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PAPER

Governance of disaster emergency wells in three cities in Japan affected by earthquakes

Takahiro Endo[1] · Tomoki Iizuka[2] · Hitomi Koga[3] · Nahoko Hamada[3]

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Abstract
Concern has grown regarding how public and private sectors should make effective use of local groundwater to alleviate negative impacts of water-supply cutoff following an earthquake event, which can be regarded as an emergency groundwater governance problem. Existing literature on groundwater governance, however, is based on the tacit assumption of groundwater utilization under normal social conditions, and scant consideration has been given to the role of groundwater following occurrence of a natural disaster. This study conducted questionnaire surveys to reveal how groundwater was used in three cities (Kumamoto, Sapporo, and Sendai) in Japan struck by large earthquakes between 2010 and 2020. Results revealed substantial differences between these cities in terms of groundwater utilization following earthquake occurrence. The time between the restoration of the electricity supply and restoration of the waterworks, and the social capital accumulated by local governments, are indicated as possible reasons for such differences. Analysis also identified policy challenges for improved groundwater governance in an emergency: (1) establishment of a strategy for emergency water supply through combined use of groundwater and other water sources, (2) enhancement of methods for timely inspection of groundwater quality following occurrence of a disaster, (3) maintenance of records of the number of registered disaster emergency wells (DEWs), (4) creation of methods for publicizing locational information on DEWs with adequate regard for the privacy of well owners, and (5) recognition of the importance of making DEWs part of overall disaster preparedness.

Keywords Earthquakes · Emergency · Socio-economic aspects · Water supply · Japan

Introduction

Public sector reforms in industrialized countries during the 1980s prompted studies on governance. The main focus of such work was the reconsideration of the role of central government, extending from the outsourcing of its functions regarding civil society to market-led organizations on the one hand, and to decentralization of various authorities to lower-level government on the other (Chandhoke 2003; Bevir 2009).

✉ Takahiro Endo
endo@omu.ac.jp

[1] College of Sustainable System Sciences, Osaka Metropolitan University, 1-1 Gakuen-cho, Nakaku Sakai, Osaka 599-8531, Japan

[2] Faculty of Contemporary Policy Studies, Josai University, 1-1 Keyaki-dai, Sakado, Saitama 350-0295, Japan

[3] Kumamoto Ground Water Foundation, 8-16 Ansei-cho, Chuoku Kumamoto, Kumamoto 860-0801, Japan

This perspective spread to the field of groundwater-related issues and studies on groundwater governance commenced in the late 2000s (Villholth and Conti 2018). Although the definition of "groundwater governance" has been expressed in many ways (Megdal et al. 2015; FAO 2016; Villholth and Conti 2018; Closas and Villholth 2020), it broadly means the processes of reaching a solution to groundwater issues in three respects: involvement of various stakeholders, collaboration between different levels of government, and utilization of combined policy instruments (Mukherji and Shah 2005). Instead of a top-down approach by central government, this concept emphasizes the collaboration of various stakeholders that range from groundwater users, citizens, private firms, nongovernmental organizations, and local government. Moreover, it pays attention to various policy instruments that include direct governmental control, economic incentives, and voluntary contributions by groundwater users.

A large-scale international project named the "Groundwater Governance Project" was undertaken by international

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organizations such as the Food and Agricultural Organization (FAO), World Bank, and Global Environmental Fund in the mid-2010s. This foundational project proposed actors, laws and institutions, policy planning, and scientific information as the four main components of groundwater governance (FAO 2016). Subsequently, many case studies conducted in various parts of the world reported that collaboration between the public and private sectors was useful for effective use of groundwater resources (Varady et al. 2016; Lubellet al. 2020; Milman and Kiparsky 2020). However, despite associated improvements in groundwater governance, the problem of groundwater governance following a natural disaster has been neglected.

How best to secure water supply following the occurrence of an earthquake is often a major social problem, especially in urban areas. Generally, urban water supply depends on long-distance transportation networks that deliver water from outside the urban area (Larsen et al. 2016). However, such networks are vulnerable because they are often not resistant to earthquakes. In many areas, local groundwater, which has characteristics of ubiquitous availability, ease of access, vast storage potential, and reliable supply and quality, could represent a viable substitute (Shivakoti et al. 2019). Los Angeles (USA), for example, which is a huge urban area located in one of the most geologically active regions of the planet that is often called the "Ring of Fire" (Rinard Hinga 2015), has a plan to use local water resources such as groundwater and recycled water in an emergency under the assumption that its long-distance aqueducts would be out of commission following a large earthquake event (City of Los Angeles 2014).

As another example, a stable water supply after a disaster, especially an earthquake, continues to be a serious social problem in Japan, which is also located in the Ring of Fire. Although the country covers only a small portion of the global land area, Japan and the surrounding regions experience approximately one-tenth of all earthquakes that occur worldwide (Cabinet Office, Government of Japan 2021).

The primary problem with groundwater in Japan after the Second World War used to be land subsidence due to excessive pumping of groundwater for industrial purposes in urban areas. National and local governments responded to this challenge mainly through construction of industrial waterworks based on surface water, and direct regulation with technical standards of well diameter and depth (Endo 2015). Consequently, groundwater use became so severely limited, owing to such command-and-control type regulation, that it has become a forgotten resource in certain locations.

However, the 1995 Great Hanshin-Awaji Earthquake, which deprived highly urbanized Kobe and its surrounding cities of tap water, marked a turning point. Following this event, many local governments began to pay attention to existing wells maintained by individual households and business entities for emergency uses. These wells are often called disaster emergency wells (DEWs). Currently, at least 75.6% of all municipalities in Japan (1,316 out of 1,741 municipalities) have plans to use groundwater in an emergency (Endo 2021a; Kataoka and Shivakoti 2013).

This gives groundwater a new role as a disaster prevention resource rather than as an industrial resource. In recognition of this point, in the most recent Basic Plan for the Water Cycle issued in 2022, the Japanese central government has recommended that local governments take into consideration the use of groundwater in the event of a large-scale disaster. Accordingly, groundwater management systems that differ from conventional systems are emerging in various places. Because DEWs cannot always be promoted through top-down direct regulation, collaboration is vital between local governments and groundwater users, i.e., groundwater governance in an emergency.

However, previous groundwater governance studies generally addressed groundwater utilization under normal social conditions, and few studies with the rare exception of Vrba and Verhagen (2006) and Vrba (2016) have considered groundwater governance in an emergency situation. Moreover, earlier research on water supply in an emergency mainly involved simulation studies to predict the effects of water-supply cutoff (Brink et al. 2012; Balaei et al. 2018; Davis et al. 2020), while actual use of local groundwater following the occurrence of an earthquake has rarely been investigated. Keshari et al. (2006), Villholth (2007), Sukhija and Rao (2011), and Tanaka (2016) all reported on groundwater utilization following earthquake events, but the information provided was fragmentary. Some studies in the field of public health have considered groundwater use in an emergency (Gupta et al. 2007; McCann et al. 2011). However, their main concern was health risk evaluation and not the investigation of measures to promote public–private collaboration for effective use of local groundwater in emergency situations.

