# Evaluating Seismic Performance of Water Supply System with Multiple-Functionality-Based Measurement

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ABSTRACT: Water supply system (WSS) is an essential part of the infrastructure system of a city and plays an important role in resisting and recovering from natural disasters. Disruption of WSS due to seismic damage of pipelines would impair its city functionalities including fire suppression, water supply of critical facilities and domestic water supply. Some metrics have been proposed in existing literatures to evaluate the performance of WSS subjected to disaster events. Nevertheless, these metrics, aiming at a specific functionality of WSS, e.g. fire suppression or domestic water supply, cannot give a comprehensive evaluation with its multiple functionalities included. In this regard, this paper proposes an economic loss-based metric to evaluate integratedly the consequence of disruption of two functionalities, fire suppression and domestic water supply, of WSS subjected to hazard event. The direct economic losses associated with the two broken functionalities are estimated and compared through the case study of a water distribution network of a city in South-West China subjected to earthquake. It is found that the two functionality losses have small correlation and the strategy to improve the seismic performance should consider both of them integratedly.

KEYWORDS: Seismic performance; Water supply system; Functionality; Resilience

## 1. INTRODUCTION

As an essential part of the urban lifeline system, urban water supply system (WSS) is responsible for providing domestic and industrial water, ensuring fire suppression and maintaining urban landscape for the daily functioning a city. When subjected to hazard events, e.g., earthquake, the performance of WSS is also crucial for the rescuing actions and recovery process of the city. Historical events, such as the 1906 San Francisco earthquake and the 1995 Kobe earthquake (Kuraoka and Rainer, 1996), have clearly demonstrated the importance of WSS. The disruption of WSS after an earthquake not only impairs fire-fighting capacity, but also disrupt residential, commercial, and industrial activities, so great concern has been aroused to enhance the performance of WSS against earthquake.

Numerous metrics have been proposed to quantitatively evaluate the post-earthquake performance of WSS, which depend on the approach to simulate WSS behavior following hazard event. Broadly, the simulation models used to estimate WSS behavior can be categorized as two types: topological and flow-based. Based on graph theory, the topological model is computational efficient and can be used to predict the condition of connectivity between the source and demand nodes, but it does not truly reflect the physics-based principles of pipeline hydraulics for determining the flows and pressures. On the other hand, flow-based model follows the physics-based principles, whose results are more realistic but the computation is time-consuming, especially when dealing with large-scale systems. Current metrics are established mainly from the consequence of damaged WSS itself, e.g., connectivity, volume and pressure, however, to estimate the impact of WSS damage to the well-being of society, the consequence of WSS damage should be evaluated in the context of a city, rather than the WSS itself, and the functionalities of WSS should be considered comprehensively.

In this paper, a new approach is proposed to quantitatively assess the post-earthquake performance of WSS from the perspective of functionality loss of damaged WSS after an earthquake. Providing sufficient water for domestic use and for fire suppression are two main functionalities of the WSS, which are accounted for in the new approach. The direct economic losses due to the disruption of the two functionalities are estimated based on the flow-based analysis of the damaged WSS incorporating the features of surrounding built environment. The approach is illustrated through the evaluation of WSS of a city in South-West China, and the discussion on the difference and correlation of the two functionalities losses are performed.

## 2. METHODOLOGY

### *2.1. Analyzing post-earthquake hydraulic performance of water supply system*

#### *2.1.1. Repair rate of the pipeline system*

The infrastructure of urban WSS consists of several basic components such as water works, pumps, tanks and pipelines. The pipeline system is vulnerable to earthquake because of ground shaking and permanent ground deformation caused by earthquake, while the nodal elements like tanks and water works are vulnerable to wind (Chmielewski et al. 2016). Plenty of researches have been carried out to calculate the failure probability of buried pipeline under earthquake attacks (Hwang et al. 1998; O'Rourke and Deyoe 2004). In this study, a statistical model by Japan Water Works Association (JWWA) is adopted to model the seismic fragility of pipelines. In this model, the repair rate of the pipeline is calculated as follows (JWWA 2009):

$$RR = C_p \times C_d \times C_g \times C_l \times R \tag{1}$$

in which $RR$ refers to the repair rate of a pipe; $C_p$, $C_d$, $C_g$, $C_l$ are correction factors related to the pipe material, pipe diameter, local topography and land liquefaction, respectively; $R$ is the standard repair rate, which can be calculated with the peak ground acceleration (PGA) or velocity (PGV) as follows:

$$R = \begin{cases} 2.88 \times 10^{-6} \times (PGA - 100)^{1.97} \\ 3.11 \times 10^{-3} \times (PGV - 15)^{1.30} \end{cases} \tag{2}$$

Noted that the units of PGA and PGV are cm/s$^2$ and cm/s, respectively.

