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How informal water supply points using private wells worked in an emergency: A quantitative evaluation

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ABSTRACT

The effectiveness of an emergency water supply using private wells has been asserted theoretically but not evaluated in detail. This paper aims to consider the effectiveness and shortcomings of emergency water supply based on local wells and to support policy formulation regarding groundwater usage in the event of a disaster. In Kamisu City, Ibaraki Prefecture, Japan, not only public-operated formal water supply points using water trucks but also informal water supply points using private wells were open to address water outages following the Great East Japan Earthquake of 2011. This study clarified the pattern of appearance and spatial distribution of those points by combining information from local newspapers, Internet archives, and an original questionnaire survey. In addition, the function of informal water supply points was quantitatively evaluated using GIS by comparing cases with and without informal water supply points. Analysis revealed that informal water supply points expanded the size of the serviced population within a 500-m radius of the water supply points by 47%, compared with cases when only formal water supply points were available. However, well water was not necessarily suitable for drinking owing to quality issues. As a policy lesson, the importance of sharing well information is indicated.

Key words: Disaster, Earthquake, Emergency, Governance, Groundwater, Water supply

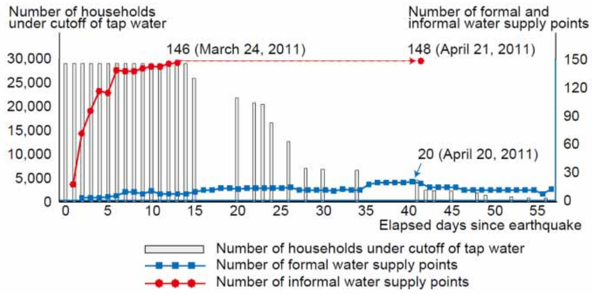
HIGHLIGHTS

- In emergency, informal water supply points (IWSPs) using private wells are superior to public ones in terms of service area and speed of availability.
- In this case study, IWSPs expanded the size of the serviced population within a 500-m radius of water supply points by 47%.
- Groundwater cannot always be potable owing to quality problems.
- Information sharing on IWSPs could encourage the appearance of additional water providers.

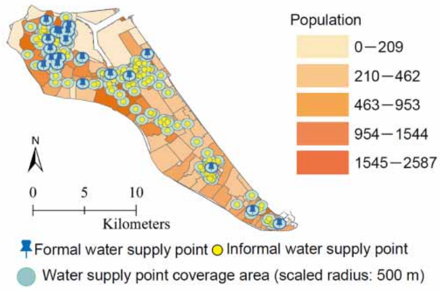
GRAPHICAL ABSTRACT

How informal water supply points using private wells worked in an emergency: a quantitative evaluation

Informal water supply points based on local wells are superior to formal water supply points operated by public institutions in terms of speed of availability.



Informal water supply points dispersed widely represent an efficient alternative source of water in areas poorly served by formal water supply points.



Quantitative evaluation of emergency water supply in cases with and without informal water supply points

	The size of the serviced population within a 500-m radius of the water supply points	Percentage of Kamisu City population
Case 1 (20 formal water supply points)	35,886	39%
Case 2 (20 formal water supply points + 148 informal water supply points)	79,500	86%

1. INTRODUCTION

Groundwater plays a major role in the provision of a safe and sustainable water supply for many cities, but its importance has received less attention than that of surface water (Howard, 2015). One of the reasons for this oversight is that groundwater represents a hidden component of the water cycle. Especially in urban areas, infrastructure such as roads and buildings often cover springs and groundwater-fed streams, thereby making the true value of groundwater difficult to realize (La Vigna, 2022). Earthquakes provide an opportunity to reaffirm the value of groundwater in urban areas.

This paper aims to clarify how informal water supply points, managed by local well owners, supplemented formal water supply points operated by public organizations during water outage periods following an earthquake. It also seeks to support the formulation of policies regarding the utilization of groundwater as a means of emergency water supply, drawing from the experience of Kamisu City (Ibaraki Prefecture, Japan), an area affected by the Great East Japan Earthquake of 2011. Here, 'water supply point' refers to locations and facilities where water is distributed to disaster victims. Formal water supply points indicate locations where water was distributed via water trucks owned by local governments, typically set up at public facilities such as city offices and schools.

Informal water supply points denote places where water was provided through privately owned wells, with detached houses and local restaurants being typical examples.

During the early growth of an urban area, local resources are usually developed to meet the demand for water by residents. If the local water resources become insufficient due to population growth, one solution is to seek alternative water sources further away (Giordano, 2009; Porse *et al.*, 2016). For this reason, an urban water supply often depends on long-distance networks for the transport of water from remote areas (Larsen *et al.*, 2016). However, long-distance water transport networks can be vulnerable to the effects of earthquakes, which can cause supply disruption depending on their magnitude. Groundwater, which is often located directly beneath an area with demand, can have the characteristics of stable quality and large storage capacity. For this reason, groundwater is often considered an alternative water resource during periods of natural disasters such as droughts and earthquakes (Shivakoti *et al.*, 2019).

