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Measures for groundwater security during and after the Hanshin-Awaji earthquake (1995) and the Great East Japan earthquake (2011), Japan

Tadashi Tanaka [1*]

1. University of Tsukuba, 1-1-1 Tennodai, Tsukuba City, Ibaraki 305-8577, Japan
   e-mail: tadashi@geoenv.tsukuba.ac.jp

Abstract Many big earthquakes have occurred in the tectonic regions of the world, especially in Japan. Earthquakes often cause damage to crucial life services such as water, gas and electricity supply systems and even the sewage system in urban and rural areas. The most severe problem for people affected by earthquakes is access to water for their drinking/cooking and toilet flushing. Securing safe water for daily life in an earthquake emergency requires the establishment of countermeasures, especially in a mega city like Tokyo. This paper described some examples of groundwater use in earthquake emergencies, with reference to reports, books and newspapers published in Japan. The consensus is that groundwater, as a source of water, plays a major role in earthquake emergencies, especially where the accessibility of wells coincides with the emergency need. It is also important to introduce a registration system for citizen-owned and company wells that can form the basis of a cooperative during a disaster; such a registration system was implemented by many Japanese local governments after the Hanshin-Awaji Earthquake in 1995 and the Great East Japan Earthquake in 2011, and is one of the most effective countermeasures for groundwater use in an earthquake emergency. Emphasis is also placed the importance of establishing of a continuous monitoring system of groundwater conditions for both quantity and quality during non-emergency periods.

Keywords Emergency groundwater resources・Disaster・Japan・Earthquake・Groundwater management

NOTE TO COPYEDITOR – PLEASE INSERT THE FOLLOWING AS A FIRST-PAGE FOOTNOTE:

This article belongs to a group of articles that consider groundwater resources for risk reduction in emergencies

Introduction

A catastrophic earthquake and tsunami devastated the Pacific coast of north-eastern Japan on March 11, 2011, and has been called the 'Great East Japan Earthquake'. The magnitude of the earthquake was 9.0, and it is considered to be the biggest magnitude ever measured in Japan. This great earthquake was caused by thrust faulting between the Pacific and North American plates (Ujiie et al. 2013; Chester et al. 2013; Fulton et al. 2013) extending 450 km in the south-north direction and 200 km in the east-west direction as shown in Fig. 1. Three prefectures in the Tohoku (north-eastern) region of Japan — Miyagi, Iwate and Fukushima — were most seriously damaged. By the earthquake and tsunami, around 19,000 lives were lost; 6,000 people were injured and 385,000 houses collapsed (National Police Agency 2014). Many cities and towns in the Tohoku region still await reconstruction and the area around the Fukushima Daiichi (No.1) Nuclear Power Plant is still evacuated due to radioactive contamination.

Fig. 1

In the Great East Japan Earthquake, around 2,300,000 households were cut off from the municipal water supply immediately after the earthquake and 1,000,000 households were still suspended even after 1 week passed. Maximum length of cut off time from the municipal water supply reached nearly 5 months after the earthquake in some severe disaster-struck districts (National Water Well Association of Japan 2013).

Before this Great East Japan Earthquake, Japan experienced another big earthquake called the Hanshin-Awaji Earthquake (M 7.3) which occurred on January 17, 1995. At that time, this big earthquake was the worst natural disaster in Japan after the World War II. It happened on the Niigata-Kobe strain concentration belt as shown in Fig. 2. This intraplate strain concentration belt might be caused by viscosity heterogeneities in the mantle (Yamasaki and Seno 2004). Many other big earthquakes associated with this belt have devastated Japan recently as indicated in Fig. 2. In the Hanshin-Awaji Earthquake, around 1,270,000 households were cut off from the municipal water supply immediately after the earthquake and 490,000 households whose drinking water still suspended even after 1 week passed. Maximum length of suspended municipal water supply reached 3 months after the earthquake.

Fig. 2

Usually, earthquakes cause severe damage to life services such as water, gas and electricity supply systems. Among those, security of safe water is the most serious problem in the disaster areas, especially in a mega city located in the tectonic regions in the world, as it takes a long time after the earthquake for recovery of the municipal water supply system (Table 1).

Table 1

After the Hanshin-Awaji earthquake, the Research Committee on the Security of Water in the Great Earthquake Disaster was established in Japan and the Committee published a report 'On securing of water in the Great Earthquake Disaster in a mega city in Japan' in 1999 (Research Committee on the Security of Water in the Great Earthquake Disaster 1999). In addition, the Ministry of Land Infrastructure, Transport and Tourism (MLIT) published the 'Guidelines for groundwater use in earthquake disasters' (MLIT 2009). These actions mean that water-use problems in earthquake emergencies have been studied and monitored carefully in Japan since the 1995 Hanshin-Awaji Earthquake.