#### *2.1.2. Modeling damaged water supply system*

Seismic performance of the WSS based on Monte Carlo simulations is evaluated using a special hydraulic analysis computer program, Graphical Iterative Response Analysis of Flow Following Earthquakes (GIRAFFE) (Shi et al. 2006). GIRAFFE is a software developed by Cornell University for hydraulic simulation of damaged water distribution network. It can eliminate negative node pressure in a heavily damaged network by working iteratively with EPANET (Rossman 2000), an advanced software for flow analysis, and provide a more realistic hydraulic assessment of the seismic performance of WSS.

In this study, we use GIRAFFE to run a Monte Carlo simulation with fixed simulation runs. Before the simulation, the topological features and physical properties of the original water distribution network are defined, and the repair rate is calculated according to the seismic intensity. In Monte Carlo simulation, the damage configurations of water distribution network are randomly generated based on the input repair rate and pipe lengths, then hydraulic analyses are performed with nodes of negative nodal pressure eliminated, and finally Monte Carlo simulation results are collected to calculate the statistical properties of quantities of interest.

### *2.2. Measuring functionality loss of the water supply system*

The functionalities of Urban WSS include delivering water from sources to end users and providing water for fire suppression in routine daily life, as well as after hazard events. In this paper, the associated losses due to the damaged functionalities of domestic water supply and fire suppression are considered to quantify the impact of damaged WSS to the society, and serve as metrics to measure functionality loss of WSS in terms of domestic water supply and fire suppression, respectively.

#### *2.2.1. Direct economic loss due to insufficient domestic water supply*

The people's need for potable water may not be satisfied immediately after an earthquake which may damage the WSS intensely. In that case, emergency water supply is necessary for the daily life of disaster sufferers. Thus, the direct economic loss due to insufficient domestic water supply ($L_{\mathrm{D}}$) can be defined as the total cost of emergency water supply to satisfy the daily need of residents after the disaster event. There are several ways to provide potable water including delivering bottled water and constructing temporary distribution pipelines. A simple and highly applicable method of emergency water supply is to set up emergency water treatment plant and deliver water with water tankers. The cost associated with water treatment plant and water tankers is usually regarded as an investment in disaster preparedness, and is not included in $L_{\mathrm{D}}$. In this paper, the city is divided into several water demand sectors based on the service area of each major water demand nodes, and $L_{\mathrm{D}}$ can be calculated as follows:

$$L_{\mathrm{D}} = \sum_{t=t_0}^{t_1} \sum_{i=1}^{n_s} L_{\mathrm{D},i}(t) \tag{3}$$

in which $n_s$ refers to the number of sectors; $t_0$ and $t_1$ refer to the time when the emergency water supply begins and ends, respectively; $L_{\mathrm{D},i}(t)$ is the cost to supply water to sector $i$ at time $t$. The determination of $t_0$ and $t_1$ depends on the restoration process of the water supply system. $L_{\mathrm{D},i}(t)$ consists of the cost for water intake and treatment and the cost for water delivery. Assuming the cost for water intake and treatment is proportional to the quantity of potable water and the cost for water delivery is proportional to the quantity and distance of delivery, we have:

$$L_{\mathrm{D},i}(t) = aQ_i(t) + bD_iQ_i(t) \tag{4}$$

in which $a$ is the unit cost for water intake and treatment; $b$ is the unit cost for delivering water to a unit distance; $D_i$ is the distance of delivery from emergency water plant to sector $i$; $Q_i(t)$ is the quantity of water delivered to sector $i$ at time $t$. Coefficients $a$ and $b$ can be calculated based on the actual situation of the emergency water supply after earthquake, such as using surface water or ground water, quality of raw water and capacity of the water tanker, etc. According to the observation of emergency water supply after the 2008 Wenchuan earthquake, the capacity of water distribution network is assumed to be restored linearly to the pre-earthquake level in 30 days, and $a$=1.2RMB/ton, $b$=0.35RMB/ton/km (Zhang 2012), which are adopted in the case study in the next section.

