AN OVERVIEW OF THE WATER NETWORK TOOL FOR RESILIENCE (WNTR)

Katherine A. Klise[1], Regan Murray[2], Terranna Haxton[2]

[1] Sandia National Laboratories, PO Box 5800 MS 0751, Albuquerque, NM 87185

[2] U.S. Environmental Protection Agency, 26 W. Martin Luther King Dr., Cincinnati, OH 45268

[1]kaklise@sandia.gov

ABSTRACT

Drinking water systems face multiple challenges, including aging infrastructure, water quality concerns, uncertainty in supply and demand, natural disasters, environmental emergencies, and cyber and terrorist attacks. All of these incidents have the potential to disrupt a large portion of a water system causing damage to critical infrastructure, threatening human health, and interrupting service to customers. Recent incidents, including the floods and winter storms in the southern United States, highlight vulnerabilities in water systems and the need to minimize service loss. Simulation and analysis tools can help water utilities better understand how their system would respond to a wide range of disruptive incidents and inform planning to make systems more resilient over time.

The Water Network Tool for Resilience (WNTR) is a new open source Python package designed to meet this need. WNTR integrates hydraulic and water quality simulation, a wide range of damage and response options, and resilience metrics into a single software framework, allowing for end-to-end evaluation of water network resilience. WNTR includes capabilities to 1) generate and modify water network structure and operations, 2) simulate disaster scenarios, 3) model response and repair strategies, 4) simulate pressure dependent demand and demand-driven hydraulics, 5) simulate water quality, 6) calculate resilience metrics, and 7) visualize results. These capabilities can be used to evaluate resilience of water distribution systems to a wide range of hazards and to prioritize resilience-enhancing actions. Furthermore, the flexibility of the Python environment allows the user to easily customize analysis. For example, utilities can simulate a specific incident or run stochastic analysis for a range of probabilistic scenarios.

The U.S. Environmental Protection Agency and Sandia National Laboratories are working with water utilities to ensure that WNTR can be used to efficiently evaluate resilience under different use cases. The software has been used to evaluate resilience under earthquake and power outage scenarios, run fire-fighting capacity and pipe criticality analysis, evaluate sampling and flushing locations, and prioritize repair strategies.

This paper includes discussion on WNTR capabilities, use cases, and resources to help get new users started using the software. WNTR can be downloaded from the U.S. Environmental Protection Agency GitHub site at https://github.com/USEPA/WNTR. The GitHub site includes links to software documentation, software testing results, and contact information.

Keywords: Water distribution systems, resilience, software

1 Introduction

Water distribution systems are a crucial component of urban infrastructure, delivering safe drinking water to support human health, the economy, and the environment. At the same time, water distribution systems face multiple challenges that put them at risk of not being able to maintain this critical function. Aging infrastructure increases susceptibility to pipe breaks and water quality problems. Changes in winter runoff and shifting population centers create uncertainty in water supply and demand. Natural disasters such as hurricanes and earthquakes have the potential to disrupt water service for extended periods of time. Remote access to control points make cyber interference a growing concern.

Recent incidents, such as the South Napa earthquake, Hurricane Katrina and Hurricane Harvey, Superstorm Sandy, West Virginia's Elk River chemical spill, and the Lake Erie algal bloom have all significantly impacted water distribution systems and threatened human health [1, 2, 3, 4]. These types of disruptive incidents can cause a wide range of damage, including pipe leaks, water contamination, and the inability to operate pumps. This type of damage can severely impact the water utility's ability to maintain water service and provide adequate pressure to fight fires. In response to these threats, drinking water utilities are taking steps to enhance resilience to disruptions that could occur in their region [5]. An important step in that process is understanding how to respond to disruptive incidents and understanding how mitigation and recovery actions reduce undesired outcomes.

The National Infrastructure Advisory Council defined infrastructure resilience as "the ability to reduce the magnitude and/or duration of disruptive incidents. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event" [6]. For water utilities to become more resilient, they must understand how their system will perform during disruptive incidents and prioritize choices that could help absorb, recover from, and adapt to such incidents. Simulation and analysis tools have the potential to help water utilities respond to disruptive incidents, plan recovery actions, and become more resilient over time.