The Intergovernmental Hydrological Program of UNESCO, through its Groundwater for Emergency Situations project, investigated methods of groundwater exploration that could be used during extreme natural disasters, including earthquakes (Vrba & Verhagen, 2011). Previous studies have assumed that groundwater could serve as an important source of emergency water supply following floods (Michalko *et al.*, 2013; Davis *et al.*, 2020) and wildfires (Robinne *et al.*, 2021; Robichaud & Padowski, 2023). In addition, simulation studies of groundwater use for post-disaster emergency water supply have been conducted (Brink *et al.*, 2012; Balaei *et al.*, 2018), and certain large cities on the Ring of Fire (e.g., Tokyo and Los Angeles) have considered the use of groundwater in their disaster prevention plans, given the potential risk of water supply disruption attributable to earthquake occurrence (Kataoka & Shivakoti, 2013; City of Los Angeles, 2014). However, all of the above studies and policies assume future disaster risk and are not based on examples of actual earthquake disasters.

Earlier studies reported on actual groundwater use by the victims of earthquakes, but most research on this topic is fragmentary (Chadha *et al.*, 2006; Keshari *et al.*, 2006; Villholth, 2007; Tanaka, 2016). Specifically, because of their wide distribution, the use of private wells is expected to be effective as a means of complementing public water supply support activities. A case study, based on questionnaire surveys, reported that at least 55 private wells had been deployed to meet domestic needs in areas without formal water supply points following Japan's Kumamoto earthquake of 2016 (Endo *et al.*, 2022). In addition, another study, based on field surveys, showed an increase in the groundwater dependence ratio to meet drinking water needs following Indonesia's Lombok earthquake of 2018 (Hidayat *et al.*, 2020). However, apart from these exceptions, surprisingly few studies have quantitatively evaluated the usefulness of private wells as an emergency water supply.

Reasons for the lack of research are that earthquake disasters are sudden and it is difficult to save data concerning the use of private wells. Earthquakes are difficult to predict, and their occurrence often causes damage to water infrastructure and loss of government functions. In such chaotic situations, records of formal water supply points, operated by public organizations, might be kept, but details of informal water supply points operated by private well owners scattered throughout an affected area are rarely documented. For example, the Christchurch earthquake of 2011 in New Zealand, Kumamoto earthquake of 2016 in Japan, and Northridge earthquake of 1994 in the United States all caused water outages, and although specifics of the emergency water supply provided by the relevant governments have been reported (McReynolds & Simmons, 1995; Giovinazzi *et al.*, 2011; Nojima & Maruyama, 2016), details of whether and how private wells might have been used for a supplementary water supply have not been mentioned at all. One study has highlighted that the scale of disaster response by public institutions tends to be overestimated because the details are generally well documented, but that the mutual assistance of disaster victims tends to be underestimated because the specifics are not recorded (Fritz & Mathewson, 1957). This circumstance is directly applicable to the case of emergency water supply.

The purposes of this research are to clarify the effectiveness and shortcomings of emergency water supply based on private wells and to support the formulation of policy regarding the use of groundwater in the event of a disaster based on the experience of Kamisu City, Ibaraki Prefecture, Japan. If the effectiveness of water supply activities using private wells can be demonstrated, which has rarely been studied previously, it could lead to expansion of available policy options for emergency water supply.

The remainder of this paper is structured as follows. Section 2 describes the methods used to obtain water supply point data for Kamisu City following the occurrence of the Great East Japan Earthquake. Section 3 presents the results, and Section 4 discusses the findings and policy recommendations. The conclusions are presented in Section 5.

2. METHODS

2.1. Study area

The Great East Japan Earthquake, which occurred with its seismic center located at the point 38°06.2′N, 142°51.6′E in the Pacific Ocean on March 11, 2011, caused enormous damage throughout eastern Japan (Japan Meteorological Agency, 2012) (Figure 1).

One major consequence was the water supply outage attributable to the destruction of water supply infrastructure. According to the Ministry of Health, Labour, and Welfare, Japan (2013), 2.946 million households had their water supply disrupted because of the earthquake (including the number of households whose water supply was cut again at the time of the largest aftershock in early April). In terms of prefectures, the Ibaraki Prefecture suffered the most damage. The maximum number of households without water supply reached 801,000 (Ministry of Health, Labour and Welfare, Japan, 2013). Among the municipalities in the prefecture, the damage to Kamisu City was especially severe. It was the only city within the prefecture where the water supply was entirely cut off, and it is where it took the longest time (57 days) for the water outage to be completely resolved. The problem was not only the damage caused to the water purification plant that supplies water to the city but also the severe disruption to the network of distribution pipes due to liquefaction (Kamisu City, 2021).

