

# **A Framework to Incorporate Infrastructure Damage and Household Disaster Preparedness in the Assessment of Emergency Water Needs**

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## **ABSTRACT**

This paper investigates the effect of accounting for both physical damage to infrastructure and household disaster preparedness in estimates of potable water needs after earthquakes. A case study is presented involving the water supply system to the city of San Francisco after a  $M_w = 7.9$  earthquake. Accounting for household preparedness helps identify regions in the city where water supply is interrupted, and many people may not have personal resources to access alternative sources of water. Considering both infrastructure disruption and household characteristics may inform decisions to allocate emergency water resources across the city during emergency response.

## **1. INTRODUCTION**

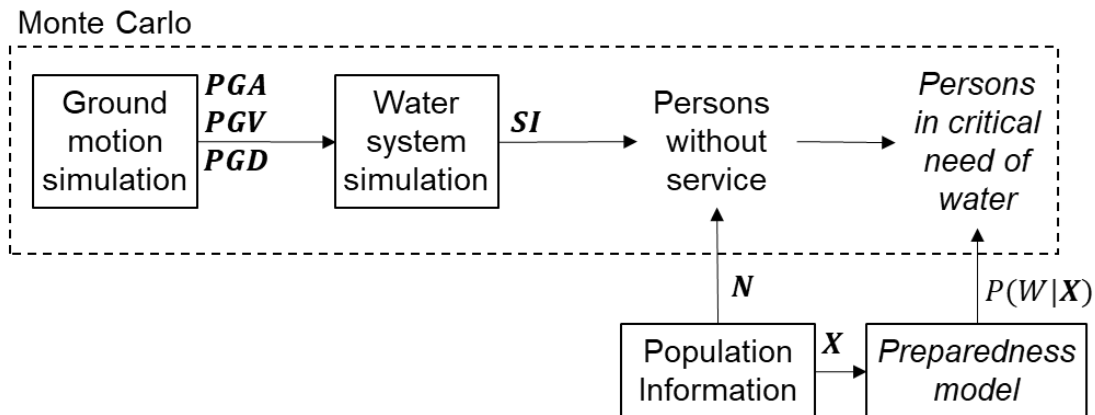
Interruptions to the water supply system are expected consequences of large earthquakes (Schiff 1995). In disaster response, emergency water sources can be used while repairs to the system are conducted (EPA 2011). Tanker trucks supplied emergency water after earthquakes in Northridge (McReynolds 1995), Kobe (Kameda 2000), Kashmir (Miller 2008), and Christchurch (Poole et al. 2012). The use of tanker trucks is also included in the emergency plans recently developed by the State of Washington (Office of Drinking Water 2017), and the San Francisco Public Utilities Commission in San Francisco (SFPUC 2017).

The American Water Works Association guidelines for emergency planning highlight the importance of setting priorities for the allocation of emergency water sources (AWWA 2001). In doing so, it is necessary to determine the areas most impacted by water shortages. Studies of post-earthquake scenarios for Los Angeles used the serviceability loss of the water system as a proxy of the unmet water demand (Romero et al. 2016, Tabucchi et al. 2008). Other scholars suggest that a better metric is the product of the serviceability loss and the population affected (Cimellaro et al. 2016, Brozović et al. 2007). These approaches assume that water shortages are experienced equally by all. However, studies have demonstrated that certain households are more capable of coping with short disruptions to water supply due to their disaster preparedness (Levac et al. 2012).

This study accounts for households' disaster preparedness in order to identify regions of a city where service is disrupted and persons do not have access to alternative sources of water. This information may provide valuable insights into the management of emergency water resources. This paper introduces a framework to incorporate household disaster preparedness on the estimation of post-earthquake unmet water demand. Preliminary results for a study of San Francisco are presented to illustrate the approach and impacts of considering household preparedness.

## 2. FRAMEWORK DESCRIPTION

Figure 1 shows the steps proposed in this study to account for household disaster preparedness when estimating the post-earthquake unmet water demand. The first step is to simulate the ground motion. The outputs from this step are vectors of the peak ground acceleration, **PGA**, peak ground velocity, **PGV**, and permanent ground deformation, **PGD** for all locations of interest. The next step is to simulate the state of the water system using the vectors **PGA**, **PGV** and **PGD** as inputs. In this step, damage to water treatment plants, tanks, pipelines, and other infrastructure is assessed. The output from this step is a vector containing the serviceability index for different locations in the city, **SI**. The serviceability index is the ratio of water available to an area after the earthquake to water available before the earthquake (Todini 2000). If the serviceability index is mathematically interpreted as a probability (Cimellaro et al. 2016), the expected number of persons without service in an area with population  $N$  can be calculated as  $N \cdot (1 - SI)$ . As indicated in Figure 1, uncertainties in the hazard, damage, and persons affected can be captured using a Monte Carlo approach.