After suffering the Great East Japan Earthquake, the Japanese Association of Groundwater

Hydrology (JAGH) held a symposium on “The way of groundwater use as the emergency water source at the time of the earthquake” (JAGH 2012; Taniguchi and Nakajima 2013). In addition, the UNESCO-IHP-GWES group (IHP is the International Hydrological Programme, and GWES is Groundwater for Emergency Situations) published a book “Groundwater Resources for Emergency Situations: A Methodological Guide” in 2011 (Vrba and Verhagen eds. 2011). The scientific community’s recent activities imply that groundwater resources are recognized as an important water source for emergency situations caused by severe natural hazards such as earthquake and tsunami disasters.

Case studies on groundwater resources for emergency situations especially in earthquake and tsunami disasters are reported from widely differing regions. Chadha et al. (2006) reported on groundwater risk management during the 2001 Bhui earthquake in India. The impact of the 2004 Indian Ocean tsunami on the Indian coastal groundwater system is reported by Keshari et al. (2006). The effect of this 2004 tsunami on groundwater resources in the Maldives islands is reported by van der Linden (2011) and the impact of this 2004 tsunami and rehabilitation of groundwater supplies in eastern Sri Lanka is described by Villholth et al. (2011). Beside earthquake and tsunami disasters, van der Linden (2006) described the emergency groundwater supplies during flood and drought disasters in the Netherlands as an example of delta area.

The afore-mentioned case studies, however, mainly focused on the *risk management* of groundwater resources during earthquake and tsunami disasters and the methodology and technology for emergency remediation or rehabilitation of groundwater resources. There is little information on the usefulness of groundwater resources and measures for groundwater security in the earthquake *emergency* itself. An overview of the use of groundwater resources for risk reduction in emergencies is given in the accompanying essay in this volume of *Hydrogeology Journal* by Vrba and Renaud (2015). The purpose of this paper is to clarify the importance of groundwater resources in the earthquake emergency and to show some examples of groundwater use regarding the Hanshin-Awaji Earthquake and the Great East Japan Earthquake, as one of countermeasures for water security in earthquake disasters.

Groundwater resources of Japan

Geologically, groundwater resources in Japan constitute storage in mainly the alluvium, Pleistocene series and Neogene series strata (Editorial Committee on Groundwater of Japan 1986). Alluvium is deposits of Holocene and the final stage of the Pleistocene, constituted with sand, sandy clay, gravel and volcanic deposits. Those deposits are widely distributed in the coastal plains, flood plains, and sand dunes and at the foot of volcanoes. In Japan, until around 50 years ago, groundwater resources in the alluvium were widely used for domestic or municipal water supplies by shallow wells. The Pleistocene series is constituted from many alternations of coarse and fine deposits caused by several sea level fluctuations due to glacial cycles in the middle and late Pleistocene. This series of deposits provides the main groundwater storage aquifers of Japan. The Neogene series is the deposits of Pliocene and Miocene constituted with relatively fine grained and highly compacted materials and volcanic rocks. In general, the strata of this series are of lower permeability than younger age deposits.

Aquifers are distributed in all Japanese islands from north to south and the estimated total area of relatively large groundwater basins is 66,000 km^2 corresponding to 17.6 % of the entire land area of Japan (Marui et al. 2009). It is reported that the maximum storage volume of groundwater resources in the alluvium, Pleistocene series and Neogene series is 160, 16,440 and 27,580 km^3, respectively (Marui et al. 2009). Therefore, the total potential storage volume of the groundwater resources of Japan is estimated as 44,180 km^3. As the fresh groundwater storage volume of the world is estimated at around 10,530,000 km^3 (Shiklomanov ed. 1997), so the estimated total groundwater storage volume of Japan corresponds to 0.42 % of the world.

From the view point of the climatic water balance of Japan, around one-half of the average annual rainfall evaporates and around one-third runs off as overland flow, and the rest (one-sixth) infiltrates to beneath the surface. The average annual rainfall in Japan is estimated as 1,690 mm (30 years average for 1981-2010, MLIT 2014), thus infiltrated amounts are estimated around 280 mm/year. Although all infiltrated water does not become groundwater resources, the maximum recharge rate might be estimated by multiplying this value and the country land area (of 378,000 km^2), which is around 106 km^3/year, a value which may be the annual potential recharge rate of groundwater resources in Japan.

