount of water required for each household for the purpose of cooking and drinking, and it is calculated using the two standards, the sphere standard, which is 5.5 liters per day per person, emergency water supply target which is 3 liters per day per person. To estimate the water requirement for HE and HWO, we have multiplied the sphere standard and emergency water supply target by the number of HE and HWO, respectively.

The study conducted a survey to understand the drinking water stockpiling behavior of each household by household type and utilized this data to estimate the drinking water stockpiling within the city. The drinking water stockpiling by household type from the survey data is shown in Table 2. Designated evacuation shelter locations and their water stockpile capacities were identified using Prefectural GIS and the Gifu City Regional Disaster Prevention Plan. In addition to shelter reserves, municipal school pools and approximately 100 earthquake-resistant firewater tanks were included in the supply volume, with school-based water purifiers assumed to generate 24 m^3 of potable water per day. Non-earthquake-resistant facilities and community center tanks were excluded.

Water demand was calculated using both the Sphere Standard (7.5 L/person/day, including 5.5 L for drinking and 2.0 L for hygiene) and Japan's emergency water supply target (3 L/person/day). These requirements were mapped mesh-by-mesh and compared with shelter-level supply, taking into account the five nearest evacuation routes and shelter accessibility constraints. Accessibility analysis was limited to a 2 km pedestrian threshold, reflecting both national guidelines and precedents from the Kobe City Resilience Plan. Water demand is calculated by differentiating stockpiled water from water requirements. In scenarios where stockpiled water is less than the water requirement, which means demand for water, we identify the households that need water. The households with water shortages are spatially distributed using the ArcGIS Pro software. We have optimized the distribution of water supply using RStudio Desktop, considering the amount of water to be supplied and the shortest path analysis between the center of the mesh and designated evacuation shelters in the ArcGIS Pro software.

As can be seen in Figure 2, the stockpiled waters at designated evacuation shelters are referred to as the supply. Whereas, the water shortage is defined as the difference between demand and supply. Water shortage rate is defined as the demand minus supply divided by the demand. The water shortage and water shortage rate analysis are carried out for three subsequent days, considering the consumption of water based on the sphere standard and emergency water supply target water consumption. The study aims to investigate the water shortage for three consecutive days following an earthquake using this innovative method by combining survey data with census data, specifically distributing the households by different household type, assigning water stockpiling behavior to estimate the amount of stockpiled water, estimating water demand, water shortage, and water shortage rate, and optimizing the water distribution to carefully analyse and estimate the water shortage.

