Hydrogeology Journal
https://doi.org/10.1007/s10040-022-02547-9

PAPER

Groundwater as emergency water supply: case study of the 2016 Kumamoto Earthquake, Japan

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Received: 1 January 2022 / Accepted: 12 September 2022

Abstract

Securing water supply is an extremely important issue following an earthquake. Recent earthquakes in Japan have prompted focus on the use of groundwater or disaster emergency wells (DEWs). Water supply networks are vulnerable to earthquakes because they comprise long-distance pipelines that are not always earthquake-resistant. Groundwater, however, can usually be found directly below an area where water is required and can serve as an alternative water source. Although previous studies discussed the importance of groundwater in relation to natural disasters, with special reference to drought, little attention has been given to the use of groundwater following earthquakes. In this study, two questionnaire surveys were conducted of DEW owners and welfare facilities for elderly people in Kumamoto (Japan), which was struck by an Mw 7.3 earthquake in 2016, to identify the advantages and disadvantages of using groundwater as an emergency water supply and ascertain policy issues to be resolved for making DEWs effective. Results showed that not only 30 DEWs but also at least 25 privately owned wells not registered as DEWs were open to the public in the early restoration stage, improving people's access to water and decreasing the burden on the Kumamoto city government's emergency water supply. However, it was revealed that groundwater might not always be potable owing to quality concerns. Additionally, only a limited number of welfare facilities used the available adjacent DEWs and DEW recognition level remains low. These findings indicate that improving information disclosure regarding emergency groundwater use is a policy issue to be resolved.

Keywords Earthquakes · Emergency · Groundwater management · Water supply · Japan

Introduction

How to secure water supply, a fundamental requirement of daily life, is one of the most crucial problems following the occurrence of an earthquake (Noji 2005; Loo et al. 2012; Balaei et al. 2018). Water supply networks are vulnerable to the effects of earthquakes because they comprise long-distance pipelines that are not always earthquake-resistant. It is considered that groundwater could play an important role as an alternative water source because it can usually be found directly below an area in which water is required (Vrba and Renaud 2016).

Many earlier studies discussed groundwater use in response to the impact of natural disasters. While most focused on the role of groundwater in periods of drought (Gleeson et al. 2010; Famiglietti 2014; Alley et al. 2016; Jasechko and Perrone 2020), few studies considered groundwater use following the occurrence of earthquakes. Water shortage following an earthquake is completely different from that in times of drought. It occurs in a sudden and unpredictable way and must be resolved rapidly when water-related infrastructure and social organizations have possibly lost their ordinary functions.

This, however, does not mean that the use of groundwater following disasters other than drought has not been investigated. The Intergovernmental Hydrological Programme of the United Nations Educational, Scientific, and Cultural Organization dealt with methods to find groundwater following natural disasters, including earthquakes, as part of the Groundwater for Emergency Situations project (Vrba and

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Published online: 17 October 2022

Verhagen 2006). Vrba (2016) identified that groundwater could provide an emergency water supply after an earthquake, and discussed various institutional and technical components for effective groundwater governance in emergency situations. Additionally, Davis et al. (2020) estimated the capability of groundwater to meet the minimum requirements for drinking water in a flood event through a case study of urban springs in Kharkiv (Ukraine).

Although such studies addressed the potential role of groundwater in future disaster events, few studies have investigated how groundwater was actually used in an emergency. It is true that Keshari et al. (2006), Sukhija and Rao (2011), Tanaka (2016), and Villholth (2007) all presented examples of groundwater use for various purposes following earthquakes; however, the information presented was very fractional. Therefore, further work remains to be undertaken to investigate the actual use of groundwater following the occurrence of natural disasters and to evaluate its potential as an emergency water supply.

This paper reports a case study of the Mw 7.3 (Mj 7.0) earthquake that struck Kumamoto (Japan) in 2016 (hereafter, referred to as the Kumamoto Earthquake). Although the physical impact of the earthquake on the local groundwater environment was investigated in depth by Hosono et al. (2019, 2020) and Ide et al. (2020), the use of groundwater following the occurrence of the disaster has been poorly investigated. Koga and Hamada (2020) did conduct a questionnaire survey of local well owners to ascertain the level of use of groundwater following the earthquake. They asked local well owners questions regarding the effect the earthquake had on groundwater pumping and whether the water from the wells was made available to the public; however, the number of questions was very limited.

In this paper, the work of Koga and Hamada (2020) is expanded by widening the objects of investigation. Two questionnaire surveys were distributed among the owners of local wells and welfare facilities for aged people in Kumamoto. Local well owners were identified as those whose wells were registered as disaster emergency wells (DEWs) in Kumamoto as of March 2020. Although there was some overlap with the respondents to the earlier questionnaire survey, the lists of people surveyed were not identical. These well owners were considered able to have played a role as potential groundwater suppliers following the Kumamoto Earthquake. The latter group surveyed were considered potential groundwater users and represented the newly added investigation objects.

Widening of the investigation objects was performed to support the following purposes addressed in this paper. The first purpose is to understand in detail how local groundwater was used following the occurrence of the earthquake by looking at both supply and demand. The second purpose is to examine the advantages and disadvantages of using groundwater as an emergency water supply. The third purpose is to identify policy issues that could make the use of groundwater more effective following an earthquake.

This remainder of the paper gives an overview of the Kumamoto Earthquake and the institutions concerned with DEWs, along with the method of the questionnaire survey. The survey results are presented and there is a discussion.

The Kumamoto Earthquake and Disaster Emergency Wells

The Kumamoto Earthquake

The Kumamoto Earthquake constituted a series of seismic events that followed the foreshock (14 April 2016) and the mainshock (16 April 2016). These were the first recorded earthquakes with large intensity to strike the same area twice within a 28-h period (Kumamoto Prefecture 2019). The seismic centers of the earthquakes and the administrative boundary of the city of Kumamoto are shown in Fig. 1.

The population of the city at the time of the earthquake was 740,204 (Kumamoto City 2021). As a consequence of the earthquake, there were 139 fatalities and 2,581 people were injured. In addition to the human casualties, 181,373 houses were partially or totally destroyed because the area of damage extended beyond the city limits (Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications 2016).