The Water Network Tool for Resilience (WNTR, pronounced winter) is a Python package designed to simulate and analyze resilience of water distribution networks [7, 8]. The United States Environmental Protection Agency (EPA), in partnership with Sandia National Laboratories (SNL), developed WNTR to integrate critical aspects of resilience modeling for water distribution systems into a single software framework. The following paper includes a description of WNTR capabilities, applications, and resources to help new users get started using the software.

2 Software capabilities

The water distribution system analysis community commonly uses EPANET [9] to model pressures and flows in water distribution systems. WNTR was developed to extend these capabilities to include a wider set of hydraulic and water quality scenarios that are important to consider when modeling disruptive incidents and recovery efforts. WNTR can simulate hydraulics using both demand driven and pressure dependent demand. Pressure dependent demand simulations allow the user to better understand disruptions that isolate portions of the network or reduce the ability of the network to supply water to customers. These conditions are common when simulating large pipe leaks and power outages. WNTR also includes the ability to generate damage states by sampling from fragility or survival curves. The damage state for individual components (e.g., pipes, pumps, tanks) can be selected from a wide range of statistical distributions. This functionality allows the user to simulate stochastic disaster scenarios, selecting a probability of damage for each component. Response and repair strategies, such as repair time and the number of available crews, can also be assigned a probability. Within WNTR, simulation results can be used to compute resilience using different metrics, including hydraulic, topographic, water quality, and cost metrics. Example metrics include water service availability, extent of contamination, betweenness centrality, and number of articulation points [6]. WNTR includes graphing capabilities to visualize results using network graphics, timeseries plots, animation, and interactive graphics.

The water network model that is used in WNTR can be created directly from an EPANET-formatted water network model input (EPANET INP) file. Network structure and operations can be modified within WNTR and the resulting WNTR water network model can be saved back to an EPANET INP file. This compatibility allows users to easily switch between EPANET and WNTR.

WNTR is a Python software package that integrates several open source Python packages commonly used by the data science community, including: Numpy and Scipy [10] for efficient numerical computation, Pandas [11] for powerful time series analysis, NetworkX [12] for topographic analysis of the network structure, along with Matplotlib [13] and Plotly [14] for high quality graphics and animation. Combining these tools with hydraulic and water quality analysis allows users interested in water distribution system analysis to quickly get started with WNTR and facilitates broad flexibility to build custom analysis. The capabilities in WNTR can be linked together in many ways, from simple to complex analysis. For example, WNTR can be used to simply generate network models and compute topographic metrics based on the network structure. WNTR can also be used to run complex stochastic analysis of system resilience given specific information on disruption and recovery actions.

To ensure software quality assurance, WNTR utilizes the publicly available continuous integration software Travis CI. Software tests are run automatically each time changes are made to the repository and cover a wide range of tests to confirm that the code is performing as expected. In addition to the publicly available software tests, WNTR is also tested on private servers using several large water utility network models before each new release of the software. The current testing suite includes a wide variety of water network models, ranging in size up to 55,000 nodes.

3 WNTR Applications

EPA and SNL are working with water utilities to ensure that WNTR can be used in a wide range of scenarios to evaluate resilience. Applications are highly dependent on the threats and vulnerabilities specific to individual utilities. For example, some water utilities might be most interested in evaluating the impact of source water contamination, power outages, or pipe breaks. The following section describes three types of analyses performed using WNTR. While these applications have been performed using real water utility network models to provide results specific to each utility, the following examples use publicly available water network models to demonstrate the same capabilities.

3.1 Compromised source water analysis

The following application analyzes a water distribution system after the water supply has been compromised. Several scenarios could cause a water supply to be compromised: contamination of the source water; a major failure at the treatment plant; a frozen intake; or a malfunctioning pump station at the intake. Given the wide range of causes, many water utilities would like to know how long they could maintain water service if they lost access to their source water, how conservation efforts by customers might extend water use, and how they could best serve critical customers in that situation.