#### *2.2.2. Direct economic loss due to insufficient water for fire suppression*

Post-earthquake fire is a common and dangerous secondary disaster following an earthquake. If WSS is heavily damaged and cannot satisfy the fire suppression demand, post-earthquake fire tends to grow out of control and cause much more severe damage to the community. Lots of researches have been carried out to analyze the features of post-earthquake fire including the spatial-temporal feature of fire outbreak, the fire spread behavior (Zhao et al. 2005; Lee and Davidson 2010; Scawthorn et al. 2010). In order to quantitatively evaluate the loss due to the damaged fire-fighting capability, this study utilizes a schematic model to incorporate basic characteristics of post-earthquake fire and the interaction between fire propagation and fire-fighting capability.

At the beginning, the city is divided into several clusters in which buildings have similar structural characteristics, and adequate space is reserved between different clusters to prevent fire from spreading among them. Building clusters can be categorized into two groups based on the combustibility of the structure. For clusters made up of non-combustible buildings such as reinforced concrete structures and masonry structures, fire is unlikely to spread among buildings provided buildings are well designed and constructed, even when water for fire suppression is unavailable. For clusters made up of combustible buildings like wooden structures, fire can easily spread among them if fire-fighting capability is lost.

As for the interaction between fire-fighting capability of WSS and fire spread, we assume that if the fire-fighting water supply is sufficient, the fire can be stopped from spreading immediately after it is detected, otherwise, the fire will spread freely until the whole cluster is burned out. The Chinese *Technical code for fire protection water supply and hydrant systems* (2014) requires that the working pressure of fire hydrant be greater than 0.10Mpa for fire suppression, so 0.10Mpa is used as a critical value to judge if the fire-fighting water supply is sufficient of a node. Other factors related to fire control such as fire sprinklers, firefighting abilities of the residents and reachability of the fire zone are neglected in this study.

Based on the assumptions above, the loss due to the damage to fire-fighting capability ($L_F$) is defined as the additional loss caused by post-earthquake fire as a result of insufficient fire-fighting water supply, written as the following:

$$L_F = \sum_{j=1}^{n_c} L_{F,j} \tag{5}$$

in which $n_c$ is the number of building clusters; $L_{F,j}$ is the additional loss at node $j$ due to insufficient water supply for fire suppression, which is 0 if the water supply capacity is not impaired or there is no outbreak around node $j$,

$$L_{F,j} = \begin{cases} \text{Non-combustible} & n_{f,j}(c_{\bar{f},j} - c_{f,j}) \\ \text{Combustible} & c_{\bar{f},j} - c_{f,j} \end{cases} \tag{6}$$

where $n_{f,j}$ is the number of ignitions in cluster $j$ after an earthquake; $c_{f,j}$ is the fire loss under the condition of fire-fighting capacity is available, while $c_{\bar{f},j}$ refers to that if the fire-fighting water supply is insufficient. Eq.(6) assumes that if the buildings in a cluster are combustible, the cluster will be burned completely if the water supply is broken, however, if the buildings are non-combustible, only an individual building ignited is burned in the cluster.

In this study, fire ignitions are assumed to happen immediately after earthquake, and the probability of post-earthquake fire occurrence based on the regressed data of the 1995 Kobe Earthquake is adopted, which is (Nishino 2012):

$$P_I = 0.000288 \times P_D^{0.75567} \tag{7}$$

in which $P_I$ refers to the ignition probability of a building; $P_D$ is the collapse probability of a building under an earthquake, which is assumed to be 3% in designed earthquake and 20% in maximum considered earthquake.

## 3. ILLUSTRATION AND DISCUSSION

### *3.1. Case description*

We illustrate the proposed approach in the loss estimate of damaged WSS of a city in Yunnan province in south-west China. The city is located in the east of Himalaya seismic belt with a seismic intensity of 8 (the exceeding probability is 10% in 50 years for PGA of 0.25g (design earthquake), and 2% in 50 years for PGA of 0.5g). The water distribution network includes one source node and 53 demand nodes, connected by 30.4 km of cast iron pipelines, as seen in Figure 1, in which the elevations of the nodes are also known. The urban population is around 75000 and the daily water demand is $3.4 \times 10^4$ cubic meters. The values of correction factors in Eq. (1). are shown in Table 1.