The city of Kumamoto is unusual in Japan in that its tap water is derived entirely from local groundwater. There are few other cities in Japan with a population of similar size that satisfy domestic water demand solely from groundwater (Shimada et al. 2012).

The Kumamoto City Waterworks and Sewerage Bureau oversees the local supply of drinking water. Before the earthquake, the bureau owned 112 wells and normally used 96 of them to provide water. However, these facilities were severely damaged by the earthquake. Not only the pumping stations but also the water pipes were destroyed in many parts of the city. Water is usually delivered to each household via a main pipeline and its subordinate branch pipes. Overall, 24 sections of main pipeline were damaged, and 272 and 2,213 sections of secondary and tertiary branch pipes, respectively, were affected. Moreover, the groundwater became muddy following the earthquake and the bureau was forced to stop supplying water throughout the entire city (Kumamoto City Waterworks and Sewerage Bureau 2018).

Figure 2 shows the changes in the numbers of households under cutoff of tap water (line chart) and of water stations (bar chart) provided by Kumamoto City Waterworks and Sewerage Bureau in the days following the earthquake. The foreshock on 14 April 2016 deprived 85,000 households of a water supply, but the mainshock

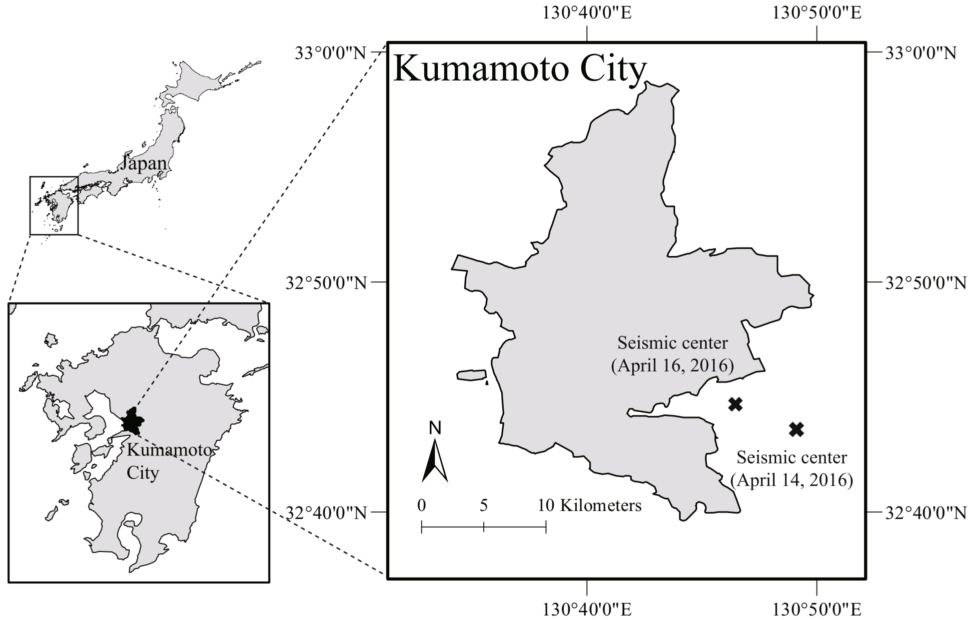


Fig. 1 Location of the study area and the seismic centers of the Kumamoto Earthquake

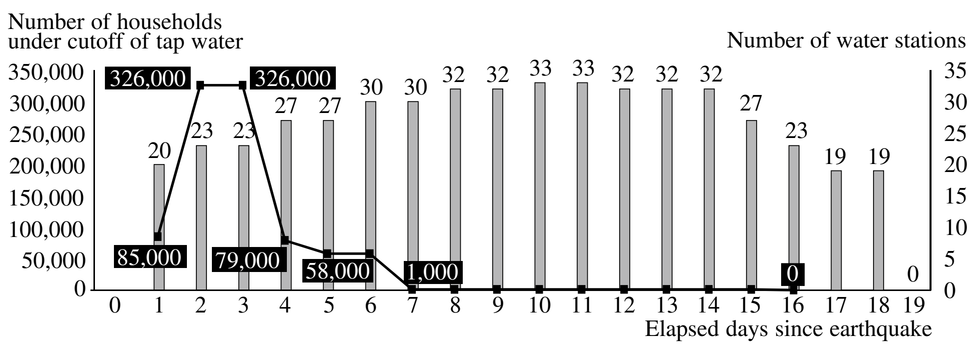


Fig. 2 Change in number of households under cutoff of tap water and water stations

on 15 April exacerbated the situation, pushing the number of cutoff households to 326,000. The number of affected households decreased to just 1,000 within a week of the foreshock and finally reached zero 16 days after the earthquake occurred (30 April 2016). It must be noted that this did not mean that all households within the city were able to use tap water again in accordance with this restoration process. The data indicate that water pipes were repaired temporarily such that tap water was able to be delivered to the front of the property of each household. Many people, however, still had to repair water pipes buried within their premises to deliver water inside (Kumamoto City Waterworks and Sewerage Bureau, personal communication 2019). This explains why Fig. 2 shows that the number of water stations kept increasing 7 days after the earthquake's occurrence when the number of affected households had decreased to 1,000, and why they remained open even when the number of affected households reached zero.

Disaster Emergency Wells

Although water supply systems across Japan are presently being reconstructed to ensure that they are earthquake-resistant, only 40.9% of this work has been completed thus far (Water Supply Division, Pharmaceutical Safety and Environmental Health Bureau, Ministry of Health, Labor, and Welfare, Japan 2021). Attention has focused increasingly on alternative water supplies such as personal storage of bottled water, reuse of rainwater, use of school pools, and rotational supply by vehicles, especially following the Great Hanshin–Awaji Earthquake of 1995 (Yamada 1998).

Recently, increasing numbers of municipalities in Japan have introduced DEWs against a backdrop of frequent occurrences of earthquakes. A DEW is a local well that is registered in advance as a supplementary water supply in case of earthquakes or other disasters. While some DEWs are constructed by local governments, most are privately owned by households, local factories, and shopping malls. Registered

DEWs are supposed to be open to the local population as a source of water for drinking or other domestic purposes in emergency situations. However, this is not mandated and the availability of such wells for public access is at the discretion of well owners. There are 1,741 municipalities in Japan, and 418 of them (approximately 25% of the total number) have introduced institutions to oversee DEWs (Endo 2021).