**Figure 1. Framework to estimate the number of persons in critical need of water. The contributions in this paper are highlighted in italics.**

The last step in Figure 1, in italics, highlights the contributions in this paper. It is here assumed that among those without service some will have access to alternative water sources, e.g., bottled water or funds to temporarily move to a location with service. Conversely, those without service and access to alternative water sources are considered to be in ‘critical need of water.’ To determine the number of persons in critical need of water, a model for household disaster preparedness is proposed in this paper. The outcome from this model is a vector of the probability that a household with demographics  $\mathbf{X}$  has the means to obtain water from an

alternative source for three days,  $\mathbf{P}(\mathbf{W}|\mathbf{X})$ . Thus, for a specific area in the city, the number of persons in critical need of water,  $N_c$  is estimated in this paper as

$$N_c = N \cdot (1 - SI) \cdot \sum_{i=1}^{D_i} \sum_{j=1}^{D_j} \alpha_{i,j} (1 - P(W|X_{i,j})) \quad (2-1)$$

where  $\alpha_{i,j}$  represents the percentage of persons in demographic groups  $i$  and  $j$  with  $D_i$  and  $D_j$  levels,  $P(W|X_{i,j})$  is the probability that persons in demographic groups  $i$  and  $j$  have access to an alternative water source. In the case study discussed in the following, the demographics of the population are obtained from Census databases. For this reason,  $N_c$  is estimated for each census tract. For real-world applications, estimating the demographics of the population serviced by each node of the water system may be more appropriate.

### 3. CASE STUDY

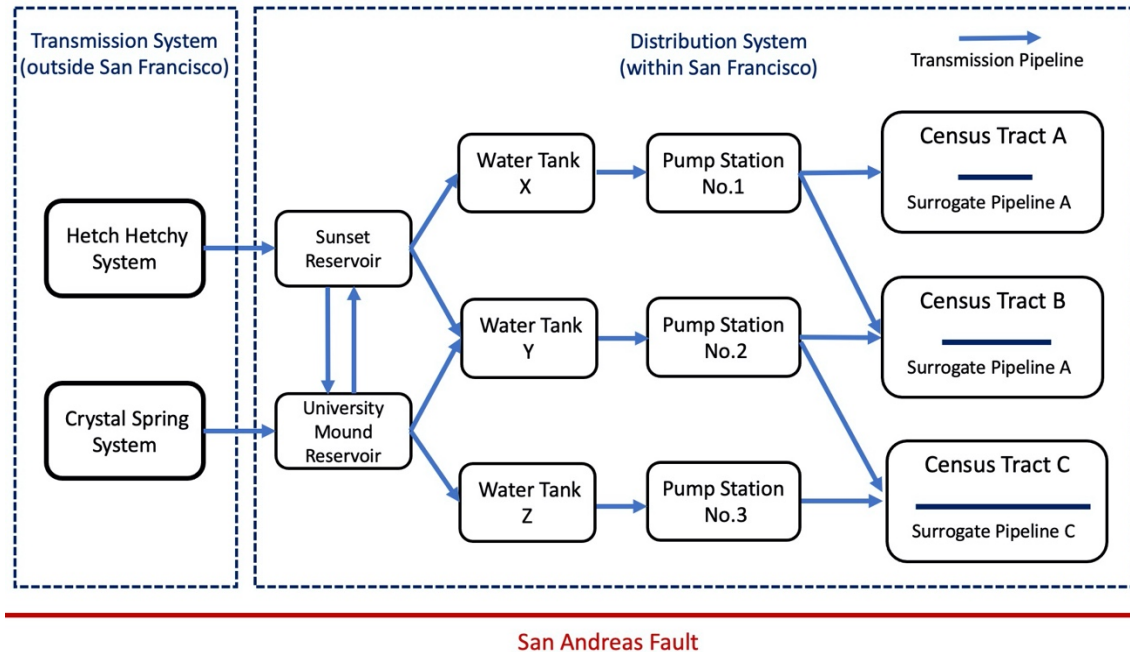
To illustrate the proposed framework, a case study involving the post-earthquake water demand in the city of San Francisco is presented. The water transmission and distribution systems in the city are simulated using primarily publicly available data. The objective is to portray how the concepts introduced in this research can be used.