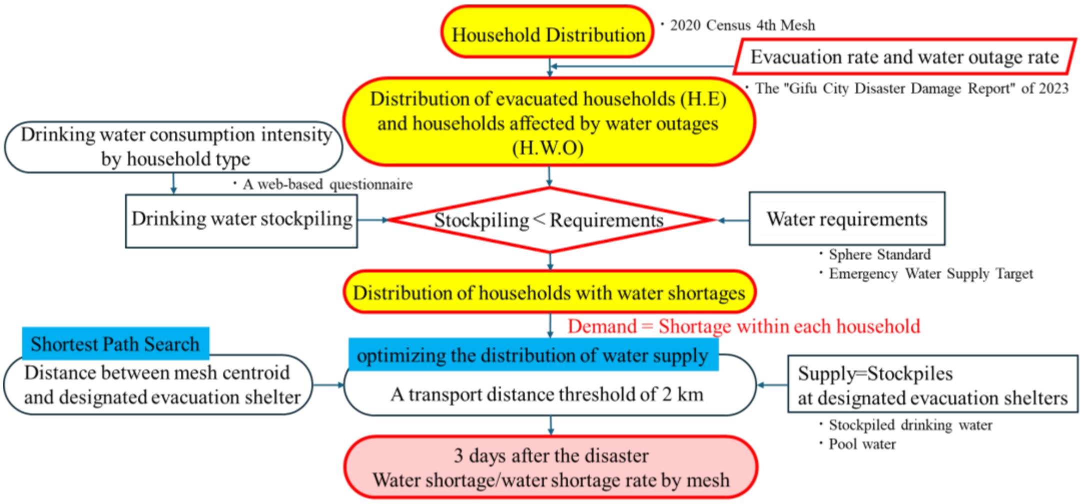

Figure 2. Water shortage estimation framework

The results of the demand–supply analysis for water distribution to the nearest evacuation shelters in this study revealed that certain mesh areas experience an insufficient water supply from their designated shelters. However, the analysis also showed that some non-nearest shelters have the capacity to accommodate a larger number of evacuees and meet local demand more effectively. This finding underscores the importance of promoting dispersed evacuation strategies and revising shelter assignments to improve overall emergency response. Local governments should consider optimizing water distribution systems to better serve both evacuees and residents affected by water outages. Therefore, to evaluate accessibility, this study defined a pedestrian movement threshold to identify reachable evacuation shelters for each mesh. Using the selected shelter for each household as a reference, the gap between water demand and supply was analyzed on a shelter-by-shelter basis. This approach provides meaningful insights into how water distribution can be balanced spatially to ensure more efficient allocation under disaster conditions.

Additionally, considering the unique urban structure of Gifu City, characterized by lower population density outside the central area and greater reliance on private vehicles, the commonly recommended 1 km walking distance for water transport (as suggested in national guidelines) is considered to be insufficient in this study. Therefore, this study adopts a 2 km pedestrian transport threshold in line with the Kobe City Resilience Plan, while acknowledging spatial variations in transport capacity and regional characteristics. Individual household attributes are excluded from the analysis to maintain a uniform city-wide modeling approach.

3.3 Survey Overview

A web-based questionnaire was administered to a group of monitors consisting of Gifu citizens in Gifu city of Gifu Prefecture to assess the quantity of drinking water stockpiled by residents on November 20 – 21, 2023. The survey sample included 500 participants, and the questionnaire focused on the following key areas: “Respondent Demographics,” “Household Disaster Preparedness,” “Disaster Response Actions,” and “Disaster Awareness.”

3.3.1 Analysis of drinking water stockpiling

In order to investigate the relationship between household type and drinking water stockpiles, an analysis was conducted for each of the five household categories. Table 1 outlines the type of each household. The terms “Elderly Single-Person Households” and “Elderly Two-Person

Households" in Table 1 correspond to the definitions of "Elderly Single-Person Households" and "Elderly 2 Persons Households" as described in the 2020 Census regional mesh statistics, specifically in the section titled "Population and Households." The survey revealed that 46.2% of households reported having stockpiled drinking water, representing less than half of the total respondents. Notably, non-elderly single-person households were more likely to report no stockpiled water, while households with two elderly members had a higher likelihood of having stockpiles, highlighting the significant differences in stockpiling behavior based on household type.

3.3.2 Drinking water stockpiling by household type

Figure 3 illustrates the results of drinking water stockpiling by household type. A majority of households with potable water reserves reported stockpiles of less than 50 liters. Table 2 provides the percentage of households with and without drinking water stockpiles by household type, along with the units of drinking water reserves per household type. Additionally, 21 data sets were excluded from the analysis due to being identified as outliers. These outliers exceeded the threshold of the third quartile + 1.5 times the interquartile range for households that reported having drinking water reserves.

Table 1. Household type

	Classification	Classification definition	Census data used
A	Non-elderly single-person households	Households with only one person under 65 years old	One-person households - Aged single-person households
B	Elderly single-person household	Households with only one person 65 years old or older	Elderly single-person household
C	Non-elderly 2-person household	Household with only one couple: husband under 65, wife under 60	Elderly couple household -2-person household-elderly
D	Elderly 2-person household	Household with only one couple: husband 65 years old or older, wife 60 years old or older	Elderly couple household
E	Household with 3 or more persons	Households with 3 or more persons	Household of 3 or more persons

*Census definition
Elderly single-person households: General households with only one person 65 years of age or older
Elderly couple households: Households consisting of only one couple (husband 65 years old or older, wife 60 years old or older)