In the city of Kumamoto, DEWs were established following the occurrence of the Kumamoto Earthquake. The severe impact of the earthquake on the water supply throughout the city highlighted that the preparations against such a situation had been inadequate. On the basis of this reflection, the Kumamoto city government decided to introduce DEWs in 2017, a year after the earthquake struck. Almost all DEWs in the city of Kumamoto are privately owned. The selection of potential DEWs adopted the following process. First, the city government identified "big pumps" that were already registered. The majority of these (2,200) were wells with a pumping volume of >30,000 m^3/year. Second, the wells had to be currently in use. Third, nearby parking needed to be available for convenient access by the local population, in case water needed to be carried to a vehicle. Finally, the city government asked the owners of such wells to register them as DEWs (Kumamoto City, personal communication 2019). Consequently, 91 organizations had accepted the offer as of March 2020. A breakdown of the registered DEW owners is presented in Fig. 3. It can be seen that the food industry, hospitals, and welfare facilities for aged or handicapped persons represent a substantial proportion of the total number of DEW owners. For reference, private gymnasiums and local shrines are examples of facilities included within the "Others" category (Kumamoto City Government Office Environment Station 2021).

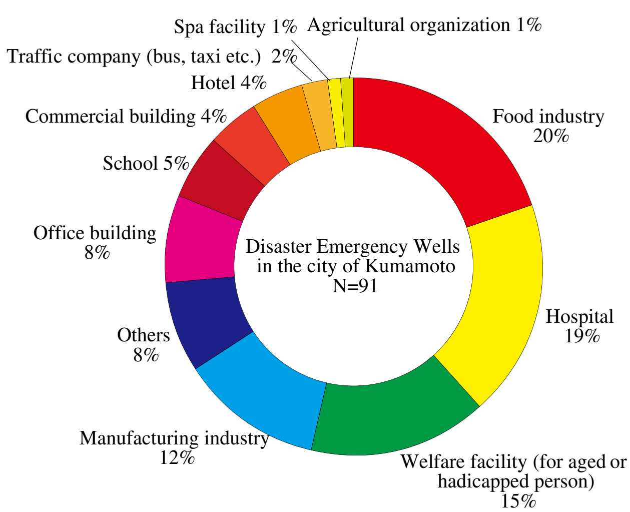


Fig. 3 Breakdown of owners of Disaster Emergency Wells in the city of Kumamoto

Method

Two questionnaire surveys were conducted. Respondents were asked to answer questions online or on paper from 12 February 2021 to 1 March 2021. The first questionnaire survey was sent to the 91 organizations whose wells were registered as DEWs. This survey 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 Kumamoto city government (Table 1). It should be noted that there were no official DEWs when the Kumamoto Earthquake occurred. Nevertheless, the survey revealed that some well owners made their wells available to the public, as discussed in section 'Provision of groundwater'.

The second questionnaire survey was delivered to welfare facilities for aged people. Whereas the objective of the first survey was to investigate the conduct of groundwater suppliers following the earthquake, the second focused on those who demanded groundwater. Overall, 328 facilities were selected

Table 1 Main topics of questions to disaster emergency well (*DEW*) owners and to welfare facilities for aged people

Question No.	Question topics
To DEW owners	
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 Kumamoto city government
To welfare facilities for aged people	
1.	Methods of water supply in the 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

as targets from GIS attribute data compiled by the Ministry of Land, Infrastructure, and Transport (MLIT), Japan (MLIT 2021). The survey posed 17 questions addressing the methods of water supply in each facility at the time of the earthquake's occurrence, effect of the water supply cutoff, recognition of DEWs and utilization of groundwater after the earthquake, emergency water sources other than groundwater, and preparedness efforts following the earthquake. The main topics of questions posed to the aged people at welfare facilities in each survey are listed in Table 1. All the questions and responses relating to the two surveys are presented in the electronic supplementary material (ESM1, survey on disaster emergency wells; ESM2, survey of welfare facilities).

Welfare facilities for aged people were selected as targets for the second survey because they represent a vulnerable group in a time of disaster and for whom special attention should be given regarding emergency water supply. This especially holds true in a rapidly aging society such as that in Japan. Additionally, unlike individual households, postal addresses can easily be obtained for such facilities, enabling efficient distribution of question sheets.

This paper focuses specifically on the responses to questions regarding the impact of the earthquake on wells, groundwater quality inspection after the earthquake, and offers of groundwater to neighbors (topics 1–3 to well owners in Table 1), recognition of DEWs and utilization of groundwater after the earthquake, and emergency water sources other than groundwater (topics 3 and 4 to the welfare facilities in Table 1).

Results

Percentage of responses

The response to the first questionnaire (sent to DEW owners) was 62.6%, i.e., 57 out of 91 organizations responded. The response to the second questionnaire (sent to welfare facilities) was 36.0%, i.e., 118 out of 328 facilities responded.

Effect of earthquakes on wells

A question was asked of DEW owners to ascertain whether they experienced problems with their wells following the earthquake (see Table 1, question No. 1 to well owners, regarding the topic 'Earthquake's influence on wells'). Respondents were required to choose one out of three reply choices: '1. Problem with well operation', '2. No problem with well operation', and '3. Not sure'. The largest number of respondents selected '2. No problem with well operation' (Fig. 4).

An additional question was asked of the 19 respondents who selected '1. Problem with well operation' to determine the nature of the troubles. The respondents were allowed to select multiple replies from among the five choices shown in Table 2. The result reveals that '4. Groundwater became muddy' and '1. Pump came to a halt owing to electricity cutoff' were the top two answers. Interestingly, none of the respondents selected '2. Electricity was available but pump was destroyed'.

Water quality inspection

To investigate the influence of water quality problems on groundwater use, a question was sent to DEW owners to determine whether they inspected the groundwater quality following the occurrence of the earthquake (see Table 1, question No. 2 to well owners, regarding the topic 'Groundwater quality inspection after the earthquake'). Of the 57 responses obtained, 37 respondents acknowledged that inspections were performed. Only three respondents conducted the inspection personally. The remainder (34 respondents) asked for full or partial support from external organizations to conduct the inspection (Table 3).