The role of groundwater in drought situations has been discussed previously (Alley et al. 2016; Jasechko and Perrone 2020), but similar research focusing on earthquake events remains lacking. The reason might reflect that drought is a natural disaster with slow onset, which means that it is possible to manage water shortages where a local government and water-related infrastructure operate normally. In this condition, it is relatively easy for the government to maintain a record of countermeasures. Conversely, earthquakes occur with little or no warning and sometimes impose severe limitations on the function of government and water-related infrastructure. Moreover, groundwater tends to be supplied from privately owned wells in the chaotic period that ensues immediately after the occurrence of an earthquake; thus, it is very difficult to maintain adequate records of groundwater use under such conditions. This lack of information has prevented studies on the role of groundwater at the time of an earthquake event.

Using a questionnaire-based survey, the objectives of this study were to reveal how groundwater was used in three cities in Japan that recently experienced major earthquakes, and to draw policy lessons regarding groundwater utilization in emergency situations. The study areas were the cities of Kumamoto (Kumamoto Prefecture), Sapporo (Hokkaido), and Sendai (Miyagi Prefecture), which were struck by the Kumamoto Earthquake in 2016, Hokkaido Eastern Iburi Earthquake in 2018, and Great East Japan Earthquake in 2011, respectively.

A small number of related studies have been conducted previously—for example, the Sendai City Environment Bureau (2012) and Koga and Hamada (2020) conducted questionnaire surveys to reveal how groundwater was used following occurrence of earthquakes in the cities of Sendai and Kumamoto, respectively. The target of the survey conducted in each city was limited to local well owners. Endo et al. (2022) expanded the work of Koga and Hamada (2020) by widening the investigation objects. They distributed two questionnaire surveys among the owners of local wells (supply side) and the welfare facilities for aged people (demand side) in Kumamoto to reveal the detail of groundwater utilization after a disaster. This study broadened the work of Endo et al. (2022) in the geographical sense to the cases of Sapporo and Sendai by conducting the same questionnaire survey as performed in Kumamoto to reveal how and why groundwater utilization differed among the three cities. No such comparative study has previously been based on a single questionnaire.

The remainder of this paper provides an overview of the three earthquakes mentioned in the preceding and the institutions concerned with DEWs, together with details of the method of the questionnaire survey. The survey results are then presented, the findings are discussed, and the derived conclusions are stated.

Background

Study areas

The locations of the study areas of the cities of Kumamoto, Sapporo, and Sendai are shown in Fig. 1. All three are prefectural capitals that have the largest municipal populations to have experienced major earthquakes in the past 15 years; namely, the Kumamoto Earthquake in 2016 (Kumamoto), Hokkaido Eastern Iburi Earthquake in 2018 (Sapporo), and Great East Japan Earthquake in 2011 (Sendai), the seismic centers of which are indicated by crosses in Fig. 1.

Table 1 summarizes the details of the occurrence of the three earthquakes and the damage that they caused. The numbers of dead or missing persons and damaged houses refer to each city and its adjacent area. The damage to the waterworks refers to the inside of each city. The maximum number of households that experienced a water-supply cutoff were ~326,000 for Kumamoto, 15,000 for Sapporo, and 231,000 for Sendai. The waterworks in Sapporo experienced least damage, and restoration of the waterworks was completed within 7 days. Restoration of water delivery through the main pipes required 16 days in Kumamoto; however, additional days and construction were needed to restore the supply from the main pipes to each individual household (Kumamoto City Waterworks and Sewerage Bureau, personal communication, 2019). The waterworks were restored within 18 days after the occurrence of the earthquake in

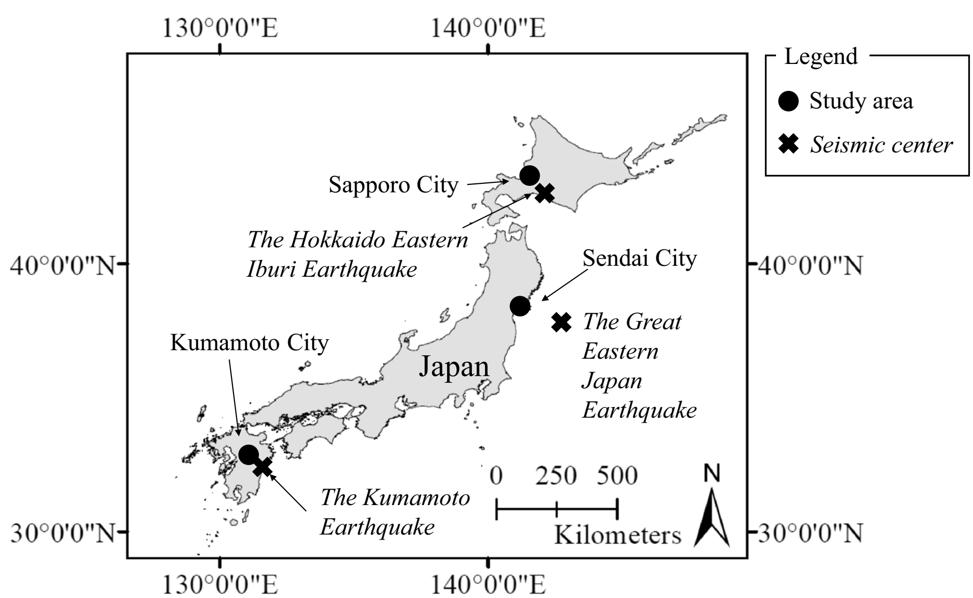


Fig. 1 Locations of the study areas and the seismic centers

Table 1 Overview of damage caused by the three earthquakes

City	Earthquake	Population as of year of earthquake occurrence	Date of earthquake occurrence	Maximum magnitude	Number of dead or missing persons	Number of damaged houses (completely or partly destroyed)	Maximum number of households with cutoff water supply	Days until restoration of waterworks
Kumamoto	Kumamoto Earthquake	740,204[a]	14 and 16 April 2016	7.3[d]	139[d]	181,373[d]	326,000[g]	16[g]
Sapporo	Hokkaido Eastern Iburi Earthquake	1,965,940[b]	6 September 2018	6.7[e]	41[e]	10,368[e]	15,175[h]	7[h]
Sendai	Great East Japan Earthquake	1,049,493[c]	11 March 2011	9[f]	~20,000[f]	~310,000[f]	231,205[i]	18[i]

[a]Kumamoto City (2021)

[b]Sapporo City (2021)

[c]Sendai City (2021)

[d]Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications (2011)

[e]Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications (2016)

[f]Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications (2019)

[g]Kumamoto City Waterworks and Sewerage Bureau (2018)

[h]Ministry of Health, Labour and Welfare, Japan (2018)

[i]Data provided by Sendai City Waterworks Bureau

inner parts of Sendai, but additional time was required to restore the supply in the coastal area that suffered the effects of a tsunami.

The main cause of such dysfunction was damage to waterworks facilities—for example, before the earthquake, the City of Kumamoto owned 112 wells and normally used 96 of them to provide water to households via a main pipeline and subordinate branch pipes. However, because of the earthquake, not only the pumping stations but also the water pipes were destroyed in many parts of the city, i.e., 24 sections of the main pipeline were damaged, and 272 and 2,213 sections of secondary and tertiary branch pipes, respectively, were affected (Kumamoto City Waterworks and Sewerage Bureau 2018).

