AN INNOVATIVE APPROACH TO MEASURING RESILIENCE BASED ON POST-EARTHQUAKE WATER DEMAND

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ABSTRACT

The quantity and quality of water supply is always a significant concern following an earthquake. Water for drinking and cooking is vital, and it is also needed for firefighting, medical systems, and post-earthquake reconstruction. The concept of "water resilience" has previously been used to measure how well a water system withstands disaster and how long it takes to recover to an acceptable level. However, although there are data for short- and medium-term water demand, community factors and water demand have been neglected in measuring resilience. This approach takes the changes in post-earthquake water demand into account to give a more accurate, dynamic evaluation of water supply resilience. As the water demand increases after the earthquake, the proposed resilience measurement evaluates the gap between post-earthquake water system functionality and water demand. As such, the proposed method calculates resilience values that are lower than the traditional method which compares the post-earthquake system functionality with business as usual functionality (or water demand). The demand-based resilience measure therefore places more emphasis on earthquake preparation planning to ensure the preparation measures (such as resourcefulness and redundancy) meet the post-earthquake water demand. The proposed measure in this paper was developed based on a review of previous research and the method was verified for the case of Christchurch following the 2011 earthquake.

KEYWORDS

Resilience, Water Demand, Water Supply Capacity, Earthquake, Conceptual Model, Christchurch

PRESENTER PROFILE

Behrooz is a Water Asset Management & Resilience Engineer at WSP-Opus. He has 9 years of experience in the disaster management field focusing on infrastructure resilience, damage estimation, mitigation planning, risk reduction, and asset management. He studied for his MSc in Disaster Management at the University of

Tehran in Iran. Having worked at the Tehran Disaster Mitigation and Management Organization (TDMMO), he has attended several disasters and gained a wealth of experience. Behrooz has been working on water supply systems resilience to determine the technical, organisational, social, economic, and environmental factors which affect water system functionality after an earthquake in his PhD journey.

1 INTRODUCTION

In the first decade of the twenty-first century, an average of 384 disasters were reported annually, resulting in an average of 106,891 victims per year. During the same period, approximately 45.5 per cent of victims and 20 per cent of total damage caused by natural disasters resulted from geophysical incidents (Guha-Sapir et al., 2012). Further damage and losses were caused by the Tohoku tsunami and earthquake in Japan in 2011 and showed clearly how unpredictable and destructive such catastrophes can be.

Post-disaster water supply has always been of significant concern for the authorities in disaster-prone countries (Makropoulos et al., 2018). Water needs to be available without interruption in all of the four stages following an earthquake – emergency, survival, operational, and full recovery (normal) stages – addressing the target levels of service. Figure 1 shows the prioritised activities – *emergency*, *survival*, and *operational* stages – that need water after an earthquake.

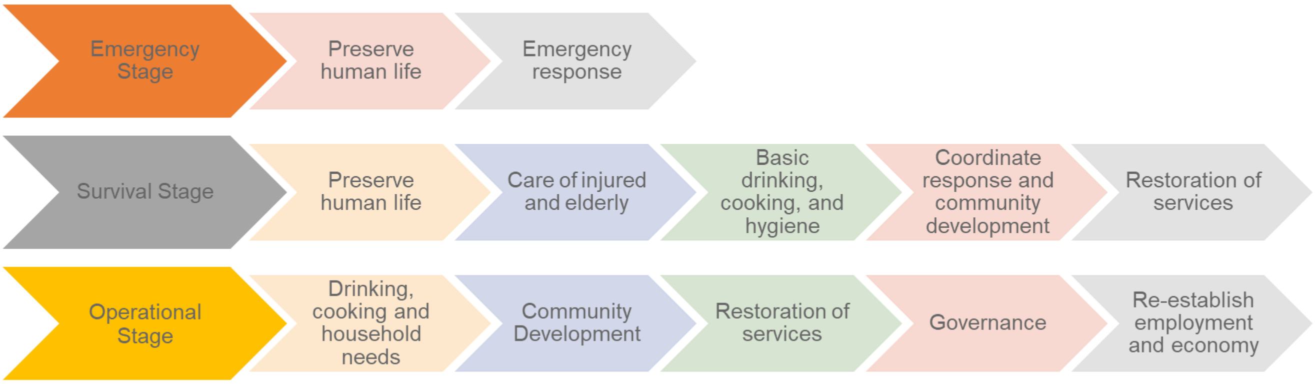

Figure 1. Main Activities Requiring Water Following an Earthquake (Opus International, 2017)

As noted by Opus International (2017), the first two stages (the emergency and survival stages) focus on supplying water to preserve human life, and for emergency responses, healthcare activities, and basic drinking, cooking and hygiene needs. These two stages comprise the post-disaster restoration phase in which basic and crucial needs require a response from water companies or other relevant authorities. The third phase, the operational stage, focuses on the re-opening of businesses and governance while the first two stages' water demand also need to be addressed.