These 37 respondents were further asked to clarify the length of time that passed before they received the inspection results. They were required to select one of the following four choices: '0–1 day (the result was obtained on the day of the occurrence of the earthquake or the following day)', '2–6 days', '7–13 days', and '14 days or more'. Overall, 34 responses to this question were obtained (i.e., three

Table 2 Troubles that affected the wells

Trouble	No. of respondents
1. Pump came to a halt owing to cutoff electricity supply	5
2. Electricity was available but pump was destroyed	0
3. Groundwater was unavailable owing to water table decline	1
4. Groundwater became muddy	9
5. Others (free descriptive answer)	6
Total	21

Fig. 4 Occurrence of problems with well operation

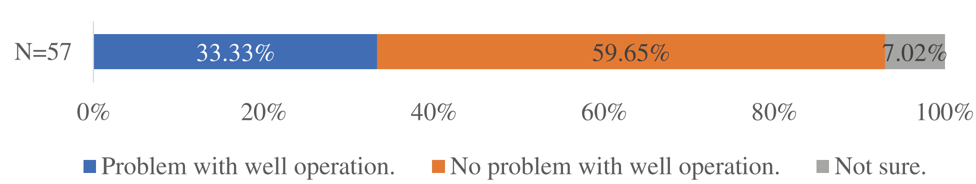


Table 3 Implementation of groundwater quality inspection

Method	Responses	(%, No.)
1. Inspection was conducted personally	5.26%	3
2. Inspection was conducted by an external organization	50.88%	29
3. Inspection was conducted personally and by an external organization	8.77%	5
4. Inspection was not conducted	24.56%	14
5. Not sure if inspection was conducted or not	10.53%	6
Total		57

Table 4 Purposes of groundwater provision by DEW owners

Purpose	Responses (%, No.)	
1. Drinking purposes (including cooking purposes)	3.33%	1
2. Domestic purposes (toilet, laundry, and bathing)	63.33%	19
3. Fire protection	0.00%	0
4. Drinking and domestic purposes	23.33%	7
5. Drinking and fire protection purposes	0.00%	0
6. Domestic and fire protection purposes	3.33%	1
7. Drinking, domestic, and fire protection purposes	0.00%	0
8. Others (free descriptive answer)	6.67%	2
Total	100%	30

respondents declined to answer). The result reveals that only 29% of respondents (10 out of the 34 respondents) obtained the results of the inspection within a week (Fig. 5).

Provision of groundwater

A question was posed to DEW owners to determine whether they provided groundwater to the local population to investigate how local wells had actually been used following the earthquake. (see Table 1, question No. 3 to well owners, regarding the topic 'Provision of groundwater to neighbors'). Respondents were required to choose one of two options: '1. Provided' or '2. Did not provide'. Of the 57 responses, 30 (52.6%) chose the first option (Fig. 6).

An additional question was asked of the 30 respondents who did provide groundwater to ascertain the primary purpose for which the water was used. Respondents were required to select just one of the eight choices shown in Table 4. The result reveals that the largest number of respondents selected '2. Domestic purposes (toilet, laundry, and bathing)', followed by '4. Drinking and domestic purposes'.

An additional question was asked of the 30 DEW owners who reported that they provided water to the local population to determine when that provision commenced. The responses revealed that a reasonably large number of DEW owners started to provide groundwater to the local population on the day of the earthquake or on the following day (Fig. 7).

Groundwater use by welfare facilities for aged people

A question was sent to the welfare facilities for aged people in Kumamoto city to determine whether they obtained groundwater from local wells (see Table 1, question No. 3 to welfare facilities, regarding the topic 'Recognition of DEWs and utilization of groundwater after the earthquake'). Respondents were required to choose one of the following two choices: '1. We obtained groundwater from local wells' and '2. We did not obtain groundwater from local wells'. Of the 116 facilities that answered this question, 44 (approximately 38%) selected the first option (Fig. 8).

An additional question to ascertain well ownership was then asked of the 44 facilities that selected '1. We obtained groundwater from local wells'. Respondents were allowed

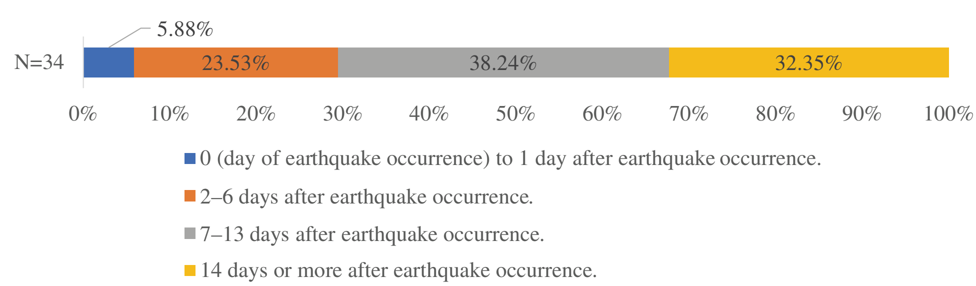


Fig. 5 Number of days that passed before the results of groundwater quality inspections were received