**Ground Motion Simulation.** This case study considers the impact on the water system of a  $M_w = 7.9$  earthquake scenario on the San Andreas fault, which is representative of the 1906 San Francisco Earthquake (Zoback 2006). The location of the San Andreas fault relative to the water system is indicated in Figure 2. Ground motion intensity measures are simulated at the centroids of each of the 194 census tracts in San Francisco and the location of the water system facilities. Note that for simplicity only one realization of the ground motion is considered in this case study.

**Water System Simulation.** Two major water transmission systems supply San Francisco: the Crystal Spring system and the Hetch Hetchy system (SFPUC 2016). The Hetch Hetchy system transports water by gravity, delivering it to the University Mound Reservoir within San Francisco. The Crystal Springs system collects water from Crystal Springs and San Andreas reservoirs and pumps it to the Sunset Reservoir. The University Mound and Sunset reservoirs are connected by two pipelines which offer redundancy in case of a disruption. From the Sunset and University Mound Reservoirs, water is delivered to a system of storage tanks and pump stations that supply San Francisco. A schematic representation of the water transmission and distribution systems is shown in Figure 2. High-level data on the structural properties of the water distribution system facilities, e.g., treatment plant or storage tank, were obtained from public reports (SFPUC 2016). Damage to facilities is estimated using HAZUS fragility curves (FEMA 2015).

In Figure 2 are indicated the transmission pipelines, i.e.,  $> 20"$ , which connect facilities, as well as distribution pipelines, i.e.,  $\leq 20"$ , which supply the consumers in each census tract. A detailed simulation of the distribution pipelines would not be possible with the information available for this study. To simplify this model, a surrogate pipeline is used to represent all distribution pipelines within a census tract, as illustrated in Figure 2. The length of the surrogate distribution pipeline is the sum of the lengths of all distribution pipelines within that census tract. The number of leaks and breaks to all pipelines is determined using the HAZUS approach

(FEMA 2015). Transmission pipelines are divided into smaller segments and the numbers of leaks and breaks are estimated based on ground motion intensities calculated at the centroids of these segments. For the surrogate distribution pipeline, ground motion intensities measured at the centroid of the census tract are used. Damage from permanent ground deformations is considered only for the surrogate distribution pipeline. The fraction of liquefiable soil within each census tract is estimated from publicly available data (DataSF 2020).



**Figure 2. Schematic representation of the water supply system to San Francisco. The arrows connecting the facilities indicate transmission pipelines.**

Once the damage state of each facility is estimated, their percent functionality is determined (FEMA 2015). For each facility, the percent functionality is used as a proxy of the serviceability index (i.e., the fraction of the pre-earthquake demand that can be met by the facility after the disaster). The serviceability index for a pipeline is estimated as a function of the number of repairs needed (FEMA 2015). Finally, the water delivered to a census tract is proportional to the minimum serviceability index which is determined accounting for the interdependencies in the system.

**Household Preparedness Model.** Once the serviceability index is estimated for each census tract, a model for the probability that households have access to alternative sources of water is needed. Data from the American Housing Survey (United States Census Bureau 2017) is used to train this model. The survey collected data on household demographics, and whether they have \$2,000 for an emergency. The availability of funds is used as a proxy for the household's ability to procure bottled water or temporarily leave their homes if service is interrupted. Households that cannot procure alternative sources of water are assumed to be in critical need of water if service is disrupted. The probability that a household with demographics  $\mathbf{X}$  would have \$2,000 for an emergency,  $P(W|\mathbf{X})$ , is estimated using a logistic regression model

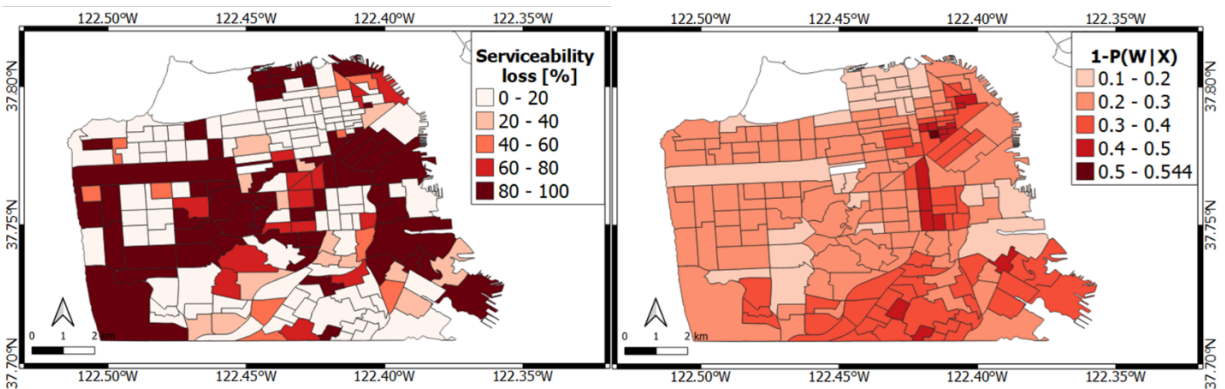
$$P(W|\mathbf{X}) = \exp(\boldsymbol{\beta}^T \mathbf{X}) / (1 + \exp(\boldsymbol{\beta}^T \mathbf{X})) \quad (3-1)$$