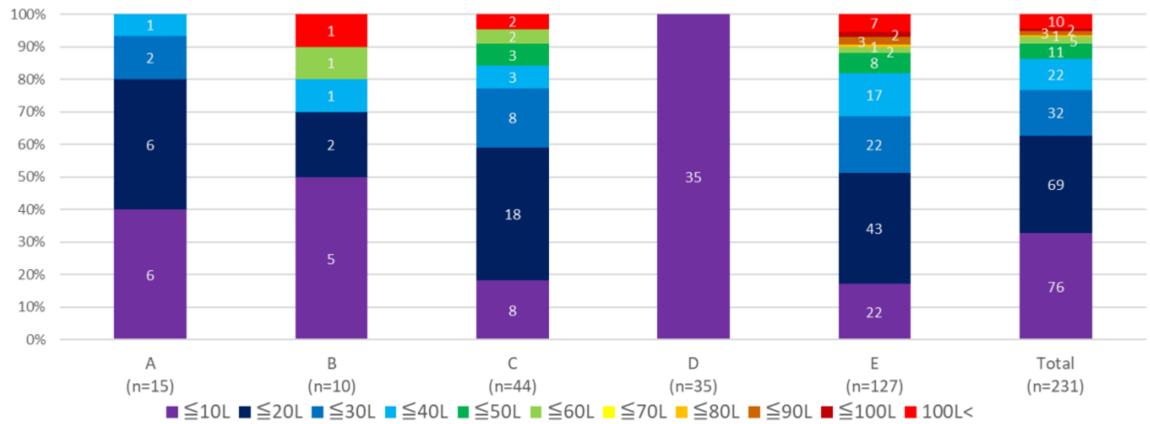

Figure 3. Amount of drinking water stockpiled by household type

Table 2. Drinking water stockpiling by household type

Household Type	Total No. of households	Households with a stockpile	Households without a stockpile	Stockpile %	Average
A	65	15	50	0.23	13.47
B	23	9	13	0.43	16.71
C	94	42	50	0.47	19.95
D	57	30	22	0.61	16.82
E	261	114	134	0.49	21.79
Total	500	210	269	0.46	19.9

*Excluding 21 outlier data for "stockpiled".

4. RESULTS

4.1 Shortage Analysis Based on Sphere Standard

Using the Sphere Standard as a benchmark for water demand, we estimated the drinking water shortage for each mesh during the three days following the disaster. Figures 4, 5, and 6 illustrate the shortage rates for each secondary mesh based on the emergency water supply target by the number of days since the disaster occurred. Tables 3 and 4 provide a detailed breakdown of the number of meshes corresponding to each shortage rate, along with the estimated water shortages according to the Sphere Standard.

Figure 4 shows sphere-based water shortage analysis for HE in the consecutive days following an earthquake. The dark green represents more water shortage, whereas the lighter green represents fewer water shortages. White mesh represents 0% water shortage, which means there is sufficient water. It can be noticed that the water shortage is fluctuating between Day 1, Day 2, and Day 3 in different meshes. It is because of considering filtering the undrinkable stockpiled water and performing optimization of water supply distribution for water shortage analysis.

As can be seen in Figure 4, there is a high shortage rate in the densely populated central area and in mountainous areas, and it is believed that water shortages occurred due to the high population density in the central area and the travel distance threshold in mountainous areas. In Figure 5, the trend remains the same, but the water shortage is more noticeable in mountainous areas, which shows that when taking into account the population affected by the water outage, the impact is greater in mountainous areas. In Figure 6, there is no change from Figure 5 up to the second day, but by the third day, there is an increase in the number of meshes with high water shortage rates. This means that if all residents of Gifu city are the target of the analysis, it is predicted that a serious water shortage would occur by the third day.

The result of this study reveals a clear upward trend in the shortage rate over time, particularly in meshes with higher population densities and those located in more remote, mountainous areas with limited access to evacuation shelters. A similar pattern was witnessed even when the target population was adjusted, which emphasizes the significant challenges in water supply during and post-disasters.