Table 2

Table 2 shows the groundwater usage in Japan in 2011 (MLIT 2014). The total amount of annual groundwater use is around 11.2 km^3/year (MLIT 2014), meaning nearly one-tenth of the annual potential recharge rate mentioned in the preceding. It can be seen from Table 2 that more than 80 % of total groundwater use is consumed for domestic, industrial and agricultural purposes. The dependence ratio of groundwater use in domestic water, industrial water and agricultural water is 21, 28, and 5 %, respectively at the present time.

As mentioned in the preceding, the potential groundwater storage volume of Japan is relatively large and the annual potential recharge rate is also high because Japanese islands are located at middle latitude and in humid climate conditions, and are formed from a relatively young geologic age strata. Nevertheless, the groundwater-use ratio compared to river water use is not so high at the present time. This is due to the fact that, in Japan, during the high economic growth period of around 1960s and 1970s, over-exploitation of groundwater resources caused groundwater hazards such as land subsidence and seawater intrusion in the major coastal plains and exploitation has been restricted by the national laws introduced in 1956 and 1962 (Endo 1992; Tanaka 2007).

General aspects of water security in an earthquake emergency

In an earthquake emergency, the most important problem for affected people is establishment of a source of water for their drinking/cooking and toilet flushing. In some cases, water for firefighting is the most urgent necessity because often hydrants do not work well during earthquake disasters. Medical activities are also impaired largely by the destruction of the water supply system.

Based on the reports of the Research Committee on the Security of Water in the Great Earthquake Disaster (1999) and the MLIT (2009), general aspects of water security during earthquake emergencies (such as the 'water demand phase'), the target amount of water needed in the emergency water supply, water needs for the utilization categories, and characteristics of the water source are summarized below.

Fig. 3

The water demand phase in the earthquake disaster may be divided into three sub-phases as shown in Fig. 3. Phase 1 corresponds to the period from immediately after the earthquake occurred to 3 days after the earthquake in which water supply focuses on the demand for firefighting, medical activities and drinking water. In phase 2, from the first day after the earthquake occurred to restoration of normal activity, water supply meets the demand for drinking/cooking, toilet flushing, bathing/washing and restoration of municipal functions. The period from 4 days after the earthquake till restoration of the city area is categorized as phase 3. In this phase, water for increased domestic-water use and water to facilitate reconstruction of building and industry are needed.

Fig. 4

Figure 4 shows the target amount of emergency water supply, which is the basis of planning by the Administration Office of Kobe city. This figure indicates an expected amount of water demand per person per day depending on the time passed after the earthquake. It seems that the amounts of water demand indicated in this figure are the minimum requirements in the earthquake emergency of a mega city.

Table 3

In the earthquake emergency, not only sufficient quantity of water but also the quality of water is required for some purposes. Table 3 summarizes the water needs for each utilization category in the earthquake disaster, considering the time and place and the required amount and quality. For medical activities, high water quality and a large amount of water is necessary immediately after the event, and it needs to be sustained for continuous supply. This is one of the largest water use problems in the earthquake emergency because transportation of such high quality water to the hospital is needed, which is difficult. Drinking/cooking and bathing/washing also needs clean water. On the other hand, for firefighting and the toilet flushing, although a huge amount of water is necessary, there is no strict requirement on water quality, as indicated in Table 3.

Table 4

Table 4 shows the characteristics of water sources for considering utilization of water in the earthquake emergency, and this table may be useful for the risk assessment of water sources. River and sea waters are in large quantity but those waters must be transported to required places; again, transportation is not usually easy in an earthquake emergency. Moreover, seawater must be treated before it is used for otherwise freshwater purposes. On the other hand, groundwater has the advantage of coincidence with respect to need and location of supply, although the amount of water will be affected from place to place. This groundwater advantage will be useful for domestic-water use and other immediate needs, such as the initial firefighting as mentioned before and toilet flushing, which are listed as crucial water requirements in an earthquake emergency. The summary indicates that in an earthquake emergency, not only the amount of water but also the quality of water is important for some purposes.