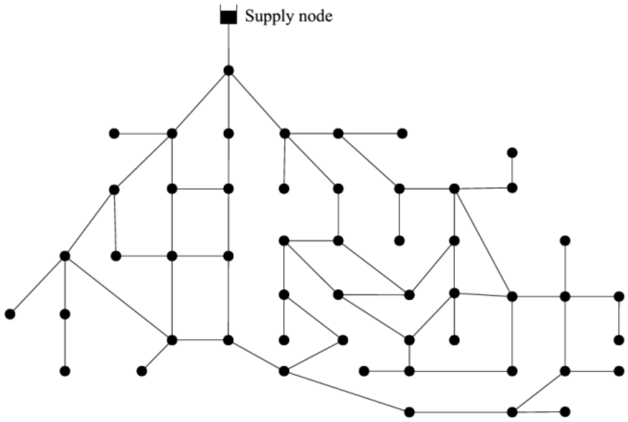


*Figure 1: schematic view of the water distribution network in Yulong.*

*Table 1: values of correction factors.*

| Factor | Value | Explanation |
|---|---|---|
| $C_p$ | 1 | Cast iron pipes |
| $C_g$ | 1.1 | Mountain area |
| $C_l$ | 1.0 | No liquefaction |
| $C_d$ | 1.0 | Φ100~Φ150 |
| | 0.8 | Φ200~Φ450 |
| | 0.5 | Φ500~Φ800 |

The buildings can be categorized into masonry structures, reinforced concrete structures and wooden structures. The layout of different building types is showed in Figure 2. For the purpose of simplicity, buildings in each type are assumed identical. $c_{f,j}$ and $c_{\bar{f},j}$ are calculated based on the burned area and average cost of replacement of building type *j*. The detailed information of the three building types is listed in Table 2.

In this study, we conducted 100,000 Monte Carlo simulations with the PGA of 0.25g and 0.5g respectively. The simulation procedure is shown in Figure 3.

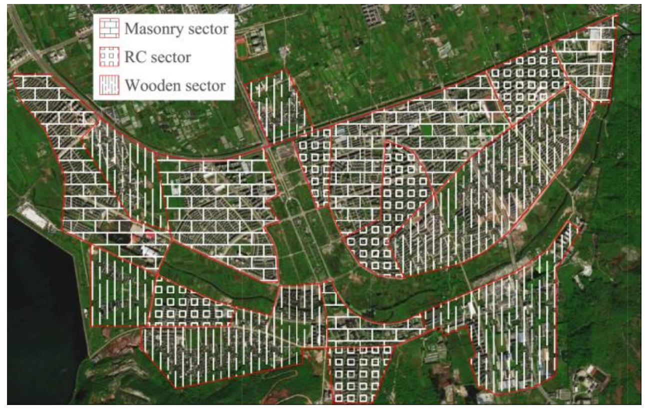


*Figure 2: layout of different building types.*

*Table 2: detailed information of each building type (in thousand RMB).*

| Type | Masonry | RC | Wooden |
|---|---|---|---|
| Number of clusters | 20 | 10 | 17 |
| Number of buildings | 5310 | 234 | 2311 |
| $c_{f,j}$ | 100 | 120 | 110 |
| $c_{\bar{f},j}$ | 300 | 4800 | ~4900 |