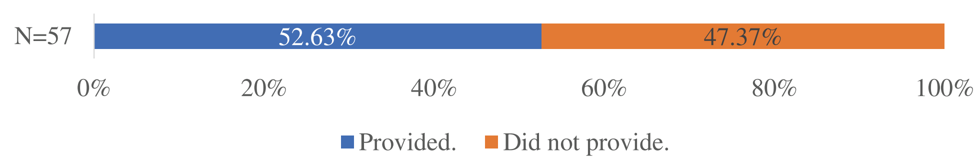


Fig. 6 Provision or lack of provision of groundwater

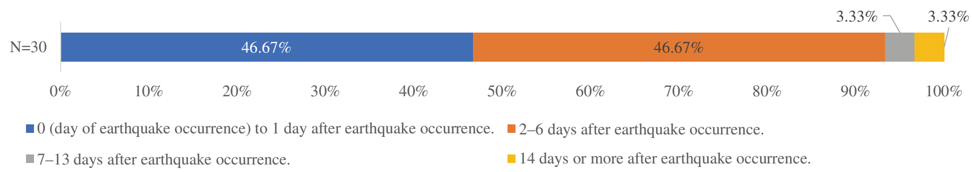


Fig. 7 Time when DEW owners started to provide groundwater

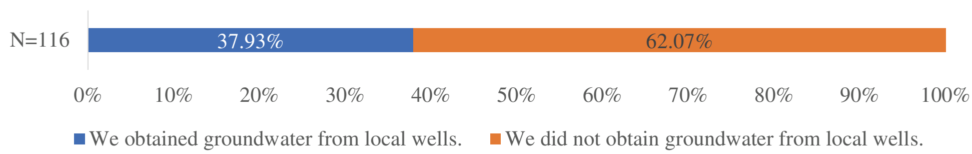


Fig. 8 Groundwater use by welfare facilities for aged people

Table 5 Breakdown of well ownership

Well owner	No. of responses
1. Resident of detached house	25
2. Resident of apartment house	2
3. Factory	4
4. Shopkeeper	2
5. Shopping complex	0
6. Local firm	0
7. Community center	0
8. School	1
9. City government	5
10. We do not know who owned the well	1
11. Others (free descriptive answer)	8
Total	48

Table 6 Purposes of groundwater use by welfare facilities for aged people

Purpose	Responses (%, No.)	
1. Drinking purposes (including cooking purposes)	18.18%	8
2. Domestic purposes (toilet, laundry, and bathing)	50.00%	22
3. Fire protection	0.00%	0
4. Drinking and domestic purposes	27.27%	12
5. Drinking and fire protection purposes	0.00%	0
6. Domestic and fire protection purposes	2.27%	1
7. Drinking, domestic, and fire protection purposes	2.27%	1
8. Others (free descriptive answer)	0.00%	0
Total	100%	44

to choose multiple options from the 11 choices listed in Table 5, whereby the result reveals that the largest number of respondents selected ‘1. Resident of detached house’.

Another question was then asked of the same 44 facilities to clarify the purposes for which they used the water obtained from the local wells. The results show that the most common use was for domestic purposes (toilet, laundry, and bathing; Table 6).

Recognition of DEWs by welfare facilities

A question was asked of the welfare facilities regarding whether they were aware of the institution of DEWs in general (see Table 1, question No. 3 to welfare facilities, regarding the topic ‘Recognition of DEWs and utilization of groundwater after the earthquake’). The 115 responses obtained revealed that only 25% of respondents had such knowledge (Fig. 9).

Emergency water sources other than groundwater

A question was asked of the welfare facilities regarding ways, other than from groundwater, via which they secured a supply of water for drinking and domestic purposes following the occurrence of the earthquake (see Table 1, question No. 4 to welfare facilities, regarding the topic ‘Emergency water sources other than groundwater’). Overall, 113 responses were obtained regarding ways to secure drinking water and 114 responses were obtained regarding ways to secure water for domestic purposes. The result shows that government water stations were not the only alternative—for example, the facilities were able to obtain water from their own water receiving tanks, their own stock of bottled water, and supportive action from external volunteers. Water delivery from relatives who lived nearby, local rivers, and school pools are examples of sources in the ‘Others’ category (Fig. 10).

Discussion

Robustness of wells

As compiled in Fig. 4, in terms of the question on whether they experienced problems with their wells following the

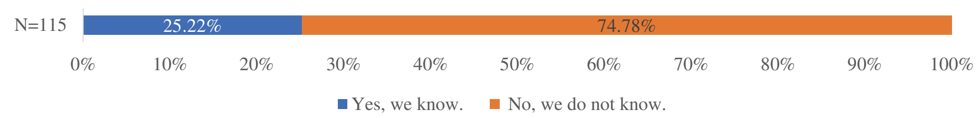


Fig. 9 Recognition of disaster emergency wells

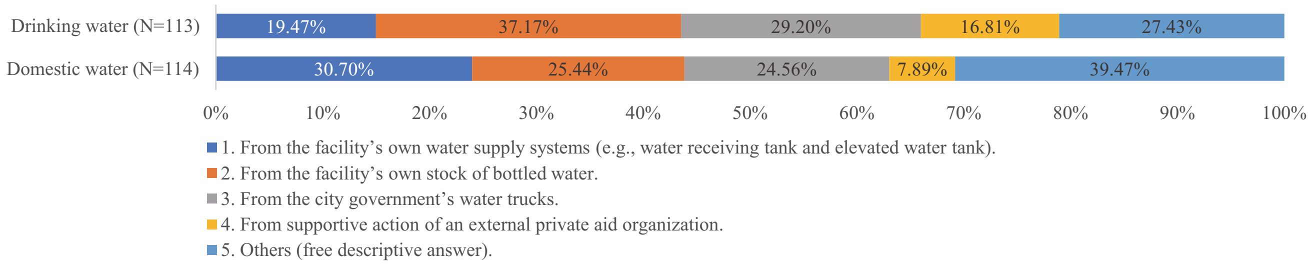


Fig. 10 Emergency water sources other than groundwater

earthquake, the option of '2. No problem with well operation' was selected more than the option of '1. Problem with well operation'. Furthermore, regarding the question on the nature of the problems (Table 2), none of the respondents selected the option of '2. Electricity was available but pump was destroyed'. These two results indicate that wells proved to be a robust facility following the Kumamoto Earthquake and that they could represent an important water supply following another similar disaster. The main cause of well dysfunction was not the destruction of the actual facility but rather the loss of electricity supply or deterioration of water quality.

This result accords with the findings of research conducted by the National Water Well Association of Japan. The association investigated 261 wells in the most severely damaged prefectures 6 months after the Great East Japan Earthquake. Their results revealed that 213 wells (81.6% of the surveyed wells) continued operation unaffected by the earthquake and/or tsunami, 34 wells (13%) were temporarily affected by seawater intrusion or turbidity but were soon returned to normal operation, and 14 wells (5.4%) ceased operating. Of the 14 wells that stopped functioning, 8 were affected by the tsunami. Overall, only three wells (1.3% of the surveyed wells) ceased operation because of structural damage. From this field survey, the association concluded that wells generally have strong resilience against earthquake-induced shaking and could play an important role as an emergency water supply (National Water Well Association of Japan 2012).