Examples of groundwater use in the earthquake emergencies experienced in Japan

Some examples of groundwater use during the Hanshin-Awaji Earthquake are reported by Tanaka (2011); specific examples of water use in the early stage of the earthquake are listed in the following:

- Immediately after: well water was used for firefighting by bucket relay with 500 citizens
- One day after : a 100-m line of citizens worked together to extract and distribute well water
- Three days after: 200 citizens used groundwater for domestic use by pumping from a 7-m deep well

Table 5 summarizes the water sources that were used by citizens in Kobe city for firefighting in the earthquake emergency. It can be seen that groundwater use for firefighting was significant compared with other water sources. It is also reported that in the case of the Hanshin-Awaji earthquake, the recovery of water supply on Awaji Island was prompt because most of households on the island have their own shallow wells on their property and they could pump up shallow groundwater using hand pumps or electricity which had already been recovered within the same day of the earthquake (Yoshioka 2006).

Table 5

Some hospitals introduced a deep well facility after the Hanshin-Awaji Earthquake, which can supply 80 % of drinking water in normal times, with a membrane filtration system and a private power plant system as shown in Fig. 5. By April 2004, 116 hospitals throughout the whole of Japan had introduced a well facility with these systems (Sugimoto 2004). The Ministry of Health and Labor carried out a survey in 2011 on water use for medical activities during the Great East Japan Earthquake and obtained answers from 489 hospitals in the devastated region. The results of the questionnaire were as follows; 207 hospitals (42.3 %) have a half-day or 1-day capacity for water storage in tanks, 126 hospitals (25.7 %) have 2 days' tank storage or more, and 229 hospitals (46.8 %) have a well facility (National Water Well Association of Japan 2013). This means that the number of hospitals with a well facility nearly doubled during the 7 years from 2004 to 2011. The efficiency of groundwater use by hospitals in the earthquake disaster area was also reported, citing the following example of a hospital located in Mito city (Ibaraki prefecture in the southern region), which was affected by the Great East Japan Earthquake:

Fig. 5

- Hospital scale　500 beds
- Daily water use amount　273 m^3
- Capacity of water storage tank　200 m^3
- Groundwater supply at non-emergency times　90 % of daily water use amount

In this case-hospital, the water supply (from groundwater) for medical use was not cut off, and it was possible for this hospital to accept many patients during the Great East Japan Earthquake, even though the suspension of the municipal water supply continued for 14 days in the surrounding area.

The case of Sendai city, which suffered serious damage during the Great East Japan Earthquake, is also reported by the National Water Well Association of Japan (2013); in this city, the registration system of cooperative well owners for disaster purposes started in 2000, and the number of registered private and company wells was 185 and 39, respectively, at the time when the great earthquake happened in 2011. The results of the survey by the city council on use of these registered wells in the great earthquake emergency are shown in Table 6. It is clear that in the region of suspended municipal water supply, 79 % and 65 % of registered private and company wells were used, respectively. It is not clear whether the electricity was restored promptly or not in this case. However, it is common for there to be hand pumps and/or generators at private and company wells, respectively.

Table 6

Countermeasures for groundwater security in an earthquake emergency

After the Hanshin-Awaji Earthquake, countermeasures for groundwater security in a disaster emergency were considered by many local governments in Japan. One of such countermeasures is the establishment of a registration system for citizen-owned wells and company wells that can form a cooperative, as mentioned in the previous section. After having experienced the Great East Japan Earthquake, this registration system by the local government has been expanded and accelerated further to entirely cover Japan. Table 7 summarized the introduction of the registration system as of 2012 (Asahi Shimbun 2012); 36 local governments had introduced the registered well system and nearly 12,000 wells were already registered by 2012. Registration information is usually accumulated by the local government. They have a plan to open the registered well and allow use of the groundwater with no charge for neighboring residents whenever the municipal water supply is suspended due to natural disasters.

Table 7

Figure 6 shows the panel indicating the “citizen’s cooperation well” for disasters in Kobe city. This registration system started in 1996 in Kobe city, just 1 year after the big earthquake, and the number of registered wells reached 437 wells by 2012 as shown in Table 7. The list of registered wells and the location maps have been prepared by the administrative office of the city and there are periodic checks on the quality of shallow groundwater (Tanaka 2011). As can be seen from Table 7, a similar registration system has been implemented by many other local governments, especially in mega cities like Tokyo and Yokohama. For example, Tokyo Metropolitan Government specified 2,769 disaster wells in 23 wards in 1995, just after the Hanshin-Awaji Earthquake (Tanaka 2011); this number reached 4,866 by 2012, increasing 3.5 times after the Great East Japan Earthquake. In Yokohama city, the number of registered wells reached 3,037 by 2012, and for each well, there has been a monthly water quality check using analytical standards the same as those used for the municipal water supply (Tanaka 2011).