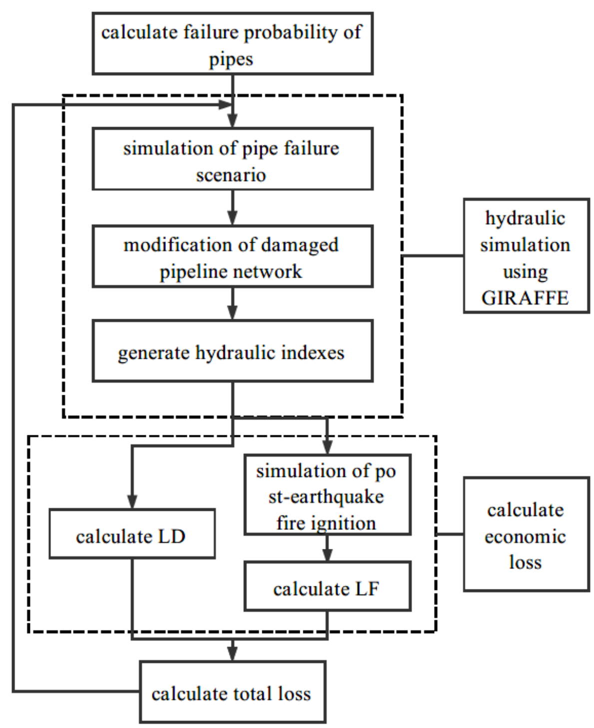


*Figure 3: simulation procedure.*

### *3.2. Result and discussion*

The distributions of the loss due to insufficient water supply for domestic use and for fire-fighting are demonstrated in Figure 4 and Figure 5, which show the cumulative probability of $L_D$ and total loss ($L_D$ + $L_F$). It can be seen that the water distribution network performs well under the attack of design earthquake (PGA = 0.25g), the probability of maintaining domestic water supply is over 60%, and the probability of insufficient water supply for fire-fighting is as low as 7.5%. However, when the PGA increases to 0.5g, a significant increase in loss due to insufficient water supply for domestic use, as well as for fire-fighting is observed. Different from $L_D$ whose probability distribution is single-mode, $L_F$ has multi-mode distribution associated with significantly larger variance. The mean value of $L_F$ is 108,900 RMB, which is significantly larger than that of $L_D$ of 42,200 RMB when PGA = 0.25g; however, when PGA = 0.5g, their mean values are comparable, e.g., averagely $L_F$ is 566,500 RMB and $L_D$ is 366,700 RMB.

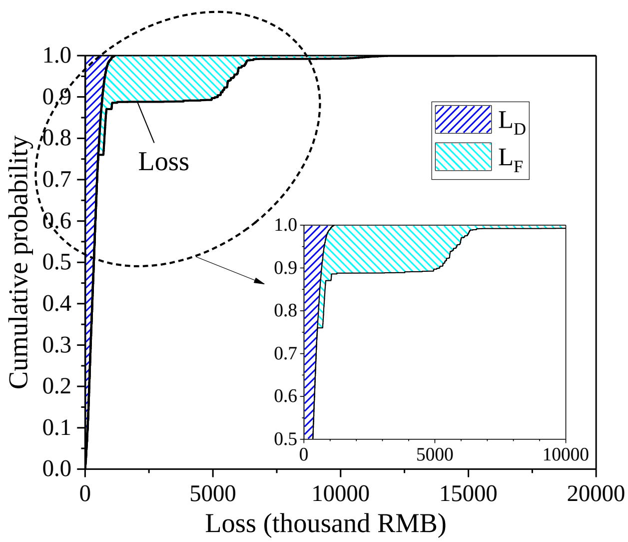


*Figure 4: cumulative distribution of $L_D$ and $L_F$ given PGA=0.5g.*

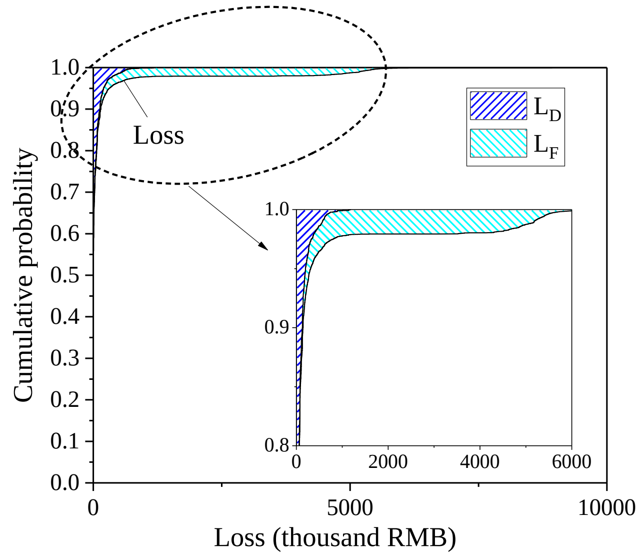


*Figure 5: cumulative distribution of $L_D$ and $L_F$ given PGA=0.25g.*

The correlation between $L_D$ and $L_F$ is also investigated, as shown in Fig.6. It can be seen that $L_D$ and $L_F$ are almost uncorrelated (correlation coefficient = 0.152) although they are caused by the damage of the same water distribution network, because $L_D$ significantly depends on the locations of broken nodes, while $L_F$ is mainly determined by the building clusters around broken nodes. Therefore, to measure the impact of WSS damage to a city, its effect on domestic water supply and fire-fighting ability should be both considered, and thus the metrics for single functionality such as system serviceability index (*SSI*) (Lee et al. 2018) are not proper.