2.2. Methods for reconstruction of water provision by formal and informal water supply points

2.2.1. Local newspaper and Internet archives

In Kamisu City, two types of emergency water supply were operated following the earthquake until the tap water supply was restored. One was the establishment of formal water supply points by public institutions such as Kamisu City government, support municipalities, and Japan's Self-Defense Forces (Japanese military organizations), where drinking water was provided using water trucks. Usually, when a large-scale disaster occurs in Japan, information on formal water supply points is publicized in local newspapers. Therefore, in this study, information on the establishment of formal water supply points were collected by investigating back issues of the Ibaraki Shimbun, a local newspaper in the Ibaraki Prefecture.

The second type of emergency water supply comprised informal water supply points established and operated by citizens who owned wells. The Kamisu City government obtained the information on the availability of wells via application from well owners and publicized the information to the population via the city's email magazines

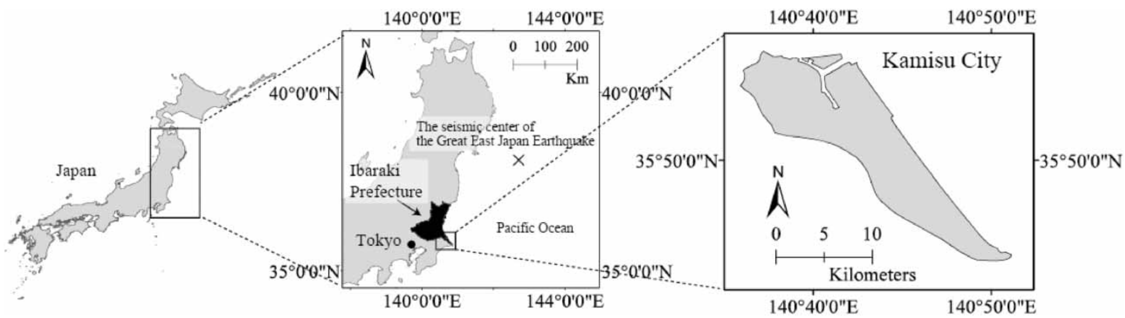


Fig. 1 | Locations of the seismic center of the Great East Japan Earthquake and the study area.

and disaster prevention radio (Kasumi City Disaster Prevention and Safety Section, Personal Communication, 2022). This study collected information on informal water supply points by searching back issues of the city's email magazines.

Since the occurrence of the earthquake, the city's email magazine has been updated frequently throughout the day. Especially immediately after the disaster, the number of updates was high, with eight updates on March 12, the day after the earthquake, and 23 updates on March 13. The disseminated information covers a wide range of topics including tsunami warnings, fire alerts, and notices of school closures, but the most frequent updates concern water supply. The information on informal water supply points included the names and addresses of owners of local wells that could supply water, which were collected for use in this study.

An Internet archive (Wayback Machine) was used to examine the email magazines from March 11, 2011 (the date of the earthquake disaster) to May 7, 2011 (the date when water outage was resolved within the city). Information on informal water supply points was posted in the magazine during March 12–24. Additional information on informal water supply points was obtained using another Internet archive called WARP (Web Archiving Project), which was created by the Japanese National Diet Library.

2.2.2. Questionnaire survey to informal water provider

A questionnaire survey, conducted to clarify the functions of the informal water supply points, was sent to 151 well owners whose postal addresses were listed in the email magazine of Kamisu City. Respondents were requested to answer the questions online or on paper between June 19 and 30, 2023. The rate of response to the questionnaire was 37.1%, i.e., 56 out of the 151 well owners responded.

The survey comprised 12 questions that were categorized into five topics: (1) location of well that was used to provide water, (2) number of well users in normal times, (3) purposes for utilizing the well before the Great Eastern Japan Earthquake, (4) well water provision after the Great Eastern Japan Earthquake, and (5) pumping capacity of the well. This study focused specifically on the responses to topics of category (4).

2.2.3. Method of functional evaluation of formal and informal water supply points

Ideally, it would be desirable to conduct a functional evaluation based on the amount of water supply, using the delivery capacity of the water trucks installed at the formal water supply points and the pumping volume data of the informal water supply points. However, as described later, many of the informal water supply points were small-scale wells of private homes, making the exact amount of pumping impossible to calculate because the pumping capacity and operating hours of each well are unknown. (Although I asked about the pumping capacity of wells used as informal water supply points in the aforementioned questionnaire, I was unable to get valid answers for quantitative evaluation.) Therefore, this study conducts a functional evaluation focusing on population covered by the water supply points as shown in Figure 2.

The population mesh data comprised the 2010 simple 100-m mesh population data available at the following site: https://gtfs-gis.jp/teikyo/. This has been developed by Akira Nishizawa, a specially appointed professor at the University of Tokyo's Center for Spatial Information Science. These data are based on the 250-m population mesh data released by the Japanese government, recalculated on a 100-m mesh unit basis. Due to the finer grid within each mesh, more accurate population calculations are possible. In this study, these data were applied to calculate the population within a radius of 500 m from water supply points. The Great East Japan Earthquake occurred in 2011, and the 2010 population mesh data are considered a reasonable reflection of the population at the time of the occurrence of the earthquake.