Low *water consumption* following earthquakes does not represent low *water demand*. Water demand is more severe after an earthquake but the water companies or other emergency sectors are not able to distribute sufficient quantity and quality of water to address the water demand and this is why the activities are prioritised. Damaged infrastructure, limited water resources capacity, and transport challenges are the main cause of a lack of water in an earthquake-struck area. As such, water consumption declines following earthquakes despite the increased water demand.

The resilience of a water supply system is defined as the ability of the system to withstand an earthquake and to recover to a normal level of functionality in a timely manner (Balaei et al., 2018). The concept of resilience complemented the single dimensionality of *risk* by envisaging the functionality of the system over time. *Functionality* can be defined depending on how the researcher is envisaging the system. One of the most common measurements for functionality considers how many people are receiving the service, in this case, *water* service, following an earthquake.

However, water demand is not considered in the resilience equation although the concept is basically user-centred. To bridge this gap, this study proposes an innovative approach to measure resilience based on water demand following an earthquake. In this paper, functionality is defined based on water flow in the aftermath of an earthquake. The demand-based resilience measure puts more emphasis on earthquake preparation planning to ensure the preparation measures such as resourcefulness and redundancy meet the post-earthquake water demand. The proposed measure in this paper was developed based on a review of previous research, and the method verified for the case of Christchurch following the 2011 earthquake.

2 WATER SUPPLY VULNERABILITY

Due to their wide-spread nature and inherent vulnerability, water supply systems can be severely affected by earthquakes. Earthquakes can cause water outage or declined levels of service due to damage to different components of water supply systems as follows (AWWA, 2001):

- Personnel shortage – earthquakes can cause personnel shortage due to their death or injury both to themselves or their families, evacuation, or other personal reasons.

- Water contamination – earthquakes can cause contamination of the raw and/or purified water supply. Excessive sediment can enter a water intake, reservoir, or any open water system due to landslides or other earthquake-induced secondary hazards.

- Air contamination – release of chlorine is a significant risk for water treatment plants where chlorine gas is in operation to purify water. Air contamination due to chlorine release can impact water system personnel severely and cause injury or death.

- Water-well damage – ground shaking can result in pipe joint break/separation and sand entering water wells. Water-well casing is also prone to bending by lateral spread. The pumps are prone to shattering from the ground shaking.

- Pipe breakage – pipe breakage presents significant challenges following an earthquake. Pipe breakage can interrupt water supply and affect water pressure within the network. The pipe breakage happens due to bending, shearing, tension (joint separation), compression (joint break), and structural collapse.

- Structure damage – dams, water intakes, water treatment plants, pump stations, storage tanks, offices, and spare parts warehouse are prone to damage due to ground shaking and/or ground failure. Structural damage can cause damage to the equipment and material and make the structures inaccessible following an earthquake.

- Power outage – electrical elements of the water supply system can fail to function in a power outage. These elements include, but are not limited to, pumps and computers.
- Communications disruption – both automatic signal equipment (telemetry) and people communication (telephones and radios) can be affected by an earthquake. Apart from physical damage, communication systems can be affected by power outages.
- Transport failure – transport failure can occur due to bridge damage, fallen debris, collapsed overpasses, etc.

Although the social, organisational, and economic factors impact on water supply systems' resilience, this paper focuses on the technical dimension of the system.

Drinking water outage, however, is not the only impact of seismic events in urban areas; other impacts can include conflagration, interruption to medical services, business continuity disruption, and other disruptions to daily life. For example, the fire following the Kanto earthquake of 1923 (which killed tens of thousands of people in Tokyo), grew because of a lack of water due to water-main breakages and to other environmental conditions like wind and high temperatures (Scawthorn et al., 2005).