Table 3. Number of meshes by shortage rate based on sphere standard estimation

Sphere Standard	HE	HE+50%HWO	HE+100%HWO

Shortage rate(%)	Day1	Day2	Day3	Day1	Day2	Day3	Day1	Day2	Day3
0	577	565	554	505	506	504	495	426	406
≦10	1	6	5	3	0	0	3	46	50
≦20	5	0	0	1	0	0	1	0	7
≦30	7	2	2	0	1	2	2	11	0
≦40	6	4	5	10	2	0	3	0	10
≦50	0	0	4	10	2	0	1	0	0
≦60	2	6	3	6	1	2	2	2	2
≦70	6	19	1	10	1	2	15	4	2
≦80	2	1	26	8	22	1	13	3	3
≦90	12	11	6	23	12	32	32	24	14
≦100	91	95	103	133	162	166	142	193	215
Total	709	709	709	709	709	709	709	709	709

Table 4. Shortage at the time of sphere standard estimation

Sphere Standard	HE			HE+50%HWO			HE+100%HWO		
	Day1	Day2	Day3	Day1	Day2	Day3	Day1	Day2	Day3
Supply (KL)	1,476	2,868	4,260	1,476	2,868	4,260	1,476	2,868	4,260
Demand (KL)	198	396	594	631	1,564	2,643	1,210	3,022	5,124
Shortage (KL)	47	89	144	164	419	703	344	979	1,670
Shortage rate (%)	24.09	22.46	24.23	26.10	26.79	26.61	28.45	32.40	32.60

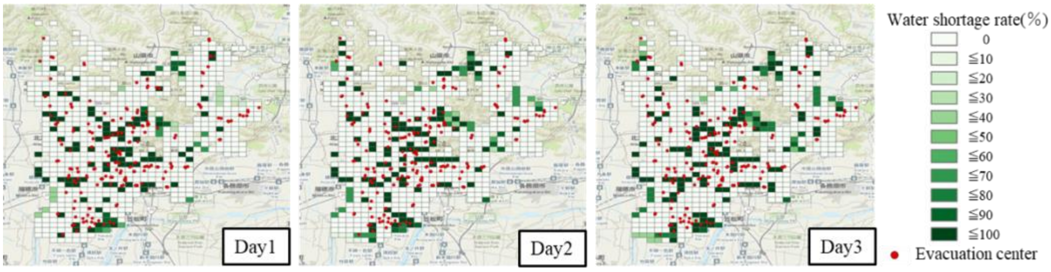

Figure 4. Sphere-based shortage rate (HE only)

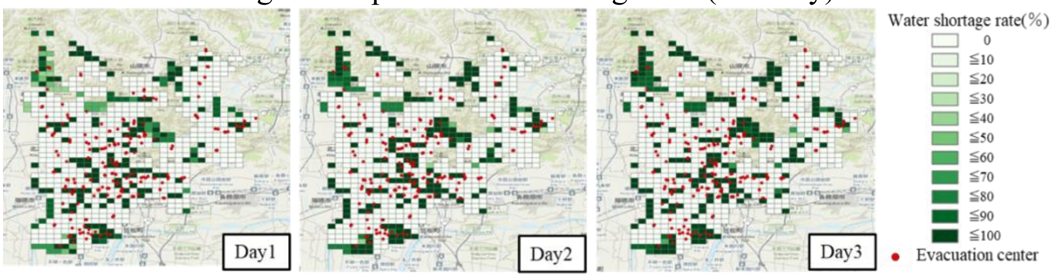

Figure 5. Sphere-based shortage rate (HE +50%HWO)

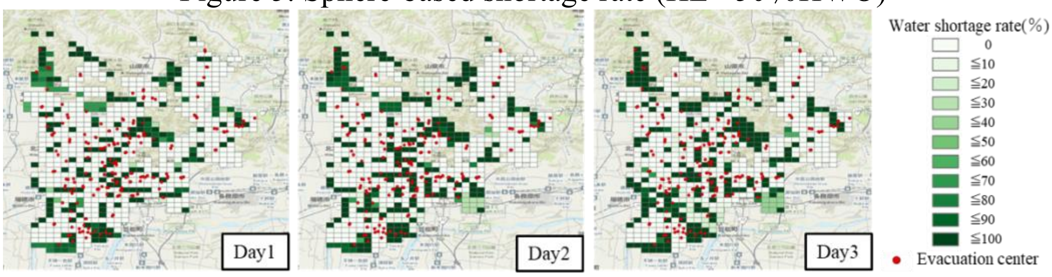

Figure 6. Sphere-based shortage rate (HE +100%HWO)