Emergency water supply in Japan

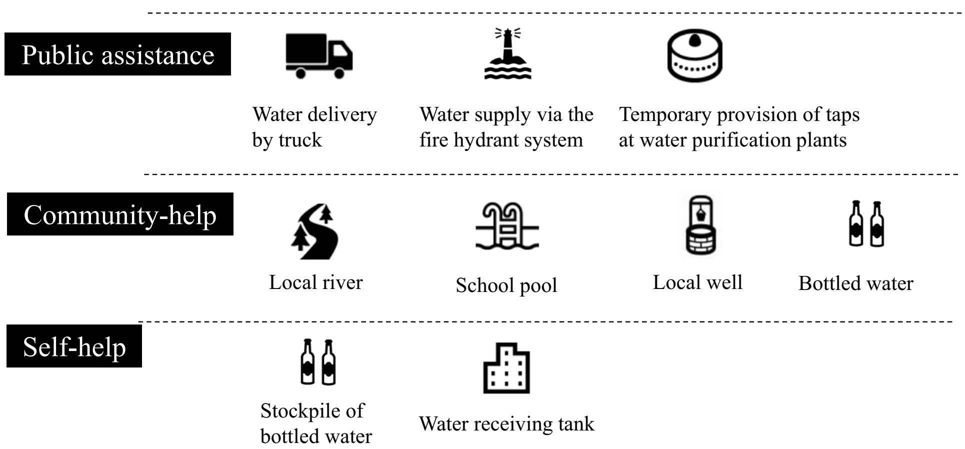
As of 2020, ~123.77 million people in Japan were using tap water, and the ratio (diffusion rate) to the total population of 126.18 million was 98.1%. Surface water accounted for 80% of the water resource with the remainder supplied by groundwater (Japan Water Works Association 2022). Although water supply systems across Japan are presently being reconstructed to ensure that they are earthquake resistant, only 41.2% of this work has been completed in terms of the main pipes thus far (Water Supply Division, Pharmaceutical Safety and Environmental Health Bureau, Ministry of Health, Labor, and Welfare, Japan 2023).

In Japan, disaster preparedness and response measures are divided into three categories–public assistance, community help, and self-help. Public assistance is provided by local government, supported by prefectural and national governments as necessary. Community help is manifested as mutual assistance provided by various private actors at the neighborhood level, including local residents, private firms, and nonprofit organizations. Self-help refers to those measures taken by individual households.

This classification is also applied to the emergency water supply (Fig. 2). Local government is responsible for the water supply following a disaster (The Basic Act on Disaster Management of 1961, Article 62). The techniques adopted include water delivery by truck, water supply via the fire hydrant system and temporary provision of taps at water purification plants (Japan Water Research Center 2015; Japan Water Works Association 2017). There is usually support in terms of human resources and equipment from the government at prefectural and national levels at the time of a large-scale disaster such as the three earthquakes previously mentioned.

Water supply by public assistance is often supplemented by community help. Local residents help each other using unconventional water sources that include local rivers, water stored in school pools, and groundwater pumped from private wells. Additionally, bottled water is often delivered from firms, nonprofit organizations, and volunteer groups from other areas.

Fig. 2 Schematic of emergency water supply in Japan



Finally, self-help is the most basic level of preparedness. Stocking bottled water at home is a common practice, while the residents of apartments or condominiums usually use water left in receiving tanks that store tap water provided by the water supply agency (i.e., local government).

An example of community help is the DEW system. Local government performs advance registration of local wells that could be used as a supplementary water supply in an emergency. Some DEWs are constructed by local government but most are owned by private bodies such as households, factories, and shopping centers. The registrants are supposed to open their wells to the public to provide water for drinking and other domestic purposes should an earthquake occur. However, provision of groundwater is not mandatory and it depends entirely on the initiative of individual well owners.

The Japanese public sector comprises three levels—1,741 local governments (village, town, and city), 47 prefecture-level governments, and 1 national government. Local governments are obliged to make their own disaster preparedness plan. As mentioned before, Endo (2021a) investigated the plans of all 1,741 local governments and revealed that at least 1,316 (75.6% of all local governments) involve the use of local wells as an emergency water supply. Among those with such plans are the local governments of the cities of Kumamoto, Sapporo, and Sendai, and the basic information of their DEWs is summarized in Table 2.

The cities of Sapporo and Sendai established DEWs in 1996 and 2000, respectively, following the occurrence of the Great Hanshin–Awaji Earthquake in 1995. The earthquake that struck the city of Kobe in 1995 deprived 650,000 households of tap water, and forced many other cities in Japan to acknowledge the importance of preparedness regarding an emergency water supply in urban areas. Initially, the local government of Kumamoto did not follow the example of the cities of Sapporo and Sendai, simply because they had thought that a big earthquake would never happen in there, which turned out to be an erroneous belief (Kumamoto City Waterworks and Sewerage Bureau, personal communication, 2019). Thus, after suffering extensive water cutoff following the occurrence of the Kumamoto Earthquake in 2016, DEWs were introduced in Kumamoto within the following year.

Disaster emergency well registrants differ among the three studied cities. The number of registrants in Kumamoto was 91 as of March 2020, comprising mainly wells owned by the food industry, hospitals, and welfare facilities; wells

Table 2 Institution of DEWs in the three studied cities

City	Inaugural year	Number of registrants	Main registrants
Kumamoto	2017[a]	91 (as of March 2020)[d]	Food industry, hospital, welfare facilities[d]
Sapporo	1996[b]	505 (as of June 2019)[e]	Detached houses, food industry, commercial complexes, hotels[e]
Sendai	2000[c]	277 (as of September 2020)[f]	Detached houses, agricultural groups, office buildings, commercial complexes[f]

[a]Kumamoto City Disaster Prevention Conference (2018)

[b]Sapporo City Disaster Prevention Conference (1995)

[c]Data provided by Sendai City Environment Bureau

[d]Kumamoto City Environment Bureau (2020)

[e]Sapporo City Health and Welfare Bureau (2019)

[f]Sendai City Environment Bureau (2020)

in detached houses were not included. There were 505 DEW registrants as of June 2019 in Sapporo and 277 DEW registrants as of September 2020 in Sendai. The DEWs registered in these cities include wells in detached houses and those owned by business facilities. The temporal change in the number of DEWs registered in each city is shown in Fig. 3.

Method

Research target

A questionnaire was distributed among the registrants of DEWs in the three studied cities. As mentioned previously, DEW registrants in the cities of Sapporo and Sendai included detached houses, but their postal addresses are not publicly available. Therefore, the study had to narrow the distribution target to well owners for whom address information was accessible. Consequently, questionnaires were sent to 91 registrants in Kumamoto, 292 registrants in Sapporo, and 53 registrants in Sendai.

Although the Sapporo and Sendai local governments had introduced DEWs before the cities were struck by the Hokkaido Eastern Iburi Earthquake and Great East Japan Earthquake, respectively, Kumamoto had not introduced DEWs at the time of occurrence of the Kumamoto Earthquake. Thus, the research targets in Kumamoto were those who became DEW registrants following the disaster.

A second questionnaire was sent to welfare facilities for aged people in the three cities. Using geographic information system attribute data compiled by the Ministry of Land, Infrastructure, and Transport, Japan (2021), 328, 954, and 934 such facilities were selected in Kumamoto, Sapporo, and Sendai, respectively. There are two reasons why welfare facilities were chosen as the research target. First, they represent a vulnerable group in a time of disaster, and thus they should receive special attention regarding the provision of an emergency water supply. This especially holds true in a rapidly aging society such as that in Japan. Second, unlike individual households, the postal address for such facilities can be obtained easily, enabling efficient distribution of the questionnaire.