Case 1 was assumed as a situation in which only formal water supply points were used. The number of formal water supply points deployed varied daily; therefore, this study focused on the situation on April 20, 2011, when

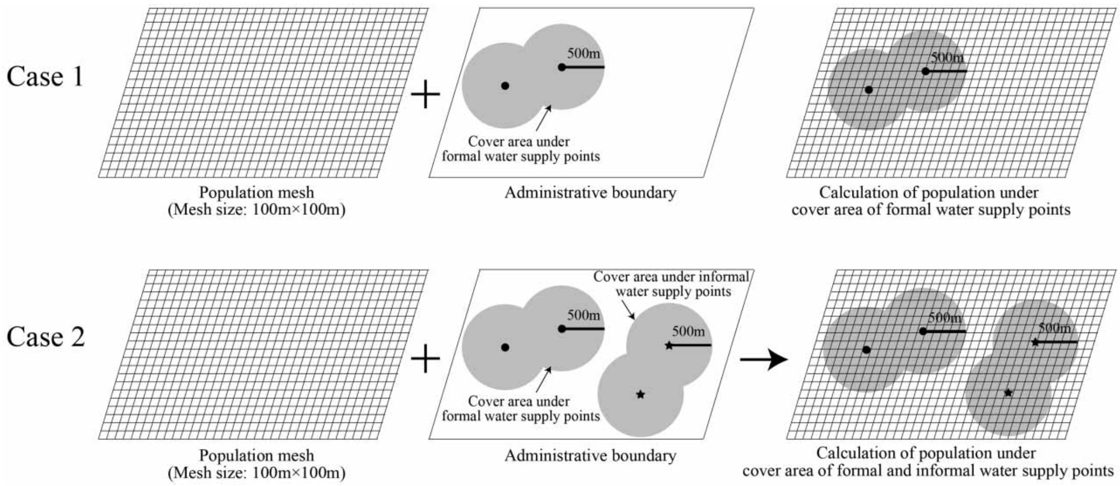


Fig. 2 | Evaluation method on the function of water supply points.

the largest number of formal water supply points was deployed during the period of water supply outage (20 points), as will be mentioned later. An area within a radius of 500 m from a water supply point was defined as the water supply point coverage area. Then, the water supply point coverage area and the above population mesh data were superimposed to calculate the size of the population included in the coverage area.

The radius of 500 m was based on the water access conditions in the Sphere Standards established by a group of nongovernmental organizations, the Red Cross, and the Red Crescent Movement. The Sphere Standard proposes a set of universal minimum standards in core areas of humanitarian response in situations of disaster and conflict. In terms of water supply, it indicates that the distance from any household to the nearest point of water supply should be <500 m (Sphere Association, 2018).

Next, as Case 2, the distribution of informal water supply points was added to that of the 20 formal water supply points mentioned above. For this, the situation on April 21, 2011, was considered when 148 informal water supply points were in operation, as will be shown later. The reason for choosing this date was that it is only one day different from April 20, when the peak number of formal water supply points was deployed, and thus it is considered to reflect the distribution of wells as of April 20. In this case, the coverage area (radius 500 m) of the formal water supply points operated by the government and that of the informal water supply points of private well owners were overlain on the population mesh data, and the size of the population included within the combined area was calculated. Finally, by comparing the size of the population within the water supply point coverage area in Case 1 and Case 2, the function of the informal water supply points could be evaluated quantitatively.

3. RESULTS

3.1. Process of emergency water supply

Figure 3 shows the changes in the numbers of both households under cutoff of tap water and emergency water supply points in Kamisu City following the occurrence of the Great East Japan Earthquake. After the earthquake, 28,931 households throughout the city lost their water supply, and this situation continued for approximately 2 weeks, i.e., the restoration of tap water did not proceed well. Subsequently, the restoration works gradually