4.2 Shortage Analysis Based on Emergency Water Supply Target

Using the emergency water supply target as a benchmark for water demand, the study estimated the drinking water shortage per mesh over the three days following the disaster. Figures 7, 8, and 9 present the shortage rate for each secondary mesh, categorized by the number of days since the disaster. Tables 5 and 6 present the number of meshes by shortage rate and the estimated volume of water shortages based on the emergency water supply target. Compared to the Sphere Standard, the analysis result reveals a more gradual increase in both the shortage rate and the number of deficient meshes. The overall shortage rate remained relatively stable at approximately 25%. However, the trend in which meshes with water shortage rates appear over time in the central and mountainous areas is consistent, indicating that changes in the amount of water required will not resolve the drinking water shortage in the region. It is because of the accessibility of rural and mountainous areas to the evacuation shelters, as well as a water supply. Usually, in low-density areas such as mountainous areas, the distribution of evacuation shelters is limited, and the distance to evacuation shelters is not as close as in urban areas. Additionally, we have used the 2 Km threshold travel distance to reach evacuation centers; however, in some cases in mountainous areas, the distance to evacuation shelters exceeds 2 km.

Additionally, the total water supply exceeded the demand, which confirms sufficient water availability to compensate for shortages in severely affected meshes. However, in densely populated areas regardless of the size of the affected population, persistent water shortages emphasize the necessity of maintaining adequate emergency water reserves in central locations. In contrast, in mountainous and sparsely populated areas, as the affected population grew, a gradual increase in the water shortage by the passage of time was found. This underscores the need for effective post-disaster water distribution strategies, such as deploying water trucks, to ensure equitable access to emergency water supplies.

Table 5. Number of meshes by shortage rate based on emergency water supply estimation

Emergency Water Supply Target	HE			HE+50%HWO			HE+100%HWO		
Shortage rate(%)	Day1	Day2	Day3	Day1	Day2	Day3	Day1	Day2	Day3
0	615	588	581	510	512	510	512	502	510
≦10	0	0	2	6	0	1	2	1	0
≦20	0	5	3	3	3	2	3	2	0
≦30	1	1	0	20	1	1	6	0	0
≦40	0	8	0	0	1	1	9	2	0
≦50	7	5	6	15	14	0	8	2	3
≦60	1	2	11	2	13	1	5	6	2
≦70	2	1	5	14	0	15	3	3	2
≦80	5	6	3	10	11	13	23	19	13
≦90	4	7	9	24	27	17	26	13	16
≦100	74	86	89	105	127	148	112	159	163
Total	709	709	709	709	709	709	709	709	709

Table 6. Shortage at the time of emergency water supply target estimation

Emergency Water Supply Target	HE			HE+50%HWO			HE+100%HWO		
	Day1	Day2	Day3	Day1	Day2	Day3	Day1	Day2	Day3
Supply (KL)	1,476	2,868	4,260	1,476	2,868	4,260	1,476	2,868	4,260
Demand (KL)	108	216	324	333	704	1189	638	1,352	2,292
Shortage (KL)	23	49	71	86	177	286	160	369	603
Shortage rate (%)	21.36	22.84	22.05	25.92	25.24	24.13	25.07	27.32	26.33

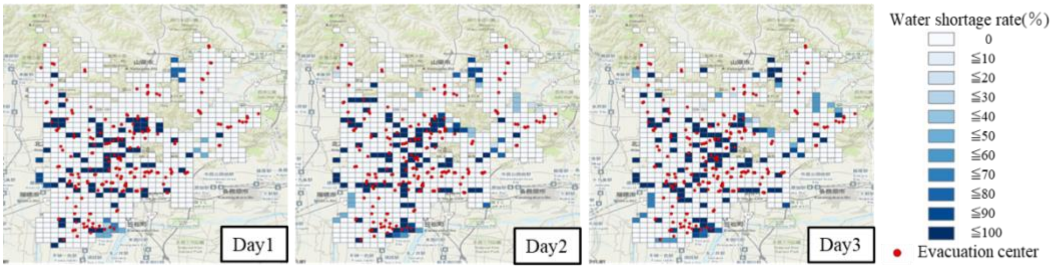

Figure 7. Emergency water supply target shortage rate (HE only)