To simulate scenarios where a water distribution system loses access to source water, valves leading to the reservoirs can be closed instantaneously or over a period of time. Network operations can also be modified to ensure that tanks empty after the shut off of the source water in order to supply the system (this can include changing pump and valve controls along with minimum tank levels). Water conservation efforts can be added by changing demands in the network, either globally or by targeting specific water users. To serve critical customers, valves can be closed to redirect water. While these simulation options exist in EPANET, WNTR allows the user to modify the network model and simulate hydraulics using pressure dependent demand, which is crucial in scenarios where water supply is severely restricted. The following example illustrates an analysis where the pipes leaving two source nodes are closed at hour 24 (using a water network model from [9]). Figure 1A includes the network graphic with labeled pipe closures and the node pressure at hour 32. Figure 1B shows tank levels, which are all drained nine hours after water supply is lost. In Figure 2, the same type of results are shown with the addition of selected valve closures to isolate the northeast and southern sections of the network. In this scenario, the northeast section maintains pressure for more than three days and pressure is slightly extended in the southern section, however, pressure and water service in the rest of the network is diminished faster. Using this type of analysis, water conservation efforts can also be tested. Based on the original scenario (with no isolation), a 50% reduction in water use can extend water availability for an extra 14 hours. This type of analysis can help water utilities plan mitigation strategies when the source water cannot be used.

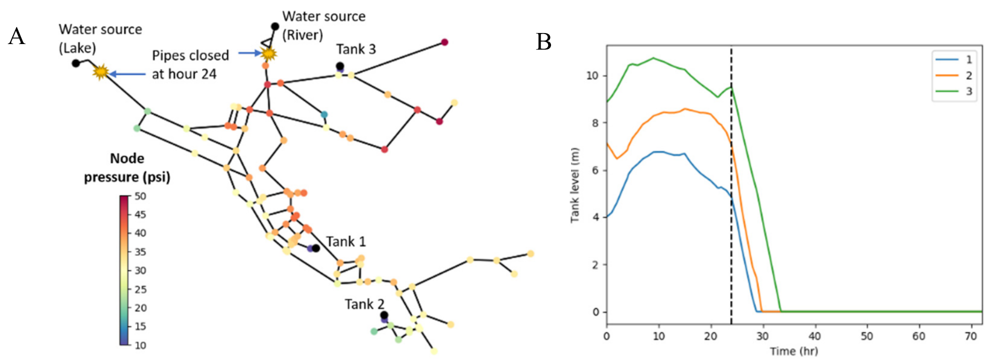

Figure 1.A) Water pressure in psi at hour 32 following pipe closure at hour 24, and B) tank levels over time (dashed line indicates the time of pipe closure).

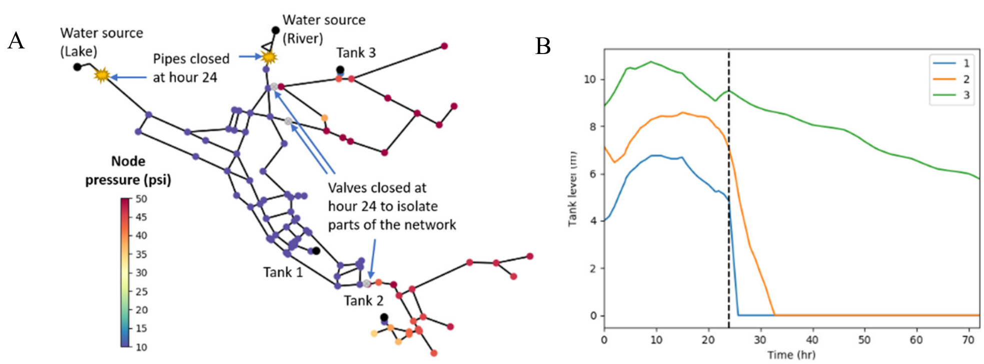

Figure 2. A) Water pressure in psi at hour 32 following pipe and valve closures at hour 24, and B) tank levels over time (dashed line indicates the time of pipe closure).

3.2 Earthquake preparedness analysis

Water utilities in earthquake prone areas, such as the California Bay Area, are interested in preparedness and mitigation strategies that could reduce damage from an earthquake. Infrastructure damage following earthquakes is well documented, and models exist to simulate seismic waves [15] and define probability of damage to network components [16]. WNTR can use these models to estimate peak ground acceleration and pipe repair rates across the network, given an earthquake epicenter and magnitude. Measured data or data simulated using third party software can also be used in the simulation. Within WNTR, the probability of damage for individual network components (e.g., pipes, pumps, tanks) can be defined using fragility curves, leak models can be used to model damaged pipes, and controls can be used to cut power to pumps. An earthquake preparedness analysis integrates these capabilities into a stochastic framework that examines the impact of earthquake epicenter, magnitude, restoration actions (e.g., pipe, tank, or pump repair), and mitigation strategies (e.g., earthquake resistant pipes) on the utility's ability to maintain water service availability across the network. Given the wide spread damage that can occur after an earthquake, pressure dependent demand is a crucial aspect of this type of analysis. Figure 3 includes a subset of results (using a water network model from [17]) from an earthquake preparedness analysis described in [18], including simulated peak ground acceleration, tank fragility curve, and the predicted population impacted by low water service availability for several days following an earthquake. Earthquake preparedness analysis can help water utilities identify network components that are particularly susceptible to damage, prioritize mitigation strategies such as hardening pipes, and plan for extended periods of low water service.