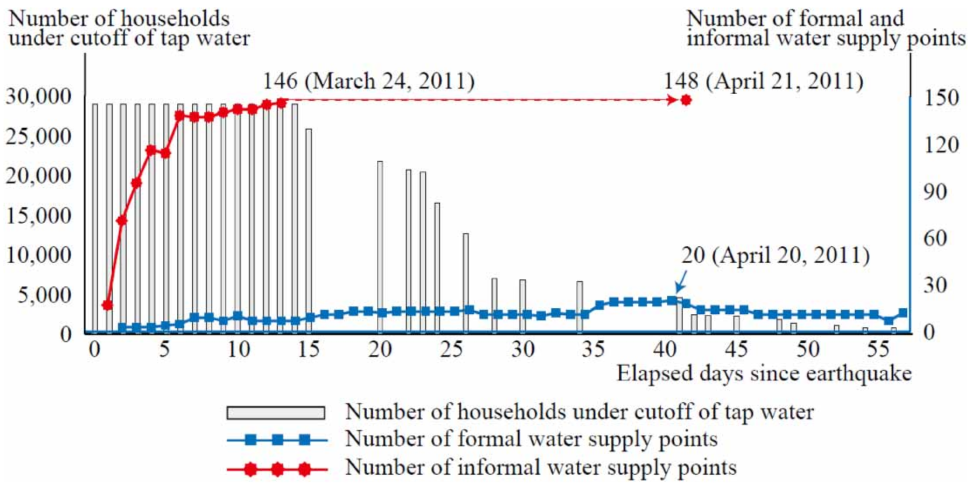


Fig. 3 | Changes in the numbers of both households under cutoff of tap water and emergency water supply points in Kamisu City following the occurrence of the Great East Japan Earthquake.

progressed; however, it took 57 days (March 11, 2011 to May 7, 2011) for the restoration efforts to cover the entire city (Kamisu City Waterworks Division, 2011).

Kamisu City government, support municipalities, and the Self-Defense Forces opened formal water supply points to meet the water demand of the population during the period of water outage. According to articles in the local newspaper (Ibaraki Shimbun), the number of formal water supply points deployed was not large. The Great East Japan Earthquake was a huge disaster and the water supply of many neighboring municipalities was also cut off at the same time. Therefore, Kamisu City had difficulty gaining assistance from adjacent municipalities in terms of emergency water supply. Up to 20 formal water supply points were in operation 40 days after the earthquake (April 20, 2011).

It should be noted that the changes in 'the number of households under cutoff of tap water' in Figure 3 are underestimated. In Kamisu City, resolving a water outage involves two steps: (1) the restoration of the main water pipelines and (2) the repair of the branch water lines to each household (Kamisu City Assembly, 2013). Therefore, the population experiencing a water outage is equal to those for whom stage (2) has not yet been completed. However, unlike stage (1), which is conducted as part of public works, stage (2) is the responsibility of each homeowner, making it impossible to obtain transition data. Consequently, the change in 'the number of households under cutoff of tap water' in Figure 3 reflects only the progress of the initial restoration process and does not include the number of people who expected the completion of stage (2).

This also helps us understand why formal water supply points remained operational even after the number of households that lost water supply decreased. Completing stage (1) did not guarantee that all households could use tap water again because there might be damage to the water pipes buried within each premise. Formal water supply points remained operational to address this situation. A similar scenario was reported in connection with the extensive water outage following the Kumamoto earthquake of 2016 in Japan (Endo *et al.*, 2022).

Following the occurrence of the earthquake, the informal water supply points supplemented the formal water supply points. According to information on Internet archives (Wayback Machine and WARP), 17 wells were open on the day after the earthquake (March 12, 2011), 146 wells were available 13 days later (March 24, 2011), and 148 wells were open 41 days after the earthquake (April 21, 2011). Data for part of this period are lacking, but many of the wells that were open on March 24 were likely to have continued to be used thereafter. This is suggested because most of the 146 wells listed as available on March 24 also appeared as available on the list issued on April 21. After the water supply was restored, Kamisu City made a list of the providers of private well water and thanked them on its website. Based on that list, a total of 164 wells were determined to have been used during the water outage period (Kamisu City Disaster Prevention Division, 2013).

3.2. Use of groundwater after the earthquake

A question was posed to well owners to ascertain the primary purpose for which the water was used (questionnaire category 4: Well water provision after the Great Eastern Japan Earthquake). The result shows that groundwater was provided not only for domestic purposes but also for drinking (Table 1). This suggests that local people did not always prefer water supplied from a formal water supply point to that provided by an informal water supply point, even when the water was used for drinking. This reflects the fact that some wells were used as a source of drinking water prior to the occurrence of the earthquake. On this point, the mayor told the city council after the earthquake: 'We are deeply aware of the need for groundwater because we received cooperation from over 100 wells that were normally used for drinking purposes as water supply points' (Kamisu City Assembly, 2011).

3.3. Well owners

Figure 4 shows the details of the owners of the wells used as informal water supply points on April 21. The largest proportion of informal water supply points (51%) consisted of wells of private homes, followed in descending order by wells of businesses, local restaurants, temples, and welfare facilities. The category 'Others' represents the remaining portion and comprised wells of barber shops, chiropractic clinics, cram schools, flower shops, inns, and laundromats. Many of the local restaurants, such as soba restaurants and Chinese restaurants, are privately run, and there are many cases where residences and shops are integrated, which is the same for barber shops and inns. Therefore, among the available open wells, it is highly probable that the percentage of wells of private homes was even higher.

Table 1 | Assumed purposes of groundwater provision.