where  $\mathbf{X} = \{\mathbf{1}, \mathbf{X}_1, \dots, \mathbf{X}_p\}$  is a vector of  $p$  household demographic characteristics, and  $\boldsymbol{\beta} = \{\boldsymbol{\beta}_0, \boldsymbol{\beta}_1, \dots, \boldsymbol{\beta}_p\}$  is a vector of regression coefficients. A review of the literature on material disaster preparedness highlighted a large group of household demographics that are potential predictors of  $P(W|\mathbf{X})$  (Levac et al. 2012). However, models with fewer predictors have been demonstrated to yield better predictions when applied to new data (Friedman et al. 2001). The least absolute shrinkage and selection operator, LASSO (Tibshirani 1996), is used to obtain a prediction model with fewer demographics as predictors. The preparedness model obtained with this approach indicates that low income, Hispanic background, presence of members with disabilities, and having moved into the region within 10 years reduce the likelihood that a household has disaster funds. In contrast, a positive correlation is observed between high income, attainment of higher education, and the likelihood of having \$2,000 for an emergency.

#### 4. RESULTS

Using the framework in Figure 1, the post-earthquake water demands in San Francisco are investigated. The left panel in Figure 3 shows the expected loss of serviceability for each census tract. Darker areas indicate lower serviceability. The right panel in Figure 3 shows  $1 - P(W|\mathbf{X})$ , i.e., an inverse measure of disaster preparedness of households. Areas with the highest loss of serviceability are distributed throughout the city while the areas where fewer people have access to alternative water sources are concentrated on the east side of the city.

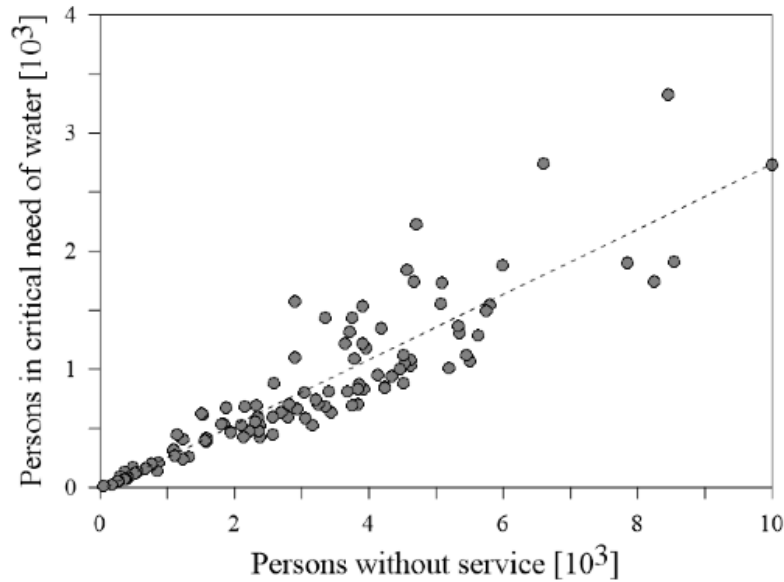
In Figure 4 the expected number of persons without service in each census tract,  $N \cdot (1 - SI)$ , is compared to the expected number of persons in critical need of water. Each dot represents one census tract. From Equation (2-1), it is noted that the slope of the dashed line in Figure 4 is proportional to the expected value of  $P(W|\mathbf{X})$  for the city. Because  $P(W|\mathbf{X})$  depends on the demographics of the census tracts, the number of persons in critical need of water may vary significantly for census tracts with similar levels of serviceability loss.