Table 3 Main questions to disaster emergency well owners

Question No.	Question
1	Earthquake's influence on wells
2	Groundwater quality inspection after the earthquake
3	Provision of groundwater to neighbors
4	Well management after the earthquake
5	Policy requests to the city government

Investigation items

The survey distributed among DEW owners comprised 21 questions addressing the effect of the earthquake on their wells, groundwater quality inspections following the earthquake, provision of groundwater to the local population, well management following the earthquake, and policy requests to the city government. The survey distributed among the welfare facilities for aged people posed 17 questions addressing the effect of water-supply cutoff, use of groundwater after the earthquake, emergency water sources other than groundwater, and preparedness efforts following the earthquake. The main questions posed in each survey are listed in Tables 3 and 4. All the questions and responses that relate to the two surveys are presented in the electronic supplementary materials—survey on DEWs (ESM1); and survey of welfare facilities (ESM2).

This analysis focuses specifically on the responses to questions regarding the provision of groundwater to neighbors (question No. 3 to the well owners in Table 3), and the recognition of DEWs and utilization of groundwater after the earthquake (question No. 3 to the welfare facilities in Table 4).

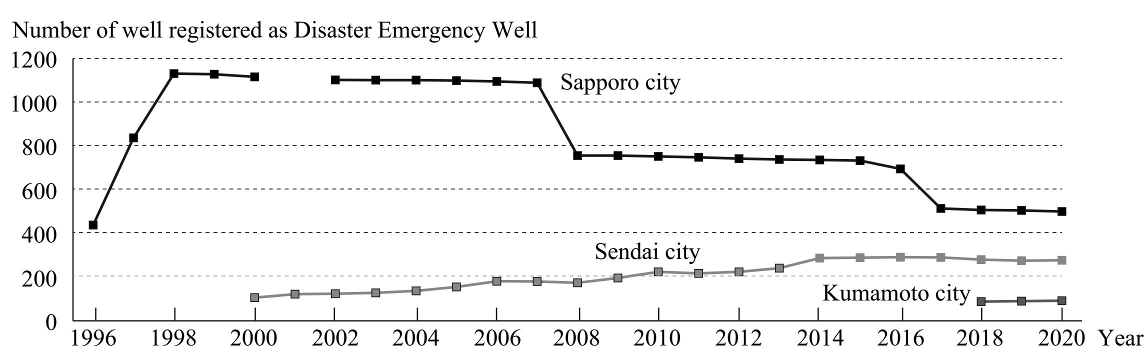


Fig. 3 Changes in number of wells registered as disaster emergency wells (DEWs) in the three studied cities

Table 4 Main questions to welfare facilities for aged people

Question No.	Question
1	Methods of water supply in facility at the time of earthquake occurrence
2	Effect of water-supply cutoff
3	Recognition of DEWs and utilization of groundwater after the earthquake
4	Emergency water sources other than groundwater
5	Preparedness efforts after the earthquake

Collection method

A questionnaire sheet and an anonymous multiple-choice answer sheet were delivered to the research targets previously mentioned. Respondents were asked to answer the questions online or on paper from 12 February 2021 to 1 March 2021. The response rate to the first questionnaire (sent to DEW owners) was 52.8–62.6%; the response rate to the second questionnaire (sent to welfare facilities for aged people) was 20.1–36.0% (Tables 5 and 6).

Results

Results of survey of DEW owners

Provision of groundwater

A question posed to DEW owners asked whether they provided groundwater to their neighbors following the occurrence of the earthquake (see Table 3, question No. 3, 'Provision of groundwater to neighbors'). The responses revealed substantial differences among the three cities in terms of groundwater provision. A positive response was received from more than 50% of the respondents in Kumamoto, only 3% of respondents in Sapporo, and approximately 32% of respondents in Sendai (Fig. 4).

Reasons why groundwater was not offered to the local population

An additional question was sent to those DEW owners who declared that they did not provide water to the local population following the occurrence of the earthquake to ascertain the reasons for such behavior. The respondents were allowed to provide multiple answers. The top three answers from each city are shown in Table 7. Respondents in Kumamoto chose '1. Because we were not a DEW registrant when the earthquake occurred', '3. Because there was no request from the city government', and '4. Because there was no request from local residents' in descending order. The most popular answers from the respondents in Sapporo were '3. Because there was no request from the city government', '4. Because there was no request from local residents', and '7. Because the pump came to a halt owing to cutoff of electricity supply'. The top three answers from the respondents in Sendai were '4. Because there was no request from local residents', '1. Because we were not a DEW registrant when the earthquake occurred', and '3. Because there was no request from the city government'.

Results of survey of welfare facilities for aged people

Use of local wells

A question posed to the welfare facilities for aged people asked whether they used local wells after the occurrence of the earthquake (see Table 4, question No. 3 'Recognition of DEWs and utilization of groundwater after the earthquake'). The responses revealed the same tendency as that of the answers from the DEW owners on the provision of groundwater to local residents. The ratio of the positive responses of either '1. We obtained water from local wells and we knew that they were registered in the disaster emergency well system' or '2. We obtained water from local wells although we were unsure whether they were registered in

Table 5 Response rate to the first questionnaire (sent to DEW owners)

City	No. of distributions	No. of replies	Reply ratio
Kumamoto	91	57	62.6%
Sapporo	292	166	56.8%
Sendai	53	28	52.8%

Table 6 Response rate to the second questionnaire (sent to welfare facilities for aged people)

City	No. of distributions	No. of replies	Reply ratio
Kumamoto	328	118	36.0%
Sapporo	954	267	28.0%
Sendai	934	188	20.1%

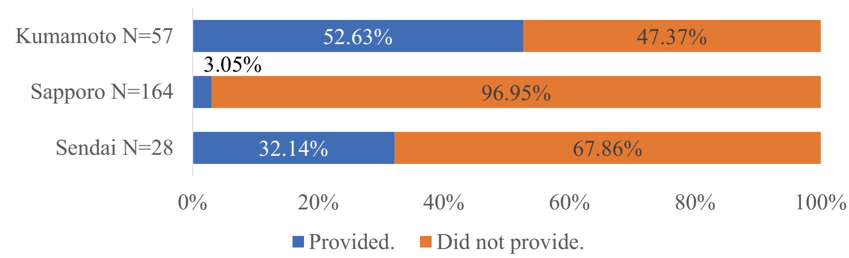


Fig. 4 Provision or lack of provision of groundwater following earthquake occurrence

the disaster emergency well system' increased with each city in the order of Sapporo, Sendai, and Kumamoto. In Sapporo, only one facility (0.38% of the total respondents) gave a positive answer, whereas approximately 38% of respondents in Kumamoto answered that they had used local wells. Approximately 7% of respondents in Sendai provided a positive answer (Fig. 5). As mentioned previously, it was 1 year after the occurrence of the Kumamoto earthquake that the Kumamoto City government introduced DEWs. Therefore, respondents of Kumamoto who selected '1. We obtained water from local wells and we knew that they were registered in the disaster emergency well system' appear to have had a lapse in memory (Fig. 5).