Answer choices	Responses	
1. Drinking purposes (including cooking purposes)	10.7%	6
2. Domestic purposes (toilet, laundry, and bathing)	19.6%	11
3. Miscellaneous purposes (other domestic purposes such as cleaning and plant watering)	3.6%	2
4. Drinking and domestic purposes	21.4%	12
5. Domestic and miscellaneous purposes	16.1%	9
6. Drinking and miscellaneous purposes	0.0%	0
7. Drinking, domestic, and miscellaneous purposes	25.0%	14
8. Others	3.6%	2
	Answered	**56**
	Skipped	**0**

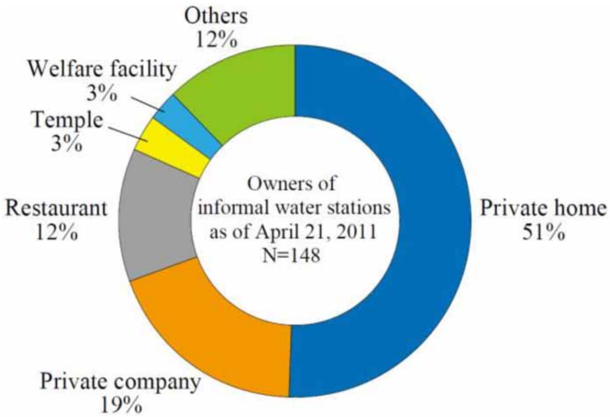


Fig. 4 | Owners of informal water supply points.

3.4. Functional evaluation of formal and informal water supply points

Figure 5 shows the distribution of formal water supply points (blue pin marks) as of April 20, 40 days after the occurrence of the earthquake, and the distribution of informal water supply points (yellow circles) as of April 21. The background shading represents the population size based on the national population census data of 2015. As mentioned earlier, the number of formal water supply points on this day (20 points) was the highest during the period of water outage. The light blue circle around each water supply point indicates the coverage area (scaled radius: 500 m) of the water supply point.

The results of the calculation of the population size within the water supply point coverage area for Case 1 and Case 2 are as follows. With only 20 formal water supply points deployed (Case 1), the population within the water supply point coverage area was 35,886, equivalent to 39% of the total population of Kamisu City (92,000) in the year of the earthquake (Kamisu City, 2022). With 148 informal water supply points available, in addition to the formal water supply points (Case 2), the population within the water supply point coverage area was 79,500, corresponding to 86% of the total population.

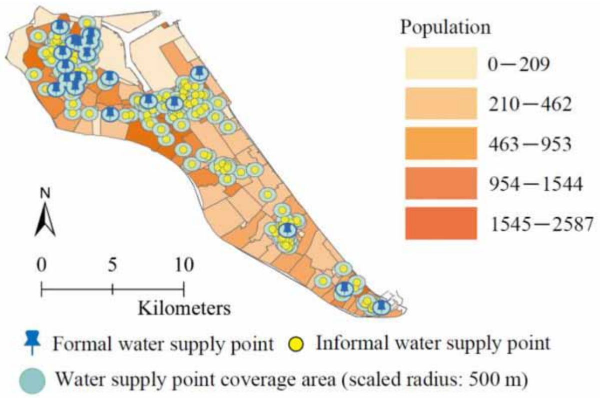


Fig. 5 | Spatial distributions of formal and informal water supply points as of April 20 and 21, 2011.

4. DISCUSSION

4.1. Rapid water supply

Figure 3 shows that the availability of informal water supply points using local wells is superior to that of formal water supply points in terms of speed. The number of available informal water supply points did not increase gradually during the 57-day water outage period; instead, it increased rapidly immediately after the occurrence of the earthquake. The pace of development in the first week after the earthquake was particularly remarkable, with 137 wells open during that period. In total, 164 informal water supply points were opened throughout the period of water supply outage; thus, 84% of the total number of informal water supply points were opened during this initial period.

A question was asked regarding the main reason for providing well water to the outside (questionnaire category 4: Well water provision after the Great Eastern Japan Earthquake). Of 56 responses, 42 (75.0%) selected: (3) Well water was provided voluntarily without waiting for a request from others (Table 2).

This could be interpreted as an example of altruistic community, whereby survivors secure their own safety and regain their composure, and when a sense of solidarity increases among the survivors, leading to mutual altruistic assistance (Fritz, 1961; Barton, 1969).

The immediate aftermath of a disaster is the most critical stage, and information on water supply point availability is of crucial importance. However, previous studies reporting on groundwater use in disaster areas have generally not addressed this topic (Villholth, 2007; Tanaka, 2016). In general, even if local wells were used during a water outage period following the occurrence of an earthquake, it is extremely unlikely that details of the start date would be recorded. In the case of Kamisu City, such information was published in the city's official email magazine, providing valuable data for analysis of the trends on a daily basis.