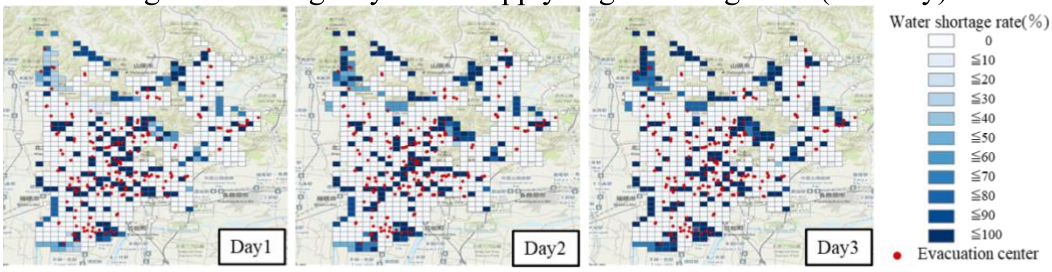

Figure 8. Emergency water supply target shortage rate (HE +50%HWO)

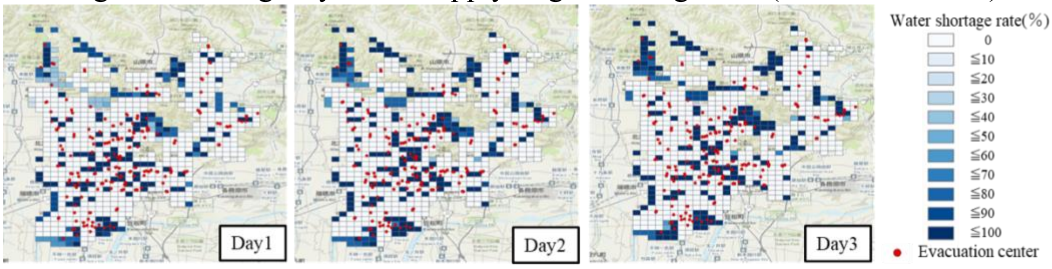

Figure 9. Emergency water supply target shortage rate (HE +100%HWO)

5. DISCUSSION

This study provides a comprehensive framework for evaluating water shortages in the aftermath of large-scale earthquakes by integrating household preparedness, municipal water stockpiles, and spatial accessibility using public open data and household survey data. The combination of GIS-based spatial analysis, evacuation scenarios, and household survey data enabled this study to develop a method for quantifying unmet water demand under various disaster scenarios. The result of this study revealed that clear disparities in drinking water availability across Gifu City, especially in densely populated urban zones and remote mountainous regions.

One key insight from the analysis is that even when the total water supply is theoretically sufficient, particularly under the emergency water supply target, certain areas still experience critical shortages due to limitations in accessibility and distribution. These findings underscore that physical stockpiles alone are insufficient; the ability to effectively deliver water to the most vulnerable populations is equally vital. This highlights the necessity for local governments to establish decentralized and strategically located water reserves that can be accessed on foot, particularly in post-disaster situations where vehicular transportation may be compromised.

The study also confirmed the inadequacy of current household stockpiling behaviors. Only 46.2% of respondents reported stockpiling drinking water, and most stockpiled volumes were far below the Sphere Standard of 7.5 L per person per day. Notably, elderly two-person households exhibited relatively higher preparedness, while non-elderly single-person households were significantly less prepared. These differences point to a critical need for targeted public awareness campaigns and community outreach strategies that promote water stockpiling, especially among vulnerable and less-prepared household types.

The study could obtain a sufficient sample size to estimate the average water stockpile by household type, and used public data and calculate the average water stockpile by household type to analyse water shortage. This method is effective for the first approximation; however, it may introduce some uncertainty into the shortage estimates. As future research, studies should develop models to incorporate more nuanced household characteristics, such as income, car ownership, household type, housing type, and geographic location, to enhance model efficiency.