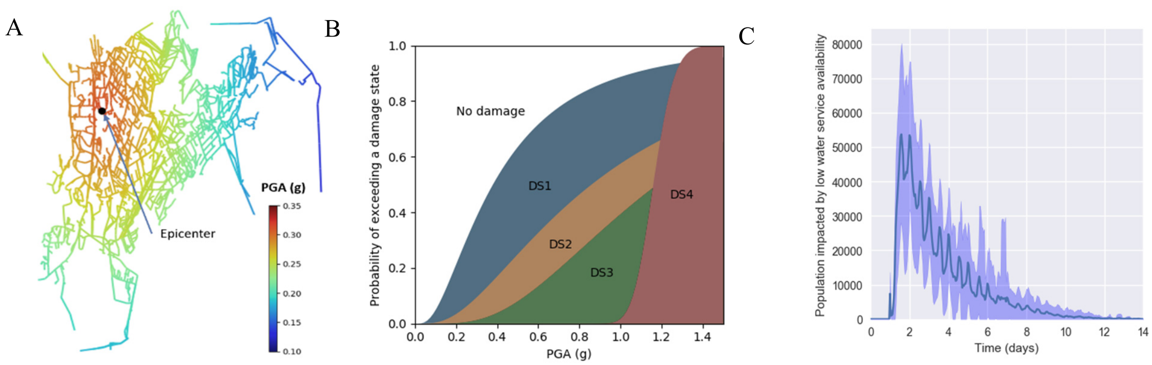

Figure 3. (A) Simulated peak ground acceleration (PGA) from a magnitude 6.5 earthquake, (B) fragility curves defining tank damage states (DS), and (C) stochastic analysis results showing the population impacted by low water service availability following an earthquake (mean value and shaded region covering 2 standard deviations).

3.3 Hydraulic connectivity analysis

Connectivity analysis can help water utilities identify critical pathways in their system. WNTR can be used to compute both topographic (i.e., spatial) and hydraulic (i.e., flow path) connectivity. While topographic connectivity, such as shortest path length and betweenness centrality, are useful metrics, including hydraulics in the analysis can help water utilities understand critical pathways under different hydraulic scenarios.

The following example illustrates the use of trace simulations to compute hydraulic connectivity (using a water network model from [19]). While this analysis can be performed using EPANET, the ability to change simulation options and analyze results directly in WNTR streamlines the process. For this analysis, trace simulations are run to track the percent of flow originating from each node in the network. This information is used to gather upstream and downstream nodes from each node. Figure 4A shows the upstream and downstream nodes for one tank. This analysis highlights where water comes from to fill the tank, and which nodes receive water from the tank. Using the same set of simulations, the analysis can be repeated for each reservoir, tank, pump, and valve in the system to gain insight into the hydraulic connectivity between critical components. Furthermore, the analysis can be repeated when the network is stressed by disruption to see how critical paths change. Hydraulic connectivity analysis can also be used to identify coverage by sensors. Figure 4B illustrates redundancy in node coverage from the 5-sensor layout. Nodes in red, orange, yellow, and green are upstream from 1, 2, 3, or 4 sensors, respectively, meaning that water quality problems in those nodes might be detectable at the sensors. Understanding node coverage and redundancy can help improve the performance of a monitoring strategy.