Limitation on well use by groundwater quality degradation

It can be seen from Table 3 that of the 57 responses received from DEW owners, 34 indicated that groundwater inspection was conducted with the full or partial support of external organizations, which implies that the samples were examined by third-party laboratories.

Figure 5 reveals that only 29% of respondents (10 out of 34 respondents) obtained the results of the inspection within a week, which implies that the availability of DEWs is not a panacea for securing drinking water. The demand might be brought about immediately following the occurrence of an earthquake and the required quality is high. It is necessary to consider the combined uses of groundwater and other water sources including storage of bottled water and installation of water tanks for individual households. As shown in Fig. 10, many of the welfare facilities in Kumamoto city adopted just such an approach of diversification.

In other words, DEWs could be highly effective as long as the use of the water is limited to purposes that do not need high quality, e.g., toilets. This is the case in Kumamoto. Table 4 shows that the primary purpose of groundwater provided by DEW owners was for domestic purposes (toilet, laundry, and bathing). Table 6 reveals that those welfare facilities that obtained groundwater from local wells used it mainly for the same purposes. The fact that DEW owners would rather provide for nondrinking water needs can be considered a reflection of the users' preference.

If application of DEWs were to be extended to include drinking water, it will be necessary to establish rapid inspection methods. After the earthquake, just such an inspection system was developed in Kumamoto. The purpose of water extracted from DEWs in Kumamoto is generally intended for drinking and other domestic purposes. If a well owner wants to provide well water for drinking purposes, the Kumamoto City Environmental Research Center is supposed to check the water quality and inform the well owner whether it can be served for that purpose within 2 days of sample collection (Kumamoto City Government Office Environment Station 2021). However, it can be seen from Table 7, which presents survey answers regarding the inspection methods and the number of days that passed before the results of groundwater quality inspections were received, that it took longer than 2 days to receive the inspection results for those who resorted to external organizations for testing. Whether the Kumamoto City Environmental Research Center is really able to inform well owners of the groundwater quality of the wells within 2 days remains uncertain.

Advantage of DEWs: improvement in access to water

An advantage of DEWs is the improvement in access to water. This point can be explained with reference to Fig. 11a, b in which the background shading represents population density based on the national population census data of 2015.

First, red circles show the DEW owners who provided groundwater to the local population. Red circles with a cross inside identify DEWs whose owners who did not reply to the questionnaire distributed in this study, but did provide a positive answer to a question on groundwater provision in Koga and Hamada (2020). It can be seen that the DEW owners who provided groundwater to the local population are largely concentrated in areas with high population density.

Second, Fig. 11 also shows the spatial distribution of the emergency water stations established by the Kumamoto city government (blue pin marks). The number of these stations varied daily but it reached a maximum (33) 10 days after the earthquake struck, as illustrated in Fig. 2 (Kumamoto City Waterworks and Sewerage Bureau 2018). Figure 11 describes the situation at that time. The blue circle (scaled radius: 500 m) around each emergency water station represents the distance of the Sphere Standard established by a group of nongovernmental organizations (NGOs), 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).

It is evident from Fig. 11b that the number of water stations was insufficient to meet the Sphere Standard. This means that the inadequate number of water stations forced local people to wait in long lines to obtain water, as acknowledged by the Kumamoto City Waterworks and Sewerage Bureau (2018). To some extent, the DEWs compensated for the lack of emergency water stations and improved access to water for the local people.

Figure 11 also presents the distribution of the welfare facilities for aged people who obtained groundwater (wheelchair symbols). Table 5 shows that 25 facilities obtained groundwater from '1. Resident of detached house'. As illustrated in Fig. 3, the DEWs in Kumamoto comprise wells owned by industries, welfare facilities, hospitals, and schools, but do not include wells associated with individual private houses. Thus, it is highly probable that private wells not registered as DEWs were also used after the earthquake. Welfare facilities that obtained groundwater from the well of a detached house are indicated by red-colored wheelchair

Table 7 Inspection methods and number of days that passed before the results of groundwater quality inspections were received

Inspection method	0 (day of earthquake occurrence) to 1 day after earthquake occurrence	2–6 days after earthquake occurrence	7–13 days after earthquake occurrence	14 days or more after earthquake occurrence	No reply	Total
Inspection was conducted personally	2	0	0	0	1	3
Inspection was conducted by an external organization	0	6	11	10	2	29
Inspection was conducted personally and by an external organization	0	2	2	1	0	5
Total	2	8	13	14	3	37

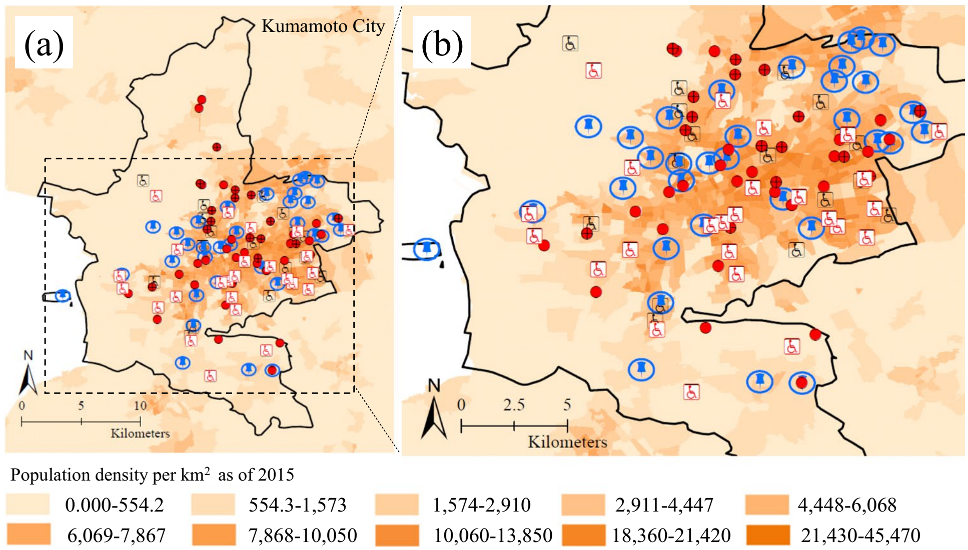


Fig. 11 **a** Spatial distribution of population (shading), DEWs that provided groundwater to the local population (red circles), emergency water stations established by the Kumamoto city government (blue pins), and welfare facilities for aged people who obtained groundwater (wheelchair symbols) in Kumamoto, and **b** enlarged map of the area defined by the dotted rectangle (**a**). A red circle with a cross inside identifies a DEW whose owner did not reply to the questionnaire distributed in this study but did provide a positive answer to a question on groundwater provision in Koga and Hamada (2020). 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 waterpoint. Red-colored wheelchair symbols identify welfare facilities that obtained groundwater from the well of a detached house not registered as a DEW

symbols. Clearly, they further reduced the burden of the relief activities of the city government.