3 WATER DEMAND

Water supply resilience is measured based on the volume of water being accessed by users following an earthquake. The volume of water being consumed by users is equivalent to water demand. Water demand is not constant over time. The factors affecting water supply demand (IPWEA, 2015) include:

- Population growth
- Land use development patterns
- Economic development
- Government policy
- Visitors and the tourism industry
- Environmental changes (e.g. climate change)
- Increases in levels of service – additional supply areas previously not serviced
- Customer performance (increased consumption trends)

Obviously, changes in population – either growth or decline – are the most important drivers for water demand. The population can change due to birth, mortality, migration and other factors such as environmental changes, political conditions, or government policies. Growth is also affected by urban development. Several factors contribute to the composition of urban forms including land use, density of residential development, natural features, and general terrain. Figure 2 shows Christchurch population growth forecast by 2030.

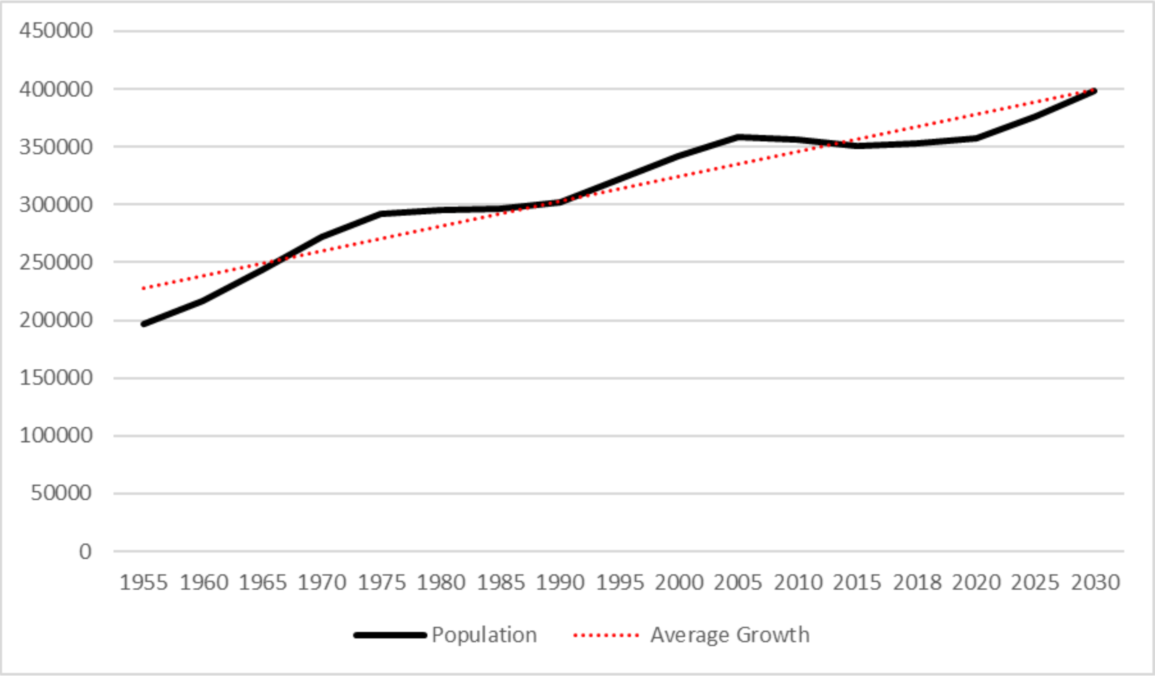

Figure 2. Christchurch Growth Forecast

As the water supply demand is dynamic, the resilience of water supply systems need to be defined in a dynamic way to reflect demand at any given time. Thus, the water supply capacity to address the water demand and targeted levels of service is time-dependent. Therefore, a resilient water supply system is not guaranteed to remain resilient over a particular time period.

Although water is undoubtedly required for almost all activities following an earthquake, some water-related activities are prioritised over others. These priorities need to be established to enable the authorities to plan properly for the post-earthquake water supply (AWWA, 2001).

Most healthcare and medical facilities need to be continuously functional following an earthquake. They need to be contacted by the water companies or consultants to identify their average daily water requirements. Fire Departments, police, and emergency management agencies are also prioritised to be supplied with enough water (AWWA, 2001). Table 1 shows the minimum water quantity and quality and the duration that water is required to be provided for the activities following an earthquake.