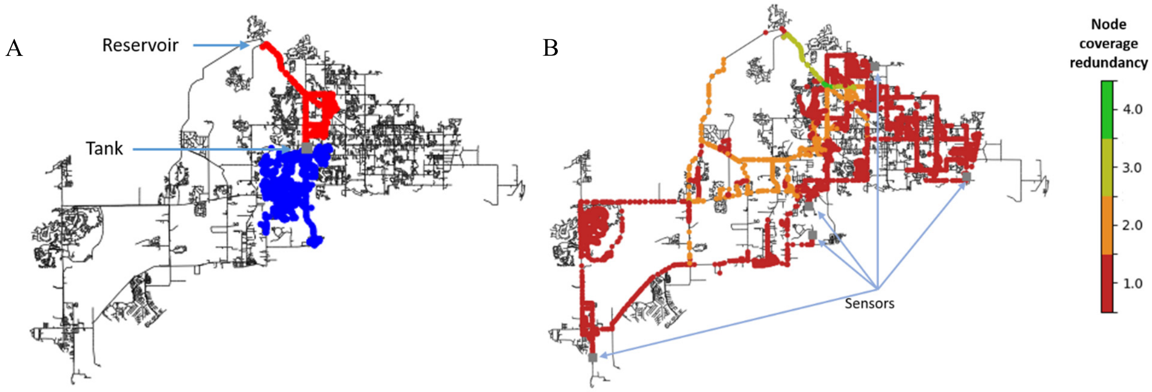

Figure 4 *(A) Hydraulic connectivity based on the location of a tank (red nodes feed the tank, blue nodes are fed by the tank), and (B) redundancy in node coverage from five sensors.*

4 Getting started

WNTR can be downloaded from the U.S. Environmental Protection Agency GitHub site at https://github.com/USEPA/WNTR. Online documentation, including installation instructions, are available at http://wntr.readthedocs.io. Python distributions, such as Anaconda, are recommended to manage the Python environment. Anaconda comes with the Python dependencies needed to run WNTR and an interactive development environment (IDE) that has enhanced editing and debug features along with a graphical user interface.

Figure 5 includes a very simple example to help get users started. The example imports WNTR, generates a water network model from an EPANET INP file, runs a pressure dependent hydraulic simulation, and plots simulation results. The WNTR Python package is imported on line 1. On line 5, a water network model, wn, is created from an EPANET INP file (Net3.inp, which is distributed with EPANET and WNTR). The water network model is a Python object that allows users to add and remove network components and controls, and change simulation options. On line 8, the simulator is defined to run a pressure dependent demand hydraulic simulation. On line 9, the simulation is run and results (including node demand, node pressure, link velocity, and link flow) are stored as a collection of Pandas DataFrames [11]. Each DataFrame is indexed by the reporting timestamp and has labeled columns for each node or link. This format is very useful for analyzing large quantities of timeseries data and includes several graphing options. Line 12 extracts node pressure at hour 5 and

```
1   import wntr
2
3   # Create a water network model
4   inp_file = 'Net3.inp'
5   wn = wntr.network.WaterNetworkModel(inp_file)
6
7   # Simulate hydraulics
8   sim = wntr.sim.WNTRSimulator(wn, mode='PDD')
9   results = sim.run_sim()
10
11  # Plot results on the network
12  pressure_5hr = results.node['pressure'].loc[5*3600, :]
13  wntr.graphics.plot_network(wn, node_attribute=pressure_5hr, title='Pressure at 5 hours')
```

Figure 5. Simple Python example script which imports WNTR, generates a water network model from an EPANET INP file, runs a hydraulic simulation, and plots the simulation results.

line 13 plots the pressure values on the network. Figure 6 shows the network graphic created from this example. The online user manual includes examples to help users integrate additional options to this simple example, including minimum and nominal pressure values, fragility curves, pipe leaks, power outages, and restoration actions.

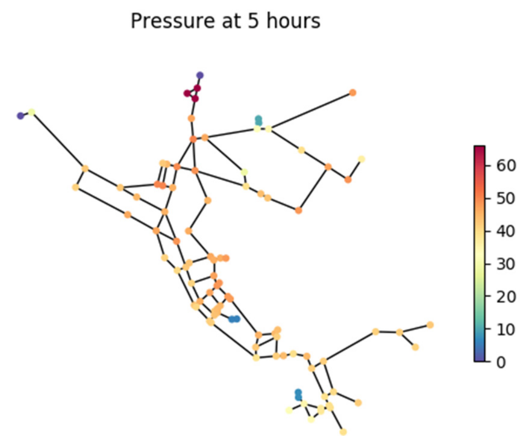

Figure 6. Network graphic created from the simple example.

5 Conclusions

The ability to predict how water distribution systems will perform during disruptive incidents and understand how to absorb, recover from, and adapt to such incidents can help enhance resilience. WNTR is a Python package designed to meet this need. The software can be used to evaluate water distribution system resilience considering a wide range of disruptive incidents, including earthquakes, power outages, water quality concerns, uncertainty in supply and demand, and cyber-attacks. The software provides the water distribution systems analysis community with a rich set of simulation and analysis tools.