Fig. 6

Regarding medical activities, the number of hospitals with a deep well and membrane filtration system has been gradually increasing in recent years and it is reported that the number of hospitals having similar well facilities reached 229 by 2011, doubling the increase seen during the seven years from 2004 to 2011 (National Water Well Association of Japan 2013).

From a policy point of view, a framework for policy-making action with regard to effective groundwater use in disaster emergencies is now being implemented by the Japanese Government based on the Water Cycle Basic Law, enforced in July 2014 (Tanaka, 2014). The establishment of a registration system for citizen-owned wells and company wells is now a policy-making action within the Water Cycle Basic Plan, which was approved on 10 July 2015 by the Japanese Cabinet following establishment of the Law. It is expected that effective groundwater use in disaster emergencies shall spread widely in Japan hereafter according to the establishment of this policy.

Beside groundwater use in disaster emergencies, utilization of rainwater from the roofs of households, which is channeled to a water storage tank and used with a hand pump, has also spread recently in Japan as a supplementary water source for domestic use during an emergency. This type of water storage tank was used in Japan for more than 150 years, during the Edo epoch (years 1603-1868; Tanaka 2011). Although the storage capacity is too small for extended shut-offs, the rainwater utilization system has been reintroduced recently as an important self-serving water source in disaster emergencies. As one of such examples, Oita city, located on Kyushu Island, established a financial support system in 2007 for citizens to set up rainwater storage tanks for which storage capacity is more than 100 L. This financial support covers half the set-up costs, and the maximum supporting expense is limited to 25,000 JPY for each set.

The Japanese Government established the 'Act to Advance the Utilization of Rainwater (Rainwater Act)' in 2014 ('2014 Act No. 17') and it has been enforced since 1 May, 2014 (House of Councillors of Japan 2014). The Act is constituted from the following four parts－responsibility, principle policy, measures for rainwater utilization advancement, and supplementary features. The act aims to spread the setting up of rainwater storage facilities as a water supply source in a disaster emergency through advertising activities and a financial support system by the local governments. It is expected that by the establishment of the 'Rainwater Act', rainwater utilization during disaster emergencies shall spread and the wider population in Japan will be sufficiently informed.

Concluding remarks

As described in this paper, groundwater resources are considered as a significant water source in an earthquake emergency, as their location and availability often coincide with need. Groundwater resources may have the advantage of use for initial firefighting and toilet flushing, which are listed as some of the crucial water use problems in earthquake disasters, especially in mega cities located in the tectonic regions in the world. To cover medical activities in an earthquake emergency, introducing a deep well facility with membrane filtration and a private power plant system is also effective for continuous water supply from the immediate period after the earthquake. For utilization of groundwater for drinking and cooking purposes in an earthquake emergency, water quality checks must be carried out during normal times. Hand pumps or diesel/petrol-driven pumps have to be available for groundwater use during an emergency because the required electricity supply may not be available after an earthquake. For these purposes, the establishment of a continuous monitoring system on groundwater condition, of both quantity and quality, at non-emergency times is necessary and is the most important countermeasure to secure groundwater resources in an earthquake emergency. Furthermore, the establishment of a registration system of citizen-owned wells and company wells that will form the basis of a cooperate during disasters－as implemented by many Japanese local governments after the Hanshin-Awaji Earthquake (1995) and the Great East Japan Earthquake (2011)－is also an effective countermeasures for groundwater security in an earthquake emergency. Finally, it is very important that there is a government framework such as funding and programs for groundwater security, which the Japanese government is now addressing.

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Figure captions

Fig. 1 Map of Japan and the seismic center of the Great East Japan Earthquake (M 9.0), which occurred at 14:46 on 11 March 2011 (modified from Japan Meteorological Agency 2011)

Fig. 2 Recent big earthquakes that have occurred in Japan (modified from Asahi Shimbun 2007a)

Fig. 3 Water demand phases in earthquake disasters (modified from Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

Fig. 4 Target amount of water supply in an earthquake emergency (modified from Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

Fig. 5 Schematic diagram of a deep well facility with a membrane filtration system, introduced by hospitals in Japan for disaster emergency (modified from Tanaka 2011)

Fig. 6 Panel indicating "citizen's cooperation well" for disaster relief in Kobe city (modified from Research Committee on the Security of Water in the Great Earthquake Disaster 1999) Citizen-owned and company wells can form the basis of a cooperative during disasters