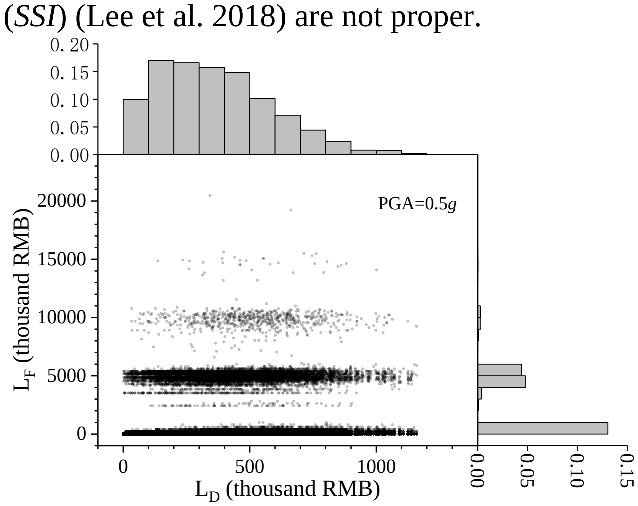

*Figure 6: correlation between $L_D$ and $L_F$ when PGA=0.5g.*

Similarly to *SSI*, the system fire-suppression index (*SFI*) of water distribution network is defined as the ratio of buildings whose water supply satisfies the need of fire suppression after the earthquake, as follows

$$SFI = \frac{\sum_{i=1}^{n} m_i \bullet I_i}{\sum_{i=1}^{n} m_i} \tag{8}$$

in which $m_i$ is the number of buildings whose water is supplied by node $i$, $I_i$ is an indicator whose value is 1 if the working pressure of fire hydrant at node $i$ is greater than 0.10Mpa, otherwise it is 0. Figure 7 plots *SSI* vs. *SFI* of all simulation results. It is interesting to note that they have relatively high correlation, because *SSI* and *SFI* are both hydraulic-based metrics. However, the economic-based metrics for domestic water supply and fire suppression are almost independent as seen in Figure 6. The advantage of economic-based metric over hydraulic-based metric is that $L_D$ and $L_F$ can be added together to form the total loss, which benefits the comparison among different WSSs and the design of optimum retrofitting strategy.

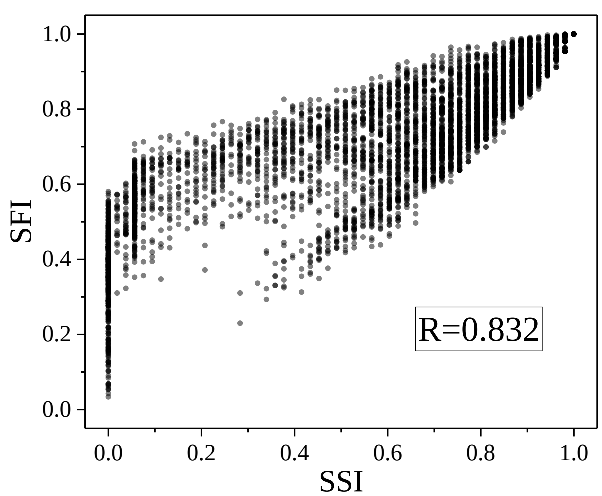


*Figure 7: correlation between hydraulic indices.*

## 4. CONCLUSIONS

To evaluate the performance WSS subjected to earthquake, an economic-based metric is proposed to consider the impact of earthquake on two functionalities of WSS, i.e., domestic water supply and fire suppression. The case study on the functionality loss of a water distribution network of a city demonstrates that:

1. The proposed multi-functionality-based metric can be used to estimate the loss due to disruption of multiple functionalities, and compare their relative contributions.
2. The economic-based loss due to disruption of domestic water supply and that due to disruption of fire suppression are basically independent, which indicates the necessity to measure the performance of WSS with multiple functionalities considered.

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