Table 1. Post-earthquake Water Supply Requirements (Opus International, 2017)

Purpose of LOS	Amount, Quality	Location, user supplied	Duration
Firefighting	SNZ PAS 4509:2008	Priority locations	▪
Emergency Response	20l/p/d SNZ PAS 4509:2008	Civil defence centres; Emergency operation centres; Ports, airports & other lifelines	2 days
Loss of life, emergency response – fire fighting	SNZ PAS 4509:2008	Relocation areas; Hospitals; Aged care centres; Prisons; Ports, airports & other lifelines; Civil defence centres; Emergency operation centres	3 days

Care of injured, elderly and others who cannot be moved	60l/p/d, potable SNZ PAS 4509:2008	Hospitals	3 days
	20l/p/d, potable SNZ PAS 4509:2008	Aged care centres Prisons	3 days
Drinking, cooking, basic hygiene	20l/p/d SNZ PAS 4509:2008	Relocation centres	3 days
	20/l/p/d	Within 500-1000m of households	3 days
	20l/p/d, potable	At household	▪
Community development, Education	20l/p/d, potable Firefighting at SNZ PAS 4509:2008	Schools	▪
Community development – meeting places	Potable water at pre-earthquake quantity, Firefighting at SNZ PAS 4509:2008	Community meeting places, e.g. cafes, sports centres	▪
Governance	Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008	Central & government facilities	▪
Employment	Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008	Shopping, business and industrial areas	▪
Housekeeping	70l/p/d, potable	Households	▪

4 WATER SUPPLY RESILIENCE

The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was proposed in the 21st century although it was introduced by Holing in ecology earlier in 1973 (Holling, 1973). Klein et al. defines resilience as a desirable property of natural and human systems in face of potential stresses and investigates the concept of resilience to weather related hazard as an example of natural hazards in coastal megacities. Through their study, Klein et al. recommend resilience to be used in a "restricted sense: to present specific system characteristics that discusses (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability" (Klein et al., 2003).

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris et al. (2008), resilience can be understood as a set of network adaptive capacities, namely economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model—Disaster Resilience of Place — to conceptualise disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the degree of recovery and resilience of the community. It also includes six groups of indicators: ecological, social, economic, institutional, infrastructure and community competence, to quantify a community's overall resilience.

This study refers to Balaei et al. (2018) to define resilience as the ability of water supply system to withstand the external shock (earthquake) and recover to a normal level in a timely manner. The magnitude of an earthquake, the vulnerability of the built environment, and user needs determine water supply capacity and dictate water requirements. Water leakage is a significant issue following an earthquake. Indian Ocean earthquake and tsunami caused 60% water leakage in Banda Aceh and had a significant adverse impact of water supply capacity. Water leakage not only decreases system capacity, it also increases water demand as the water companies have to pump excessive water into the network to address the basic needs of post-earthquake emergency activities such as firefighting, healthcare, or emergency activities.

Fire following an earthquake should not be taken lightly. Post-earthquake firefighting has always been a challenge for the authorities. After the Napier earthquake in 1931, firefighting became impossible as underground pipes had cracked and broken (Napier Council, 2018). Conflagration in San Francisco after the 1906 earthquake caused the largest life and economy loss in US history (Usami, 1996). Statistics show that 59 ignitions occurred after the earthquake and the fire department was faced with difficulties as the water supply was interrupted due to ground failure (mostly liquefaction and lateral spreading) and ground shaking. Water reservoirs were located in the intense fire zones and contained 6 per cent of the system’s capacity (21 million litres). However, the fire department could not use the whole capacity as the volume of water was less than expected due to breaks and the limitations caused burning and collapsing buildings.

Firefighting, however, is not the only driver for increased water demand following an earthquake. Water provision needs to be increased to compensate for the leakage in the network. Some activities such as those in healthcare systems need to be provided with enough uninterrupted water quantities (Chang et al., 2002). When it has been decided that no live people are trapped underneath the debris, water is required to settle down the dust and toxic fumes which are released from burning materials such as asbestos. These vaporised materials are dangerous for the residents as well as to rescue workers’ health. To deal with this and in regard to water leakage in the network, extra quantities of water are needed to be pumped into the network.