Well owners

An additional question was asked of those who selected either '1. We obtained water from local wells and we knew that they were registered in the disaster emergency well system' or '2. We obtained water from local wells although we were unsure whether they were registered in the disaster emergency well system' to ascertain well ownership. Respondents were allowed to choose multiple options from the 11 choices listed in Table 8. The results reveal that the largest number of respondents in Kumamoto and Sendai selected '1. Resident of detached house', while the respondents in Sapporo chose '8. School'.

Purpose

An additional question was asked of those who selected either '1. We obtained water from local wells and we knew that they were registered in the disaster emergency well system' or '2. We obtained water from local wells although we were unsure whether they were registered in the disaster emergency well system' to determine the purposes for which the obtained groundwater was used. Respondents were allowed to choose only one option from the eight choices listed in Table 9. The largest number of respondents in each of the three target cities selected domestic purposes (toilet, laundry, and bathing).

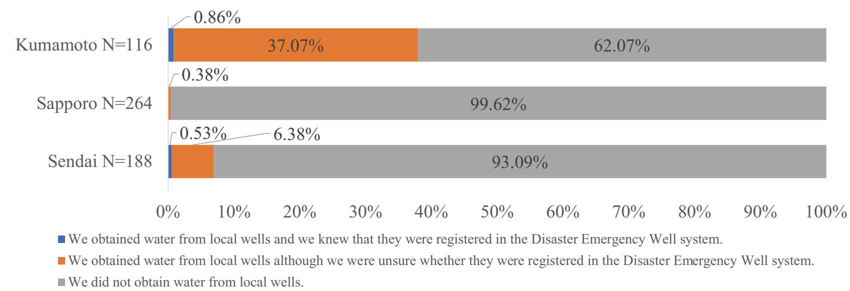
Current level of recognition of DEWs

A question was sent to the welfare facilities for aged people to ascertain whether they are currently aware of the institution of DEWs (see Table 4, question No. 3 'Recognition of DEWs and utilization of groundwater after the earthquake'). The responses reveal differences among the three cities in terms of the level of recognition of DEWs. Only 13% of respondents in Sapporo answered positively. Although the level of recognition of DEWs in the cities of Sendai and Kumamoto is comparatively high (21% in Sendai and 25% in Kumamoto), the overall level of recognition remains low (Fig. 6).

Table 7 Reasons why groundwater was not offered to the local population following earthquake occurrence

Reason	Kumamoto $N = 27$	Sapporo $N = 156$	Sendai $N = 18$
1. Because we were not a DEW registrant when the earthquake occurred	59.26%	1.28%	38.89%
2. Because a procedure for groundwater provision was not set up	3.70%	12.18%	5.56%
3. Because there was no request from the city government	33.33%	69.23%	33.33%
4. Because there was no request from local residents	33.33%	62.18%	50.00%
5. Because there was concern regarding groundwater quality	7.41%	5.77%	5.56%
6. Because the pump was destroyed by the earthquake	3.70%	2.56%	5.56%
7. Because the pump came to a halt owing to cutoff of electricity supply	7.41%	36.54%	16.67%
8. Because access to the premises was restricted	3.70%	2.56%	11.11%
9. Because water delivery apparatus such as taps and hoses were lacking	3.70%	5.77%	5.56%
10. Other (free descriptive answer)	14.81%	10.90%	16.67%

Fig. 5 Groundwater use by welfare facilities for aged people following earthquake occurrence



Discussion

Groundwater as a potential alternative water source

The spatial distributions of DEWs that provided groundwater to the local population, DEWs that did not provide groundwater to the local population, and DEWs for which the owners did not reply to the questionnaire are shown in Fig. 7. Water stations established by the city governments are also illustrated in Fig. 7. The orange-colored background shading represents population density based on the national population census data of 2015.

Local governments are supposed to open water stations when the water supply is interrupted, not only by earthquakes but also by other natural disasters. As mentioned previously, the most common method is to install water trucks in public spaces (e.g., city halls and local public schools), where water can be distributed to the local residents. The actual numbers of water stations in each city differed daily; therefore, Fig. 7 shows the situation when the maximum number of water stations was deployed in each city. The blue circle (scaled radius: 500 m) around each water station indicates the distance of the Sphere Standard defined by a group of NGOs, the Red Cross, and the Red Crescent Movement. The standard proposes a set of minimum standards that humanitarian assistance activities in disaster and conflict areas should satisfy. With regard to water supply, the standard recommends that the distance from any household to the nearest point of water supply should be less than 500 m (Sphere Association 2018).

Figure 7 shows that the Sapporo, Sendai, and Kumamoto city governments could not set up a sufficient number of water stations to satisfy the Sphere Standard, even though they received assistance in the form of water trucks and staff from the local government of other areas. To some extent, the DEWs compensated for the lack of emergency water stations and provided a supplementary water supply, supporting the theoretical assertion by both Estrella and Saalismaa (2013) and Shivakoti et al. (2019) that a local aquifer can play an important role in supplying water in an emergency.

Wells of detached houses

Not all of the wells used after the occurrence of the earthquakes are shown in Fig. 7. In the case of Kumamoto, 44 facilities selected either '1. We obtained water from local wells and we knew that they were registered in the disaster emergency well system' or '2. We obtained water from local wells although we were unsure whether they were registered in the disaster emergency well system', and 25 of those 44 facilities answered that the well was owned by a detached house (Table 8). As Table 2 shows, such privately owned wells were not included as DEWs when the system was established in the year following the Kumamoto earthquake. Therefore, wells other than those that were registered later as DEWs were used after the earthquake. Those wells are not shown in Fig. 7, but they worked as informal water stations and played a positive role in mitigating the impact of water-supply cutoff (Endo et al. 2022).

In 2012, the Sendai City Environment Bureau conducted a questionnaire survey of DEW owners, a year after the occurrence of the Great East Japan Earthquake. As mentioned previously, DEWs in Sendai include wells in detached

Table 8 Breakdown of well ownership

Owner	Kumamoto $N = 44$	Sapporo $N = 1$	Sendai $N = 12$
1. Resident of detached house	25	0	8
2. Resident of apartment house	2	0	0
3. Factory	4	0	0
4. Shopkeeper	2	0	2
5. Shopping complex	0	0	0
6. Local firm	0	0	0
7. Community center	0	0	2
8. School	1	1	0
9. City government	5	0	0
10. We do not know who owned the well	1	0	1
11. Others (free descriptive answer)	8	0	1
Total	48	1	14

Table 9 Purpose of groundwater use by welfare facilities for aged people

Purpose	Kumamoto $N = 44$	Sapporo $N = 1$	Sendai $N = 17$
1. Drinking purposes (including cooking purposes)	18.18%	0.00%	5.88%
2. Domestic purposes (toilet, laundry, and bathing)	50.00%	100.00%	58.82%
3. Fire protection	0.00%	0.00%	0.00%
4. Drinking and domestic purposes	27.27%	0.00%	11.76%
5. Drinking and fire protection purposes	0.00%	0.00%	5.88%
6. Domestic and fire protection purposes	2.27%	0.00%	0.00%
7. Drinking, domestic, and fire protection purposes	2.27%	0.00%	0.00%
8. Other (free descriptive answer)	0.00%	0.00%	17.65%
Total	100%	100%	100%

houses as well as those owned by business facilities. The responses revealed that 58 out of 185 DEW owners in detached houses and 11 out of 39 DEW owners in business facilities provided groundwater to the local population (Sendai City Environment Bureau 2012). If those 58 DEWs in detached houses were taken into consideration, the distribution density of DEWs in Sendai shown in Fig. 7 would be much higher.