Table 1 Damage to municipal water supplies in recent big earthquakes occurring in Japan (after Asahi Shimbun 2007b and National Water Well Association of Japan 2013)

Earthquake name	Occurred date	Magnitude	Number of households with suspended water supply	Maximum duration of suspended water supply
Hanshin-Awaji Earthquake	17 Jan., 1995	M 7.3	～1,300,000	90 days
Chuetsu Earthquake	23 Oct., 2004	M 6.8	～130,000	～1 month
Noto Peninsula Earthquake	25 Mar., 2007	M 6.9	～13,000	13 days
Chuetsu-Oki Earthquake	16 Jul., 2007	M 6.8	～59,000	20 days
Great East Japan Earthquake	11 Mar., 2011	M 9.0	～2,300,000	～5 months

Table 2 Groundwater (GW) use in Japan in 2011 (MLIT 2014)

Water use category	Amount of GW in use (km^3/year)	Category ratio (%)	All water in use[a] (km^3/year)	GW dependence ratio (%)
Domestic	3.2	28.3	15.2	21.1
Industrial	3.2	28.3	11.3	28.3
Agricultural	2.9	25.7	54.5	5.3
Other	2.0	17.7	6.1	32.8
Total	11.3	100.0	87.1	13.0

[a]All water includes surface water and groundwater

Table 3 Required amount and quality of water for each utilization category in an earthquake disaster (after Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

Category	Time/place	Required amount and quality
Firefighting	Till around 3 days	・No need for good water quality ・Large amount ・Constant amount
Medical activity	Continuous supply, needed immediately after disaster	・High quality ・5 L/person/day for visitors ・40-60 L/person/day for inpatients ・250 L/person/day for washing
Drinking/cooking	Continuous supply, needed everywhere	・Clean water ・3-60 L/person/day
Toilet flushing	Continuous supply, needed immediately after disaster	・No need for good water quality (but not include particles) ・Some 10 L for 2-3 days on average
Bathing/washing	Several days to 1 week after disaster	・Clean water ・60 L/person/day ・Increase with time
Maintenance of municipal function	Continuous supply for main facilities	・Necessary water quality is different depending on utilization purposes
Full restoration of water supply	Stable water supply after the disaster event is over	・Necessary water quality is different depending on utilization purposes

Table 4 Characteristics of water sources for use in an earthquake disaster (after Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

Water source	Quantity	Quality	Remarks
River, lake and pond waters	Large amount	Different depending on water source	Transportation is necessary
Sea water	Large amount	Treatment is necessary for freshwater usage	Transportation is necessary
Groundwater	Amount will be affected place to place	Pollution of shallow groundwater is a factor	Need and supply locations can coincide; Water table decline is possible; water pollution is possible; set of hand pumps is needed
Rain water	A water tank set is necessary to provide 0.22 to 2,000 m^3	Possibly clean but treatment is necessary sometimes	Need and supply locations can coincide

Table 5 Water sources for firefighting in Kobe city during the Hanshi-Awaji Earthquake (M 7.3) of 1995 (after Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

Water source	No. of utilizations
Hydrant	17
Well water (groundwater)	14
River water	11
Bath stored water	9
Industrial tank water	5
Public bathhouses water	4
Pond water	4

Table 6 Utilization of registered wells in Sendai city during the Great East Japan Earthquake (M 9.0) of 2011 (after National Water Well Association of Japan 2013)

Category of registered well	Number of registered wells in the suspended water-supply region (A)	Number of utilizations of registered wells during the disaster (B)	Percentage utilization of wells (B/A)
Citizen-owned wells	106	84	79%
Company wells	26	17	65%

Table 7 Introduction of the registered well system for disaster use by the local governments in Japan, as of 2012 (after Asahi Shimbun 2012)

Local government name	Number of registered wells for disaster use, as of 2012	Start year
Sapporo City	748	1997
Sendai City	218	2000
Yamagata City	97	2004
Utsunomiya City	133	1997
Chiba City	132	2003
Saitama City	392	2001
Tokyo Metero-politan Govern. (total of 21 wards)	4,866	1980
Kawasaki City	231	1996
Yokohama City	3,037	1995
Sagamihara City	5	2011
Kanazawa City	327	1997
Nagoya City	607	1996
Kyoto City	587	2004
Nara City	160	2009
Kobe City	437	1996
Oita City	252	2003