In this study, particular emphasis was placed on evaluating pedestrian accessibility to water sources, given the unpredictability of road conditions in the aftermath of a disaster. Disruptions such as landslides and infrastructural damage, especially in mountainous areas, often render roads impassable, making it difficult to ensure vehicle-based water delivery. Consequently, the analysis focused on 2 km walking distances, assuming that pedestrian movement is less impacted by such disruptions. However, future research should incorporate supply chain dynamics and multi-modal transportation systems, including vehicular, bicycle, and drone-based deliveries, to more accurately reflect the complexities of emergency water distribution.

Despite these limitations, the study successfully demonstrates how a multi-scalar approach, spanning households, evacuation shelters, and city-wide logistics, can inform more equitable and efficient water distribution strategies. Importantly, this methodology is transferable to other urban and peri-urban regions with similar geographic and demographic diversity. Applying this framework to other municipalities can help prioritize infrastructure investments, optimize emergency resource allocation, and build community resilience.

In addition, the development of a dynamic simulation model that accounts for real-time stockpile consumption, infrastructure damage, and accessibility constraints will be valuable. Furthermore, integrating this model with broader evacuation planning tools could enhance holistic disaster preparedness, ensuring that both water and shelter needs are addressed simultaneously. Future research could also benefit from integrating behavioral dimensions of urban resilience, such as residents' reliance on digital services and changing spatial interaction patterns. As suggested by Mutahari et al. (2025), digital service usage may significantly influence disaster response behavior and evacuation dynamics.

Lastly, by quantifying the discrepancy between water demand and available supply, this study reveals systemic vulnerabilities in both household-level preparedness and municipal stockpiling strategies. The findings underscore the importance of incorporating residential stockpiling behavior into disaster planning and highlight the critical role of government-maintained reserves in ensuring equitable water access during emergencies. The proposed methodology, integrating household survey data with spatial distribution analysis, offers a practical and transferable framework for evaluating water shortages under realistic disaster scenarios. This approach provides local governments with a valuable tool for assessing and refining emergency preparedness plans, while simultaneously promoting public awareness and action to improve household-level resilience.

6. CONCLUSION

This study examined household drinking water stockpiling and spatial accessibility to emergency water supplies in Gifu City, Gifu Prefecture, within the context of large-scale earthquake scenarios. Using a web-based questionnaire survey, household-level data on drinking water reserves were collected and integrated with municipal stockpile information from evacuation shelters and other public facilities. The analysis was conducted based on two key standards: the Sphere Standard, a global benchmark for emergency water supply (7.5 L/person/day), and Japan's emergency water supply target (3 L/person/day).

The findings indicate that overall water shortage rates in Gifu City ranged from 22–33% under the Sphere Standard and 21–28% under the emergency water supply target. Although total supply sometimes exceeded demand, particularly on Days 2 and 3 in the HE + 100% WHO scenario, certain areas continued to experience critical shortages due to limited accessibility and uneven distribution. While non-potable sources such as swimming pools can be purified on-site, the time-intensive purification process makes them unsuitable for rapid deployment via water trucks in the immediate aftermath of a disaster. Therefore, the study suggests pre-stocked potable water should be prioritized for densely populated and hard-to-reach regions.

By quantifying the discrepancy between water demand and available supply, the study highlights systemic vulnerabilities in both household preparedness and municipal provisioning. Less than half of the surveyed households reported any water stockpiles, and the majority had insufficient water for survival over three days. These findings reinforce the need for targeted public awareness on household stockpiling and improved distribution strategies by local governments. Additionally, we believe the integrated approach, combining household survey data, mesh-based spatial analysis, and supply-demand modeling, offers a practical and transferable framework for assessing urban water resilience in disaster contexts. In addition to addressing water quantity, the study emphasizes spatial equity by analyzing pedestrian accessibility within a 2 km threshold, recognizing that road infrastructure may be severely disrupted during disasters. This framework not only identifies vulnerable areas but also informs the optimal siting of future emergency water reserves.

As a future research direction, studies should incorporate household-level microdata, including variables such as housing type, income, car ownership, and building resilience, to refine demand estimation accuracy. Moreover, the integration of multi-modal logistics and dynamic supply chain models could enhance accuracy in distribution scenarios. Extending this methodology to other municipalities will help create more adaptive, inclusive, and data-driven disaster preparedness strategies, ultimately supporting the development of more resilient urban structures.

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