The DEWs in Sapporo also comprised wells in detached houses and those owned by business facilities. Unfortunately, the Sapporo city government did not conduct a survey on how those wells were used following the occurrence of the Hokkaido Eastern Iburi Earthquake (Sapporo City Health and Welfare Bureau, personal communication, 2022); consequently, no further information could be added to Fig. 7 with regard to Sapporo.

Tap water restoration, electricity restoration, and difference in use of DEWs

The city of Sapporo has the largest number of DEWs, followed in descending order by Sendai and Kumamoto (Table 2). Interestingly, the percentage of DEW owners who provided groundwater to the local population was highest in Kumamoto, followed in descending order by those in Sendai and Sapporo, which is the reverse order of that just mentioned, and it is worth examining the underlying reasons more closely.

The rate of restoration of tap water supply in each of the three cities, shown in Fig. 8a, was calculated by dividing the number of households with restored water supply by the maximum number of households that experienced water-supply cutoff. It required 7, 16, and more than 18 days for the waterworks to be repaired in Sapporo, Kumamoto, and Sendai, respectively (Kumamoto City Waterworks and Sewerage Bureau 2018; Ministry of Health, Labour and Welfare, Japan. 2018; Sendai City Waterworks Bureau, personal communication, 2021). However, repair to the waterworks does not always mean restoration of the supply of tap water to the local population—for example, in Kumamoto, the completion of water restoration meant that water pipes were repaired temporarily such that drinking water was able to be delivered to the front of each household, but many people still had to repair water pipes buried within their premises to receive water inside (Kumamoto City Waterworks and Sewerage Bureau, personal communication, 2019).

The time at which restoration of the electricity supply was completed in each of the three cities is shown in Fig. 8a. Notably, "completion" means availability of electricity for most of the city if not the entire city. Electricity restoration was completed 2, 5, and 9 days after the occurrence of the earthquake in Sapporo, Kumamoto, and in Sendai, respectively (Kumamoto Prefecture Headquarters for Disaster Control 2016; Sapporo City Headquarters for Disaster Control 2018; Sendai City Reconstruction Bureau 2013); which is in the same order but faster as for the restoration of tap water.

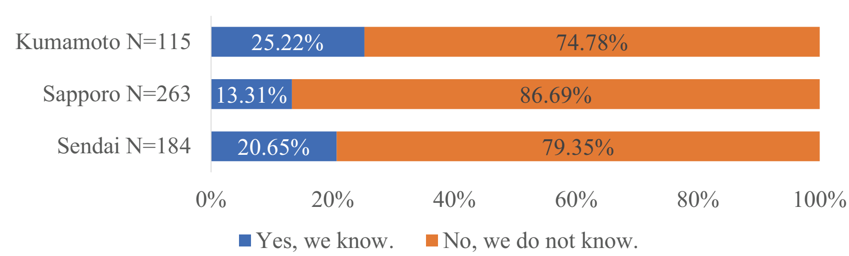


Fig. 6 Recognition of disaster emergency wells

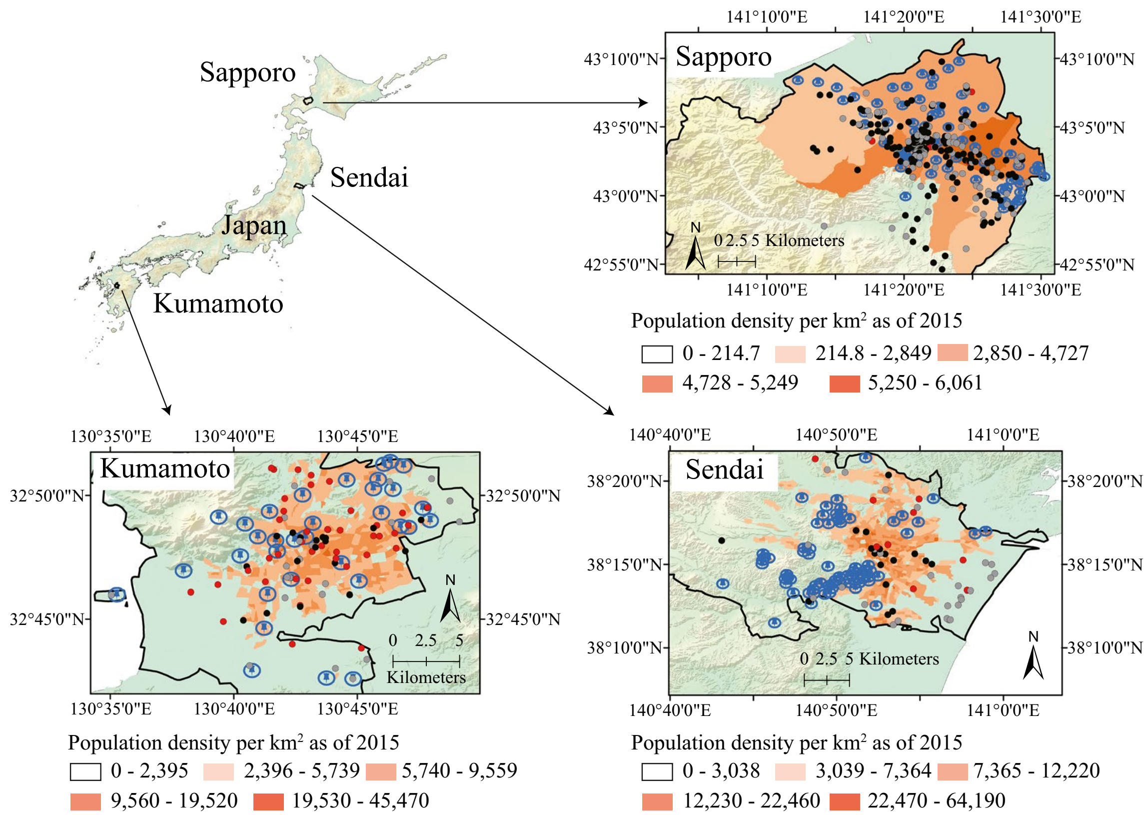
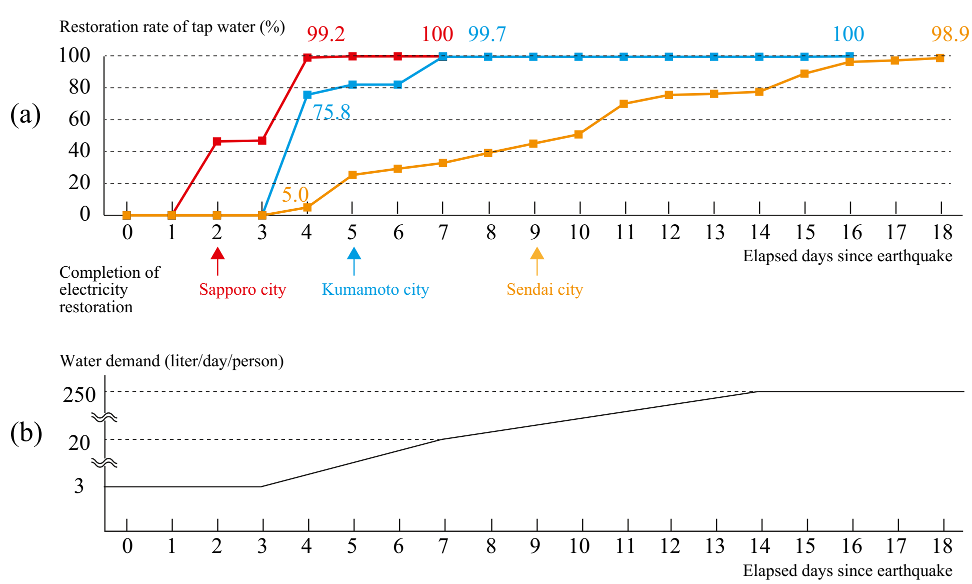