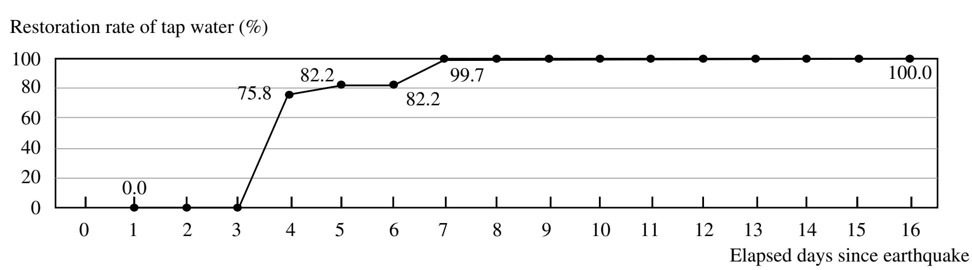
Advantage of DEWs: rapid water supply

Figure 7 shows that a reasonably large number of DEW owners started to provide groundwater to the local population on the day of the earthquake or on the following day. The importance of the timing of this provision is evident in consideration of Fig. 12. It shows the change in the rate of restoration of tap water, where the restoration rate of tap water is calculated by dividing the number of households with restored water supply by the maximum number of households that experienced a cutoff of water supply. It can be seen that tap water was completely unavailable for 3 days following the occurrence of the earthquake, but that restoration of this service occurred rapidly over the subsequent 4 days. Figure 7 highlights the importance of the role of DEWs in providing a water supply during the time when tap water was unavailable. Moreover, it was not until 10 days after the occurrence of the earthquake that the city government increased the number of emergency water stations to 33 (Fig. 2). In contrast, as shown in Fig. 7, most well owners started to provide groundwater to the local population within 6 days of the earthquake. The timeliness of this water supply can be regarded as a major advantage of DEWs.

Quantitative estimation of water provision capacity of DEWs

It is informative to consider quantitative evaluation of the water provision capacity of DEWs within 2 days of the earthquake striking. As Fig. 12 shows, no restoration of tap water was achieved during this period. As explained in

Fig. 12 Change in rate of restoration of tap water



section ‘Provision of groundwater’, 30 of the 57 respondents provided groundwater to the local population. Among them, were nine DEW owners who also satisfied the following conditions: (1) the earthquake did not cause any problems regarding the well, and (2) the well owner started to provide groundwater within 2 days of the earthquake striking. It can be inferred that these wells maintained normal pumping capacity even after the earthquake. Thus, it is possible to estimate the potential provision capacity of the DEWs by multiplying the daily pumping volume by the length of time that the wells were open to the public.

The daily pumping volume was obtained from the annual report on groundwater utilization in Kumamoto. This report is published in accordance with city ordinance and is supposed to list wells whose pumping volume was >30,000 m^3/year (82.2 m^3/day) during the previous year. This study checked the pumping volume in 2016, i.e., the year of occurrence of the Kumamoto Earthquake (Kumamoto City 2017). In cases where pumping volume was not listed, information was collected by checking the annual report of adjacent years and through personal communication.

Regarding the duration in which their well was open, the nine DEW owners responded as follows: six owners selected ‘1. An entire day’, one owner selected ‘2. Daytime’, and two owners chose ‘3. A part of daytime’. Coefficients of 1, 0.5, and 0.25 were added to each choice, respectively, and the potential total provision capacity of the DEWs was calculated as 1,423.3 m^3/day (Table 8). For reference, the Ministry of Health, Labour, and Welfare of Japan (2015) recommends that a volume of at least 3 L (0.003 m^3) of drinking water per person per day should be secured in the first 3 days following an earthquake to support life. The population of Kumamoto in the year of the earthquake was 740,204 (Kumamoto City 2021). Therefore, it is estimated that 2,220.6 m^3/day (740,204 × 0.003 m^3/day) of water is needed for the entire population. However, according to the Kumamoto City Waterworks and Sewerage Bureau (2018), water provision by the city government (via water trucks) was just 133.1 m^3 on 15 April (2 days after the earthquake struck). Clearly, the total potential provision capacity of the nine DEWs was inadequate to satisfy the total estimated water demand, but it was much larger than the volume actually provided by the city government. It is evident that the availability of these DEWs helped the city government with the emergency water supply in the early restoration stage.

Information disclosure

Figure 13 presents a modification of Fig. 11, in which the welfare facilities for aged people that used local wells (wheelchair symbols in Fig. 11) are replaced by those that did not use local wells (X marks in Fig. 13). It can be seen that many welfare facilities did not use local wells, even though some DEWs were nearer than the closest emergency water stations. One possible reason is that those facilities were unaware that DEWs were open nearby. Figure 9 reveals that only 25% of respondents (welfare facilities) had knowledge of DEWs even after the earthquake.