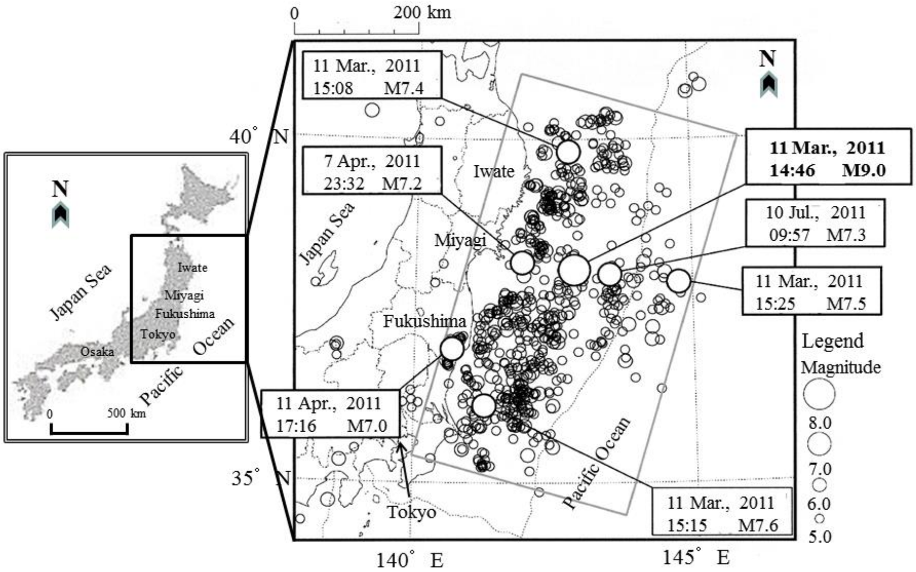

Fig. 1 Map of Japan and the seismic center of the Great East Japan Earthquake (M 9.0), which occurred at 14:46 on 11 March 2011 (modified from Japan Meteorological Agency 2011)

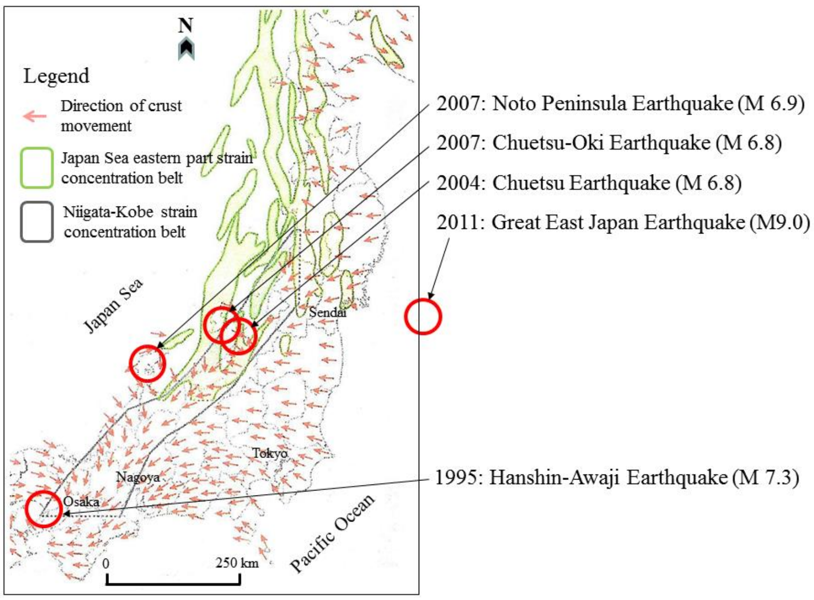

Fig. 2 Recent big earthquakes that have occurred in Japan (modified from Asahi Shimbun 2007a)