The Christchurch earthquake of 22 February 2011 is a good example of what happens to the water demand and capacity following earthquakes. Pre-earthquake peak day demand (in 2009) was 6,674 m3/hr. When the earthquake occurred, the peak demand increased significantly due to leakage, firefighting activities, and increasing hospital activities. Leakage caused a water flow increase of 43 per cent on average so the estimated peak flow following the earthquake reached 10,440 m3/hr (Johnson & O'Neill, 2012). There is no data on how much activities such as firefighting or hospital requirements increased water flow. In this paper, it is assumed that these activities increased by 20 per cent of flow following the earthquake (AWWA, 2001). Then, the peak flow is estimated to be 11,770 m3/hr.

Additionally, 22 wells were damaged and caused loss of capacity in the aftermath of the earthquake. Well-pump available flow rate (excluding wells out of service) was 9,495 m3/hr. As the aquifers normally serving Christchurch with drinking water are under pressure, extracting water from water wells is fairly easy and cheap. The delivery pump available flow rate reduced by 3,110 m3/hr to 7,790 m3/hr (Johnson & O'Neill, 2012). The city had predicted spare capacity to address future disturbance and external shocks in the water system. However, the earthquake depleted the extra capacity and caused loss of levels of service following the earthquake.

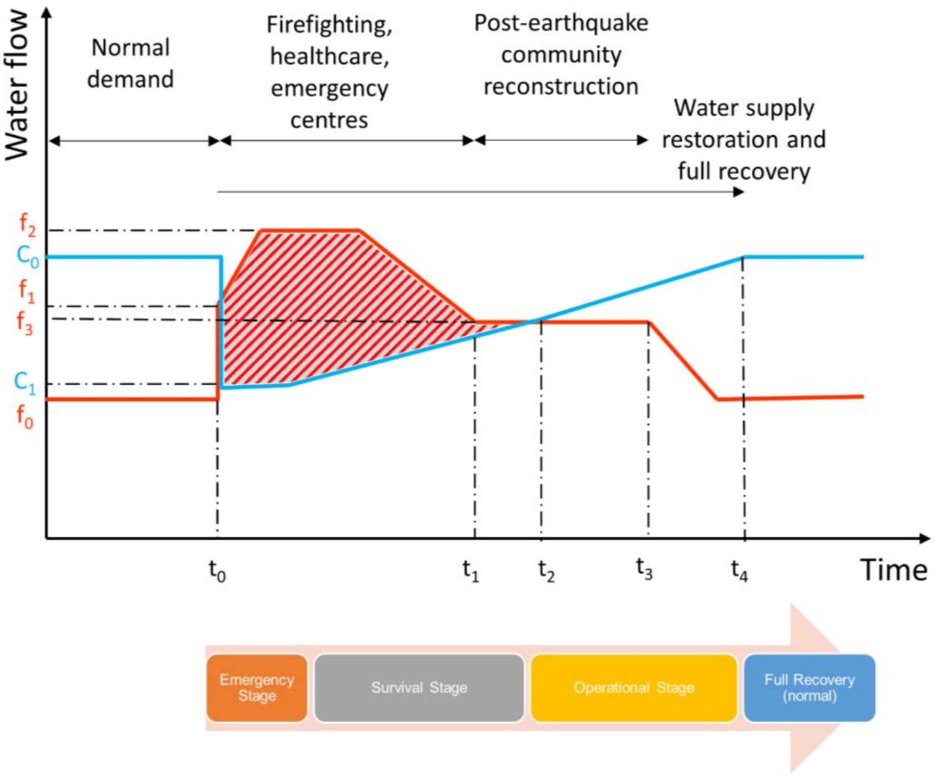

Figure 3. Water Supply Resilience based on Water Demand

Figure 3 shows a schematic view of water system resilience to seismic events. Traditionally, resilience was calculated by means of measuring the area under the blue line, which is water supply capacity over time following an earthquake, as follows:

$$Resilience = \frac{\int_{t_0}^{t_4} C_t \, dt}{(t_4 - t_0).C_0}$$

In which C_t is the water supply capacity, t_0 is the time of earthquake happening, t_4 is the time when water supply system recovery is completed, and C_0 is the water supply capacity prior to the earthquake.