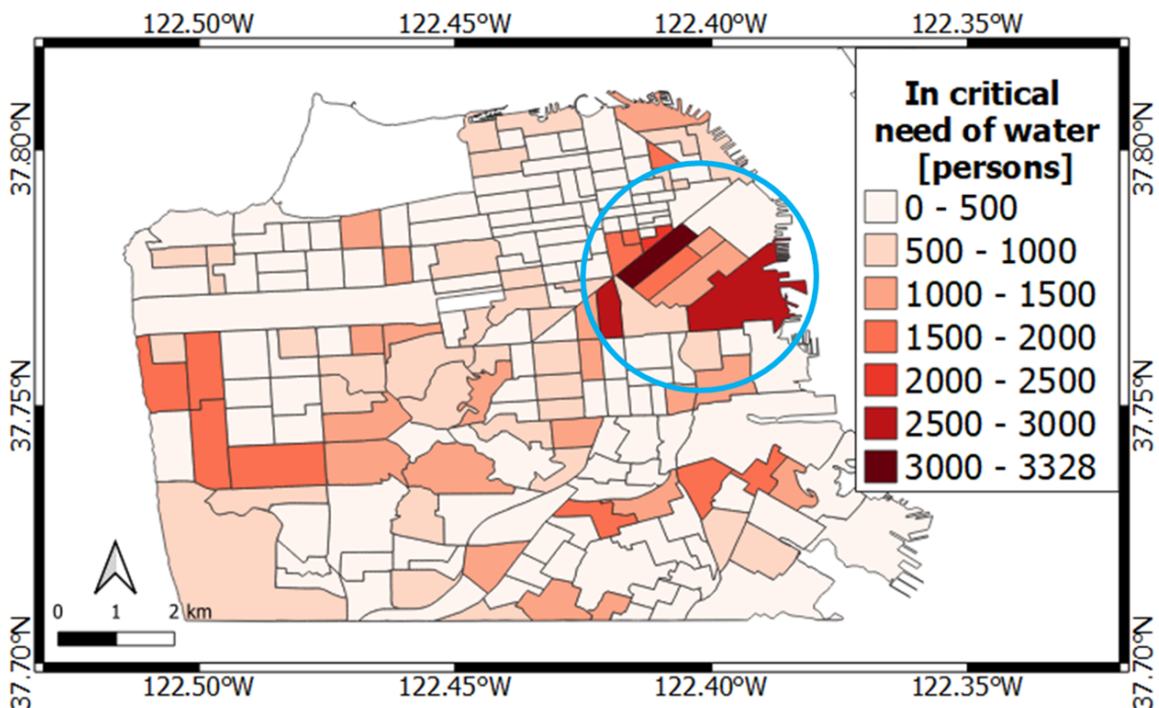
**Figure 3. Expected water serviceability loss, on the left, and probability that households will not have access to alternative sources of water, on the right.**

Lastly, Figure 5 shows the expected number of persons in critical need of water for each census tract in San Francisco. The blue circle in the figure highlights the Tenderloin and South of Market neighborhoods where up to 3,300 persons per census tract are expected to be in critical need of water. Compared to the left panel of Figure 3, Figure 5 illustrates the impact of

preparedness on earthquake impacts. Although widespread serviceability losses are expected, the highest numbers of persons in critical need of drinking water are in two neighborhoods. Results like these can highlight regions that will be more reliant on emergency water supply, which can in turn inform planning activities.



**Figure 4. Comparison between the number of persons expected to be without service and the those in critical need of water. Each point on the plot indicates one census tract, and the dashed line shows a regression fit to the data.**



**Figure 5. Persons in critical need of water in San Francisco after a  $M_w = 7.9$  earthquake scenario on the San Andreas fault.**

## 5. CONCLUSION

This paper introduces a preliminary framework to incorporate household disaster preparedness in the assessment of post-earthquake unmet water demand. A model for household preparedness is introduced. A statistical model, calibrated from American Household Survey data, indicates that households with lower income, Hispanic background, members with disabilities, and who moved recently are less likely to have \$2,000 for an emergency. In this analysis we use the statistical model to predict preparedness per census tract, inferring that households without emergency funds have less capacity to cope with water shortages. The analysis presented here integrates that consideration with the simulation of localized infrastructure service loss to quantify aggregate impacts to households. A case study involving water supply in San Francisco after a  $M_w = 7.9$  earthquake is used to illustrate the framework. Accounting for household disaster preparedness, we identify areas of the city with many people expected to be without service and access to alternative sources of water. This information can be helpful to emergency managers. The case study results include many assumptions and simplifications. However, the proposed framework can be integrated to existing and detailed water infrastructure simulation tools with minor changes, providing great flexibility. Furthermore, the integration of household disaster preparedness and loss assessment introduced in this study is not limited to water demand assessments. The proposed methodology could be applied to determine the post-disaster critical needs for shelter, food, medical supplies, among others.

## 6. ACKNOWLEDGEMENT

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