Fig. 7 Locations of DEWs that provided groundwater to the local population (red circles), DEWs that did not provide groundwater to the local population (black circles), DEWs for which the owners did not reply to the questionnaire (gray circles), and emergency water stations established by each city government (blue pins). The blue circle (scaled radius: 500 m) around each emergency water station represents the distance of the Sphere Standard proposed as a universal minimum standard distance to the nearest point of water supply. The orange-colored background shading represents population density based on national population census data of 2015. It should be noted that wells used after the occurrence of the earthquake but not registered as DEWs are not shown in this figure

The change in volume of water that should be secured after occurrence of an earthquake is shown in Fig. 8b (Ministry of Health, Labour and Welfare, Japan 2015). To support life, it is recommended that a volume of at least 3 L (0.003 m^3) of drinking water per person per day be secured in the first 3 days following an earthquake. A volume of 20–30

Fig. 8 Changes in the **a** restoration of tap water and electricity supply, and **b** water demand



L (0.02–0.03 m^3) of domestic water is necessary to satisfy toilet, bathing, and washing requirements. A volume of 250 L (0.25 m^3) of water, which is equivalent to the water supplied in normal situations, should be available 2 weeks after the occurrence of an earthquake.

Few DEWs were used in Sapporo (Fig. 4)—a primary reason was electricity supply cutoff (Table 7), which implies that many of the DEWs in Sapporo have electrical pumps rather than hand-operated pumps. The detrimental effects, however, were limited because the problem of electricity cutoff was resolved as early as 2 days after the occurrence of the earthquake. Generally, restoration of the electricity supply is considered positive for restarting the operation of local wells, regardless of whether they are private or public. It is reasonable to suppose that the use of DEWs was very limited, not only because of the early restoration of the electricity supply but also because the restoration of the waterworks was completed quickly.

Much greater use was made of DEWs in the cities of Sendai and Kumamoto. One possible reason is the period between electricity restoration and waterworks restoration. Electricity became available again 5 days after earthquake occurrence in Kumamoto and 9 days after earthquake occurrence in Sendai; however, it took longer for the waterworks to be restored in each city (Fig. 8a). Thus, the period over which electricity was available but tap water was not restored was longer than in the case of Sapporo. It is highly probable that local wells were used during this period in the cities of Kumamoto and Sendai to satisfy the growing demand for water domestic purposes, as shown in Fig. 8b. This supposition is supported by Table 9, which indicates that groundwater was mainly used for domestic purposes. Nevertheless, water demand for domestic purposes was not satisfied solely by DEWs. Endo et al. (2022) reported that bottled water, water stored in water receiving tanks, and water trucks provided by local government were also used in Kumamoto.

Social capital

As the recognition of DEWs increases, the ratio of DEWs made available to the public in an emergency increases (Figs. 4, 5 and 6). Moreover, in all three cities, a notable number of DEW owners indicated that they did not provide groundwater to the local population either '3. Because there was no request from the city government' or '4. Because there was no request from local residents' (Table 7). This suggests that it is necessary not only to set up DEWs physically but also to publicize their existence more widely to create a network between DEW owners and the local population.

Such networks, which are generally called social capital, appear as a form of mutual assistance during and after a disaster, providing various services including financial assistance, nonfinancial resources (food, water, and housing), and emotional support (Aldrich and Meyer 2015). It has been reported repeatedly that such mutual assistance has played an important role during and after the occurrence of disasters in Japan (Hikichi et al. 2017; Nakagawa and Shaw 2004; Shimada 2015). Therefore, what is required in Japan is not the creation of new social capital, but the stimulation of existing but hidden social capital. This could be achieved by teaching well owners how to invite others to use their DEW during an emergency, and by letting the public know about the existence of DEWs.

How social capital works in relation to an emergency water supply is well illustrated in the case of Kumamoto where many local wells were made available to the public following the occurrence of the earthquake, even though DEWs had not been officially instigated. As will be explained further on, Kumamoto citizens have more opportunities to receive information on groundwater than citizens of other cities, and it is reasonable to suppose that this has promoted groundwater utilization since the occurrence of the earthquake disaster.

One factor that makes the local population of Kumamoto familiar with groundwater is the high dependence on groundwater for drinking water. Tap water in Kumamoto City is entirely derived from local groundwater. There are few other cities in Japan with a population of similar size (0.7 million) that satisfy the demand for drinking water solely from the supply of local groundwater (Shimada et al. 2012). Notably, 98% of the tap water in Sapporo comes from surface water (Sapporo City Waterworks Bureau 2021) and the Sendai City waterworks depend entirely on surface water (Miyagi Prefecture Government Environment and Life Bureau 2021).

Given this background, Kumamoto launched a series of groundwater-related policies, including water conservation and artificial recharge from the late 1970s, and started to promote the phrase "No. 1 groundwater city in Japan" in various events hosted by the city government from 2007. Additionally, the city government began the "Kumamoto water examination" campaign in 2008. This examination, which is divided into three classes from the third grade (elementary grade) to the first grade (professional grade), is conducted as though it were a game such that the candidates for examination can have fun. They are supposed to start from the third grade and are given a certificate when they pass the first grade. The fact that 50,000 people took this examination during 2008–2019 shows that this campaign became an important water education tool (Kumamoto City Environment Bureau 2021a). Similar accumulative education approaches are not implemented in the cities of Sapporo and Sendai.

Such policies in ordinary situations possibly enhance recognition of local groundwater among citizens, and develop social networks between DEW owners and the local population in times of emergency. It is considered that local events hosted by the private sector such as citizen festivals, sports clubs, regional currency, common space, and social media are useful for strengthening social capital (Dufty 2012; Aldrich and Meyer 2015). The experience of Kumamoto suggests that accumulation of policies by the public sector might also foster social capital.

Policy challenges for practitioners

In practice, development of DEWs can be considered an example of groundwater governance in that it is intended to mitigate damage resulting from water-supply cutoff through collaboration between local government and private well owners. Vrba (2016) identified certain issues to be resolved to promote groundwater governance in an emergency with consideration of four different phases of a disaster event. In the preparedness phase, investigation of groundwater resources available in an emergency should be promoted. Possible scenarios of the impact of a disaster on the local population and drinking water supply facilities should be explored in the warning phase. Appropriate combined use of various water sources such as bottled water and water delivered from outside the affected area should be promoted in the impact and relief phase. Finally, new disaster-resistant emergency wells should be developed in advance of the next disaster and connected to existing drinking water facilities in the rehabilitation phase.