As mentioned earlier, some private wells were used to supply drinking water before the occurrence of the earthquake. Thus, these wells were assumed to include those pumped by electric pumps from a certain depth rather than hand-operated wells. Obviously, such wells cannot operate without electricity; however, fortunately, in the case of Kamisu City, electric power was restored reasonably quickly. According to material from the Disaster Countermeasures Headquarters of Ibaraki Prefecture, electric power was recovered by 16:00 local time on March 14 (3 days after the occurrence of the earthquake) at the latest (Disaster Countermeasures Headquarters of Ibaraki Prefecture, 2011).

4.2. Expansion of the population within water supply point coverage area

When only formal water supply points (20 locations) were deployed (Case 1), the population within the water supply point coverage areas was 35,886 (39% of the total population at that time). When informal water

Table 2 | Main reason for providing well water to the outside.

Answer choices	Responses	
1. Well water was provided at the request of the city	8.9%	5
2. Well water was provided at the request of citizens	5.4%	3
3. Well water was provided voluntarily without waiting for a request from others	75.0%	42
4. I do not remember	5.4%	3
5. Others	5.4%	3
	Answered	**56**
	Skipped	**0**

supply points using private wells (148 locations) were considered, in addition to the formal water supply points (Case 2), the population within the water supply point coverage areas expanded to 79,500 (86% of the total population). Thus, informal water supply points played a role in increasing the size of the population within the water supply point coverage areas by 47%.

One of the reasons for the marked increase in the size of the population covered by water supply points is that many of the wells of informal water supply points were in private homes (Figure 4). If the wells that became informal water supply points were mainly factory wells, then their distribution would have been concentrated in specific areas such as industrial areas. In that case, the degree of dispersion would have been reduced, and it is highly likely that the size of the population covered by the water supply points would not have increased substantially.

This indicates that the use of private wells is very effective as a means of supplementing the emergency water supply provided by public organizations because of their wide distribution. In the case of Kamisu City, the wells of individual private homes are distributed over a wide area; thus, they represent an efficient alternative source of water in areas poorly served by formal water supply points.

4.3. Problem of groundwater pollution

Eight years before the occurrence of the Great East Japan Earthquake, people in some areas of Kamisu City experienced health problems associated with drinking arsenic-contaminated well water (Hiyama *et al.*, 2017). Subsequently, the Kamisu City government designated an area in which residents were asked to refrain from drinking groundwater, although this request was not mandatory. This request was still in effect at the time of the earthquake. After the earthquake, some of the wells offered as informal water supply points were located within this designated area. Following the occurrence of the earthquake, the city government publicized information about well availability in the email magazine; however, within a week, the content was revised and wells in the designated area were removed from the list of available informal water supply points.

Figure 6 shows the extent of the designated area (area enclosed by the red frame) and the locations of the suspended wells (red circle with a cross). The background map is the population distribution of Kamisu City (2015 census), where blue pins show the distribution of formal water supply points on April 20, and yellow circles show the distribution of informal water supply points on April 21.

As mentioned above, 20 formal water supply points were open on April 20, 2011. Figure 6 shows that five of the 20 points (25% of the total) were located in close proximity within the designated area. This is thought to reflect the relatively large population of the area and the limitation on the use of groundwater. However, Figure 6 also shows that some informal water supply points (yellow marks) were open even within the designated area. Why use of all the wells in the designated area was not discontinued remains unclear, but the water that they supplied was possibly used for domestic purposes other than drinking.

This suggests that the use of private wells following the occurrence of a disaster has advantages over the provision of formal water supply points in terms of speed and expansion of supply areas, but that it is not necessarily a panacea in terms of water quality. To prevent secondary damage attributable to the use of contaminated groundwater, a disaster prevention plan should specify exactly how groundwater should be used, based on pollution monitoring during normal times.

4.4. Policy lessons for practitioners

In Kamisu City, emergency water supply was partially provided by ordinary well-owning citizens who were not usually involved in such activities. Preregistration of wells can be considered one way to promote such cooperation between public agencies and volunteers. This is a system in which wells that can be used for mutual assistance are selected in advance before a disaster occurs, and where the well owners provide