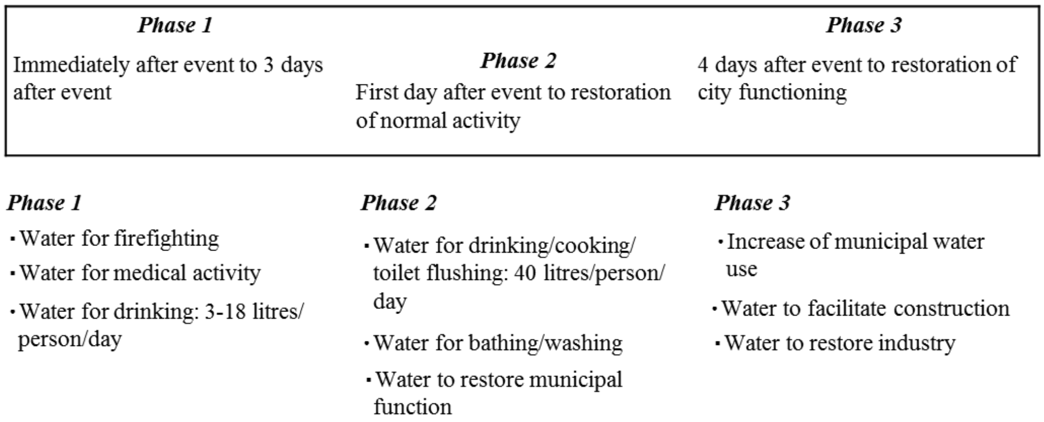

Fig. 3 Water demand phases in earthquake disasters (modified from Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

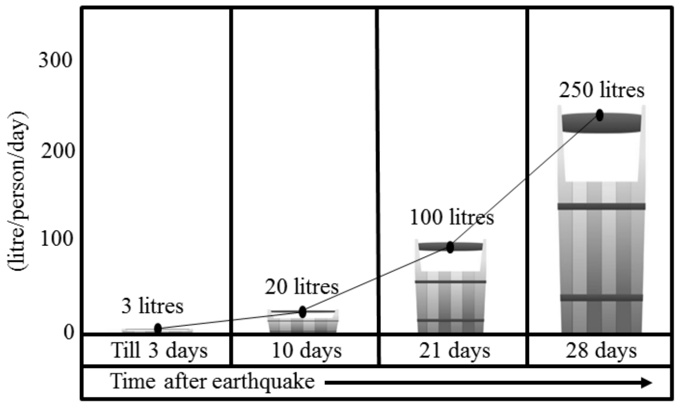

Fig. 4 Target amount of water supply in an earthquake emergency (modified from Research Committee on the Security of Water in the Great Earthquake Disaster 1999)

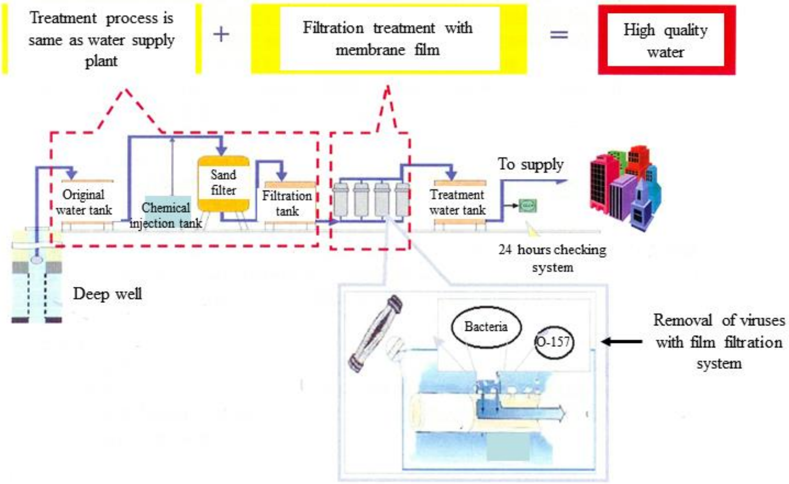

Fig. 5 Schematic diagram of a deep well facility with a membrane filtration system, introduced by hospitals in Japan for disaster emergency (modified from Tanaka 2011)

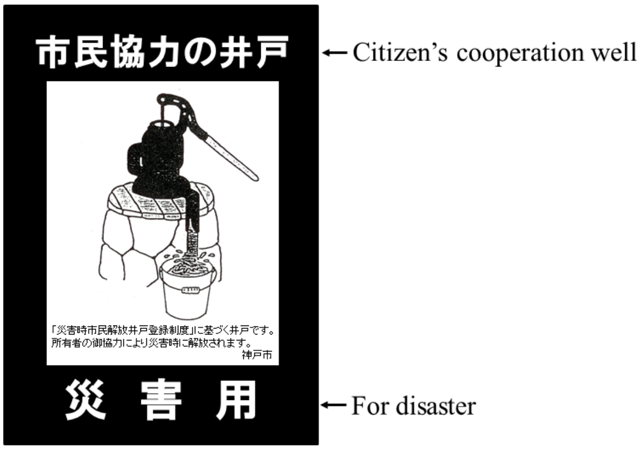

Fig. 6 Panel indicating "citizen's cooperation well" for disaster relief in Kobe city (modified from Research Committee on the Security of Water in the Great Earthquake Disaster 1999) Citizen-owned and company wells can form the basis of a cooperative during disasters