It might be true that the aforementioned proposals are reasonable, but their descriptions are rather abstract and do not focus on groundwater use in an emergency. In contrast, this paper proposes more concrete issues to be resolved to promote collaboration of public and private sectors in terms of groundwater utilization in an emergency.

Local wells in the private sector could be an important alternative to the water supply by the public sector. Even though wells might be out of commission immediately after the occurrence of an earthquake when electricity is cut off, case studies described in this paper indicate that groundwater could play a role during the period in which electricity restoration is completed earlier than water supply restoration. Therefore, consideration of a middle-ground approach is important, whereby groundwater and other water sources such as personal storage of bottled water and utilization of water receiving tanks in detached houses are used in combination, rather than consideration of an extreme approach that might completely neglect groundwater as a possible source or consider groundwater as the sole alternative to the public water supply.

However, inspection is needed in cases where groundwater is used for drinking purposes. Groundwater in an urban area is subject to human activities on the surface (Foster et al. 2011), and destruction of sewage treatment facilities by an earthquake might lead to groundwater contamination (McCann et al. 2011). The DEWs in Sapporo were originally introduced to supply drinking water in an emergency. Their primary purpose, however, was modified to secure nonpotable domestic water in April 2002 because of concern regarding groundwater quality degradation owing to the destruction of various pipes by earthquakes (Sapporo City Assembly 2003). Since their introduction, the main purpose of DEWs in Sendai has been to secure the nonpotable domestic water supply. The DEWs in Kumamoto are intended to supply water for drinking and other domestic purposes. Kumamoto has plans to allow the Kumamoto City Environmental Research Center to check the quality of groundwater obtained from DEWs if the water is to be extracted for drinking purposes. The center is supposed to issue the results of an inspection to a DEW owner within 2 days of sample collection (Kumamoto City Environment Bureau 2021b). However, Endo et al. (2022) questioned whether it would be possible to produce results within 2 days following the occurrence of a disaster, given that there were many cases when it took longer than 2 days to receive the results of an inspection of groundwater quality following the Kumamoto earthquake.

How best to maintain the number of DEWs is also an issue to be considered. In the long term, the number of DEWs might decrease, as has been the case in Sapporo (Fig. 3), where the number of DEWs owned either by business enterprises or by detached houses has declined. The main reason is suspension or abolishment of wells (Sapporo City Public Health Bureau, personal communication, 2022). A possible solution to the problem is subsidy from the local government. According to Endo (2021b), 68 municipalities in Japan have paid subsidies to DEW owners, whereby a typical example is a subsidy for installing and maintaining a well with a hand-operated pump in private premises. Another example is to offer a free inspection of groundwater quality in exchange for registration of a privately owned well as a DEW.

Better education on local groundwater and disclosure of positional information of wells are also very important simply because recognition of wells by the local population has direct influence on groundwater use in an emergency. As shown in Fig. 6, the level of recognition of DEWs is not high in any of the three studied cities, even after occurrence of an earthquake, which implies that simply registering local wells as DEWs is not sufficient, and that publicizing details of DEWs to the local population on every occasion available is highly recommended.

Table 10 lists the methods via which the three studied cities publicize positional information on DEWs. All three cities publicize positional information on DEWs on the Internet; however, information on DEWs in detached houses is not available on the Internet owing to privacy concerns. The cities of Sapporo and Sendai maintain paper records of addresses of detached houses with DEWs at the sections in charge, which can be made available upon application. This arrangement is useful for protecting the personal information of DEW owners, but it hinders effective use of DEWs in an emergency. How best to overcome the dilemma between privacy concerns and DEW recognition remains to be resolved. One possible solution is to produce a local hazard map that presents positional information on DEWs that is shared only at the community level. Thus, local people could ascertain the location of nearby DEWs in advance of a disaster, and concerns for privacy would be mitigated by the narrow extent to which the personal information of a DEW owner would be made available.

Finally, DEWs can provide water for drinking and other domestic purposes after the occurrence of a disaster, but they can also contribute to solving other disaster-related issues such as maintaining the health of disaster victims, cleaning up affected areas, and supplying water for reconstruction of housing. However, the departments in charge of such problems are not always the same in many Japanese municipalities—for example, the environmental department is generally responsible for groundwater management, whereas the health and the construction departments control health/hygiene and housing construction, respectively. A DEW system could form an important part of a comprehensive disaster management plan, but its implementation requires the breaking down of administrative silos and advance formulation of a plan for coordination among departments.

Conclusions

Disaster emergency wells represent manifestation of the policy to mitigate the impact of water-supply cutoff following the occurrence of a disaster through collaboration between local government and private well owners, which can be considered an example of groundwater governance. However, few studies have undertaken comprehensive investigation of groundwater governance in an emergency situation.

Through questionnaire surveys of DEW owners and welfare facilities for aged people, this study investigated how the groundwater resource was actually used in the cities of Kumamoto, Sapporo, and Sendai following the occurrence of large earthquakes between 2010–2020. The survey responses revealed that privately owned wells could supplement the water supply provided by the local government, demonstrating an example of groundwater governance in an emergency. The level of groundwater use following occurrence of an earthquake differed among the three studied cities. Analysis identified possible reasons as the time gap between restoration of the electricity supply and restoration of the waterworks, and the social capital based on accumulation of groundwater-related policies in normal times. A number of policy issues for promotion of groundwater governance in an emergency were proposed: (1) establishment of a strategy for emergency water supply through combined use of groundwater and other water sources, (2) enhancement of methods for timely inspection of groundwater quality following occurrence of a disaster, (3) maintenance of records of the number of registered DEWs, (4) elevation of awareness of DEWs through education and public disclosure of location information with adequate regard for the privacy of well owners, and (5) recognition of the importance of making DEWs part of overall disaster preparedness.

Japan, located in the Ring of Fire, is frequently struck by earthquakes, and the sudden and repeated water-supply cutoff due to earthquake occurrence has become a major social problem. This study addressed the hitherto unknown utilization of groundwater following the occurrence of an earthquake, but the number of cases considered was very limited. More than 1,300 municipalities in Japan have a plan to use local wells as an emergency water supply. Therefore, further case studies should be conducted to clarify the functions that groundwater could play in an emergency. Additionally, there is an urgent need to develop educational methods that could help communities understand the importance of the resource. However, groundwater is not a perfect emergency water source in Japan, and additionally, how the use of DEWs might be reconciled with legal restrictions on groundwater pumping, which were introduced to stop land subsidence in areas with large populations such as Tokyo, Osaka, and Nagoya, remains unclear. Therefore, it is important to take into consideration other potentially useful sources of water including water trucks provided by the local government, bottled water stored by the local population,

Table 10 Disclosure of positional information on DEWs by the three studied cities

City	Attribute of DEW	Method of disclosure of positional information
Kumamoto	DEWs in business facilities	Available on Internet
	DEWs in detached houses	N/A
Sapporo	DEWs in business facilities	Available on Internet
	DEWs in detached houses	Not available on Internet (application is required.)
Sendai	DEWs in business facilities	Available on Internet
	DEWs in detached houses	Not available on Internet (application is required)

and school pools. Further studies should be undertaken to ascertain how these different sources of water should be combined to provide an enhanced integrated water supply system following the occurrence of a natural disaster.

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Declarations

Conflicts of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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