This implies that a public awareness campaign is important following the introduction of DEWs. In the case of Kumamoto, DEWs are currently operated by industries, hospitals, welfare facilities, and schools; therefore, it is less problematic to disclose positional information to the public because privacy concerns are not paramount. Consequently, DEW location information has been disclosed on the official website of the Kumamoto city government. Nonetheless, the level of recognition of DEWs is not high, as shown in Fig. 9. It is partly because it takes time and effort for local residents

Table 8 Estimation of potential provision capacity of wells

Respondent	Pumping volume (m^3/day)	Duration when well was open	Coefficient	Potential provision capacity of local wells (m^3/day)	Reference
A	167.8	An entire day	1	167.8	Kumamoto City (2017)
B	96.6	An entire day	1	96.6	Kumamoto City (2018)
C	60.3	Daytime	0.5	30.1	Anonymous, private Co., personal communication, 2021
D	2,375.0	A part of daytime	0.25	593.8	Kumamoto City (2017)
E	77.5	An entire day	1	77.5	Anonymous, hospital, personal communication, 2021
F	120.0	An entire day	1	120.0	Kumamoto City (2020)
G	306.7	An entire day	1	306.7	Kumamoto City (2017)
H	6.5	An entire day	1	6.5	Anonymous, highschool, personal communication, 2021
I	97.0	A part of daytime	0.25	24.3	Kumamoto City (2017)
Total	-	-	-	1,423.3	-

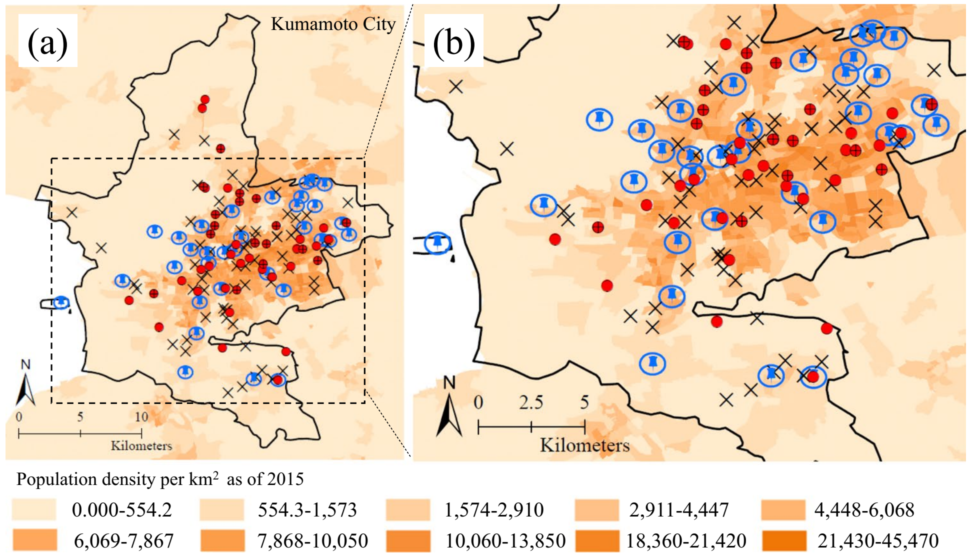


Fig. 13 **a**–**b** Same as Fig. 11a,b, respectively, but instead showing welfare facilities for aged people that did not obtain water from local wells (X marks)

to obtain such information. Providing a public awareness campaign via newspapers or during local evacuation training opportunities might help raise the level of DEW recognition.

Conclusions

This paper revealed the actual situation of groundwater use following the Kumamoto Earthquake via two questionnaire surveys distributed to DEW owners and welfare facilities for aged people in the city. The main conclusions derived are as follows.

More than half of the respondents (DEW owners) indicated that the earthquake did not provoke problems with well operation. In cases where well dysfunction was observed, the main cause was not the destruction of the actual facility but the loss of the electricity supply or deterioration of water quality. This indicates that wells proved to be a robust facility following the Kumamoto Earthquake and that they could play an important role as an emergency water supply.

It was found that 30 DEW owners provided groundwater to the local population. Additionally, at least 25 privately owned wells not registered as DEWs were also open to the public following the earthquake. DEWs began to operate in the early restoration stage and improved access to water for the local population, diminishing the burden on the emergency water supply provision by the city government. It was estimated that the potential total provision capacity of the DEWs was 1,423.3 m^3/day. This volume was inadequate to satisfy the estimated water needs for the entire population (2,220.6 m^3/day), but it was large compared with the actual water provision by the city government's water trucks of just 133.1 m^3/day 2 days after the earthquake's occurrence.

The survey revealed many cases where it took more than a week to finish groundwater quality inspections after the occurrence of the earthquake. This implies that DEWs could be an effective water resource as long as the use of the water is limited to purposes that do not need high quality, e.g., toilets, as observed in Kumamoto. Moreover, many welfare facilities did not use adjacent DEWs that were open, which suggests that improving information disclosure is a policy issue to be resolved.

Future work should investigate other cases where groundwater has actually been used as in the case of Kumamoto. An appropriate combination of groundwater with other local water sources such as storage of bottled water, building water tanks, use of school pools, and operation of water trucks by the city government should also be considered. Such studies could lead to policy improvements regarding the provision of a stable water supply in emergency situations.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10040-022-02547-9.

Acknowledgements The authors thank Kumamoto city government for providing data on the emergency water supply following the Kumamoto Earthquake. Special thanks are offered to the owners of the Disaster Emergency Wells and the welfare facilities for aged people in Kumamoto for answering our questionnaire surveys. The views presented are those of the authors and should in no way be attributed to others. Responsibility for the text (including any errors) rests entirely with the authors. We thank James Buxton, MSc, from Edanz for editing a draft of this manuscript.

Funding We thank Prof. Taikan Oki of the University of Tokyo for his continuous support. Under his leadership, we implemented the research project on groundwater use in an emergency supported by the Council for Science, Technology, and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), Enhancement of National Resilience against Natural Disasters (Funding agency: National Research Institute for Earth Science and Disaster Resilience).

We thank Prof. Shinichi Yatsuki of Kyushu University for providing us with the opportunity to join the research project on groundwater governance supported by the Japan Society for the Promotion of Science KAKENHI (Grant-in-Aid for Challenging Exploratory Research) grant number 20H04392. Special thanks go to Osaka Prefecture University for providing financial support. Finally, our research is partially supported by the Japan Society for the Promotion of Science KAKENHI (Grant-in-Aid for Challenging Exploratory Research) grant number 22K12498. 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.

Declarations

Conflicts of interest/Competing interests The authors declare no conflict of interest.

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