The post-earthquake water supply capacity (C_t) drops due to damage to pipes, reservoirs, pumps, water intakes, etc., when an earthquake happens. Lessons learnt from previous earthquakes reveal that buried lifelines' restoration is delayed as a result of other lifelines' damage (transport, communication, electricity), local traffic, and shortage of restoration crews. The post-earthquake capacity after full recovery may be less, equal, or more than pre-earthquake water supply capacity.

However, what is not paid attention to in this definition is the water demand following an earthquake. As can be seen from the graph, the water demand (shown by red line) increases in the aftermath of the earthquake due to leakage in the system (from f_0 to f_1). Afterwards, some activities such as firefighting, healthcare, and emergency centres' activities increase compared to the pre-earthquake situation and water demand (and consumption) increases from f_1 to f_2. The post-earthquake emergency activities and water demand to address those activities fluctuate and on average, it can be said that water demand remains constant for a few days, depending on the condition of the earthquake, vulnerability of the community, etc. (at f_2 level). Then, water demand starts to decline when emergency and survival stages are passed (to the level of f_3).

In this stage, post-earthquake community reconstruction starts (t_1) and the quantity of water demand varies depending on the dominant building type (e.g., concrete, steel, wood, etc.). By the end of the community reconstruction and recovery phase, water demand decreases to a new normal level.

The new normal level of water demand is usually greater than pre-earthquake water demand. If sufficient funding exists, authorities prefer to take the opportunity to renew the parts of the network that are past their useful life or are in poor condition and are due/overdue to be renewed. In addition, previous earthquakes show that earthquakes affect the labour market over both a short- and long-term period (Higuchi et al., 2012). In the short term, communities experience labour shortages but increasing salaries and wages encourage people to migrate to the earthquake-struck area for a higher income (Belasen & Polachek, 2009; Sarmiento, 2007). Canterbury's contribution to New Zealand's Small and Medium Enterprises (SME) employment experienced its lowest record in 2011 (the year when Christchurch earthquake happened) and 2012 with 12.3 per cent and 12.4 per cent respectively. A portion of this decline in the levels of employment (including the water sector) was because the employees moved to other cities for a variety of reasons such as accommodation costs (IRD, 2015). Increased numbers of residents, per se, results in higher water demand in the long term. However, there are a few cases that water demand's post-disaster new normal was lower than pre-earthquake water demand.

Based on the above explanation, water supply resilience in this study is estimated as follows:

$$Resilience = \min\left(\frac{\int_{t_0}^{t_2} C_t \, dt}{\int_{t_0}^{t_2} f_t \, dt}, 1\right)$$

In other words,

$$Resilience = \begin{cases} \dfrac{\int_{t_0}^{t_2} C_t \, dt}{\int_{t_0}^{t_2} f_t \, dt} & if\ capacity < demand \\ 1 & if\ capacity\ \geq demand \end{cases}$$

in which f_t is the water demand at time t.

When water supply capacity is equal to, or higher than, water demand, the community will not experience water shortage, then resilience is equal to one. If water supply capacity is less than water demand, it means that the users are not receiving enough quantities of water following the earthquake. In this case, water supply resilience is estimated by dividing the water supply capacity by water demand.

To measure resilience of water supply at time t, we have to consider the target levels of service to be addressed for the same time as water demand and system capacity changes over time. Referring to Christchurch earthquake in February 2011, as can be seen from Figure 2, Christchurch population has been increasing over time. Then, the same state of damage in the water supply system will cause more people losing water services and lower index for resilience of the water system will be obtained.

5 CONCLUSIONS

This study presented a novel approach in measuring water supply system seismic resilience based on water demand. In this approach, water demand is compared to water supply capacity to measure the water system's capacity in addressing the water demand following an earthquake. The authors believe that post-earthquake water demand increases in a short-term due to water leakage and emergency activities such as firefighting and hospital water requirements. In the same period and when water demand increases, water supply capacity declines. The difference between water supply capacity and water demand is considered as the actual lack of resiliency compared to the traditional definition which envisages only the capacity drop as the lack of resiliency of the system.

The proposed method is conceptual and need to be tested and verified based on real data from earthquakes. The existing data from previous earthquakes do not show accurate increase in water demand due to different activities such as firefighting or healthcare. There are also uncertainties in predicting quantity of water needed for firefighting as it highly depends on a number of factors that cannot be controlled such as wind that can spread out the fire significantly.

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