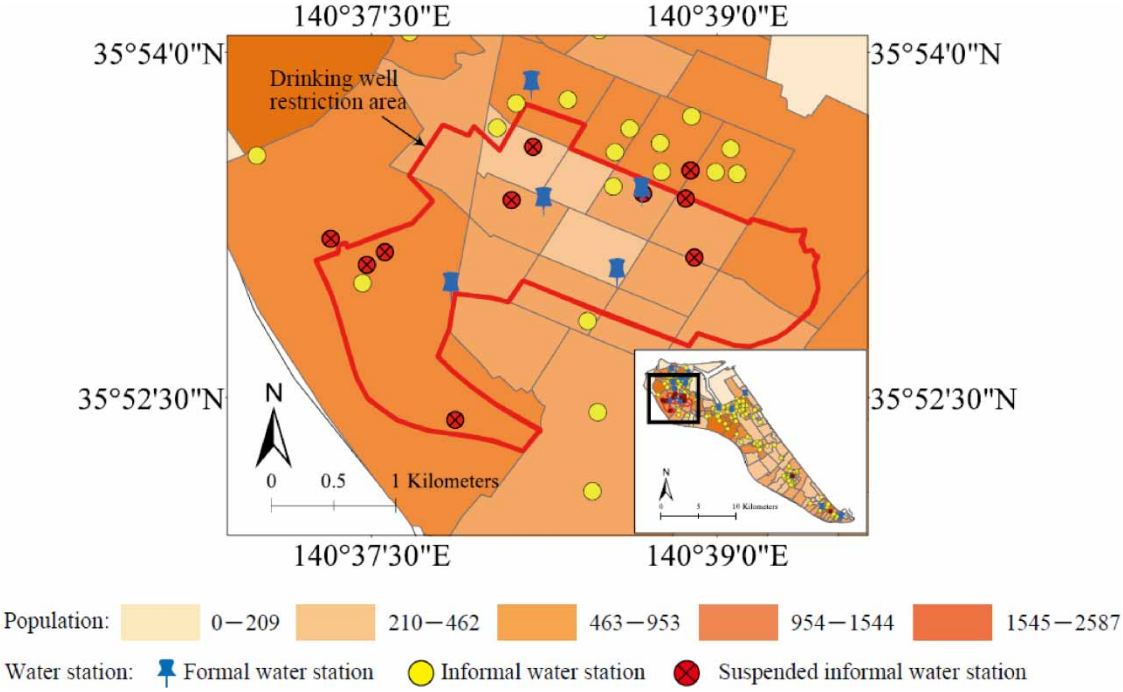


Fig. 6 | Extent of the drinking well restriction area and the locations of the suspended informal water supply points.

groundwater should a disaster strike. However, the case of Kamisu City suggests that while preregistration is valuable, it is even more important to prepare an information-sharing system. This is because it is not known which of the preregistered wells will actually be open following the occurrence of a disaster, and because the possibility exists that unregistered wells might also be made available.

What is unique in the case of Kamisu City was that the government quickly established such an information-sharing system. In Kamisu City, information on informal water supply points was publicized through the city's email magazines and disaster prevention radio. There are a few cases where groundwater was used following earthquakes in Japan (Endo *et al.*, 2022, 2023). However, it was not reported that local governments had played active roles in transmitting information about available wells. This implies that local governments are not always ready to be an information hub, and it is necessary to prepare a plan for this function in advance.

Although information sharing was carried out for the benefit of the victims, it also served the additional purpose of encouraging other owners of potential informal water supply points to make themselves known. For example, one respondent to the questionnaire survey reported that he had been inspired by information on the disaster prevention radio that there were people distributing well water. Then, he started to provide groundwater and asked the city government to publicize the location.

In Kamisu City, information on informal water supply points were updated seven times in the March 12 (the day after the earthquake) email magazine and five times in the March 13 email magazine, and new well information was added each time. This suggests that new offers of the use of well water in Kamisu City might have been stimulated by the dissemination of information by the city government.

Volunteer activities in Kamisu City did not stop at the opening of wells. For example, a citizen created a web-based map of informal water supply points by using the postal address listed in the city's email magazines. The map was accessed more than 20,000 times during the water outage period (Kamisu City Disaster Prevention Division, 2013). Such activity is generally called digital volunteerism (Whittaker *et al.*, 2015).

The email magazine issued by the city government and disaster prevention radio are not the only tools for information sharing. Information can also be shared via social media platforms such as X (Twitter), potentially providing details about local wells that city government officials might be unaware of. Consequently, digital volunteers could be in prime position to aggregate and disseminate this wide range of information.

5. CONCLUSIONS

The objectives of this research were to clarify the effectiveness and shortcomings of emergency water supply using private wells and to support policy development regarding the use of groundwater in the event of a disaster, using Kamisu City as a case study.

The advantages of using private wells as informal water supply points are as follows. First, they are superior in terms of speed of availability in comparison with that of formal water supply points. Second, local wells tend to be widely dispersed and thus represent an efficient alternative source of water in areas poorly served by formal water supply points. However, the use of private wells in an emergency is not a perfect solution when the issue of water quality is considered.

As a policy lesson regarding the use of private wells in an emergency, the importance of sharing well information was highlighted. Information sharing not only improved the convenience of accessibility to a water supply for the disaster victims but also might have led to the discovery of additional potential informal water supply points. They also resulted in the emergence of digital volunteers, who created web-based maps of the distribution of wells to support local people.

This study examined the effectiveness and shortcomings of the use of private wells as an emergency water supply in Kamisu City. In future, detailed fact-finding surveys on other such cases should be conducted and compared with the findings of this study.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository: https://drive.google.com/file/d/1-_UyLnVn7grnlvOeI6-cH8U9sANUAbBls/view?usp¼sharing

CONFLICT OF INTEREST

The authors declare there is no conflict.

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