EPA and SNL are planning to conduct a series of case studies working directly with water utilities, state regulators, and EPA regions to address resilience scenarios of concern. Through these case studies, further enhancements to WNTR will be identified and implemented.

6 Disclaimer

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development funded and collaborated in the research described here under an Interagency Agreement with the Department of Energy's Sandia National Laboratories. It has been subjected to the Agency's review and has been approved for publication. Note that approval does not signify that the contents necessarily reflect the views of the Agency. Mention of trade names, products, or services does not convey official EPA approval, endorsement, or recommendation.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

7 References

[1] D. Reed, R. Stephenson and S. Hyland, "Recovering from Hurricane Sandy: Coordination, planning bolster storm response," *Opflow,* vol. 39, no. 5, pp. 10-14, 2013.

[2] M. Scharenaker, "Katrina stories highlight new realities of disaster planning," *Journal of the American Water Works Association,* vol. 98, no. 6, pp. 16-30, 2006.

[3] L. Johnson and S. Mahin, "The Mw 6.0 South Napa Earthquake of August 24, 2014," Pacific Earthquake Engineering Research Center, Sacramento, CA, 2016.

[4] E. Osnos, "Chemical Valley: the coal industry, the politicians, and the big spill," *The New Yorker,* vol. April 7, 2014.

[5] U.S. EPA, "Drinking Water and Wastewater Resilience," [Online]. Available: https://www.epa.gov/waterresilience.

[6] National Academy of Sciences (NAS), "Disaster Resilience: A National Imperative," prepared by the NAS Committee on Science, Engineering, and Public Policy. The National Academies Press, Washington, DC, 2012.

[7] "WNTR: Water Network Tool for Resilience," [Online]. Available: https://github.com/USEPA/WNTR.

[8] K. Klise, D. Hart, D. Moriarty, M. Bynum, R. Murray, J. Burkhardt and T. Haxton, "Water Network Tool for Resilience (WNTR) User Manual," U.S. Environmental Protection Agency, EPA/600/R-17/264, Cincinnati, OH, 2017.

[9] L. A. Rossman, "EPANET 2 Users Manual," US Environmental Protection Agency, EPA 600/R–00/057, Cincinnati, OH, 2000.

[10] S. van der Walt, S. C. Colbert and G. Varoquaux, "The NumPy Array: A Structure for Efficient Numerical Computation," *Computing in Science & Engineering,* vol. 13, pp. 22-30, 2011.

[11] W. McKinney, Python for Data Analysis: Data Wrangling with Pandas, NumPy, and IPython, Sebastopol, CA: O'Reilly Media, 2012.

[12] A. A. Hagberg, D. A. Schult and P. J. Swart, "Exploring network structure, dynamics, and function using NetworkX," in *Proceedings of the 7th Python in Science Conference (SciPy2008)*, Pasadena, CA, 2008.

[13] J. D. Hunter, "Matplotlib: A 2D Graphics Environment," *Computing in Science & Engineering,* vol. 9, pp. 90-95, 2007.

[14] C. Sievert, C. Parmer, T. Hocking, S. Chamberlain, K. Ram, M. Corvellec and P. Despouy, "plotly: Create interactive web graphics via Plotly's JavaScript graphing library," Software, 2016.

[15] K. Kawashima, K. Aizawa and K. Takahashi, "Attenuation of peak ground motion and absolute acceleration response spectra," in *Proceedings of the 8th World Conference on Earthquake Engineering (WCEE)*, San Francisco, CA, 1984.

[16] American Lifelines Alliance (ALA), "Seismic Fragility Formulations for Water Systems, Part 1," American Lifelines Alliance, 2001.

[17] J. Watson, R. Murray and W. E. Hart, "Formulation and optimization of robust sensor placement problems for drinking water contamination warning systems," *Journal of Infrastructure Systems,* vol. 15, no. 4, pp. 330-339, 2009.

[18] K. Klise, M. Bynum, D. Moriarty and R. Murray, "A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study," *Environmental Modelling and Software,* vol. 95, pp. 420-431, 2017.

[19] A. Ostfeld, J. Uber, E. . Salomons and T. Walski, "The Battle of the Water Sensor Networks (BWSN): A Design Challenge for Engineers and Algorithms," *Journal of Water Resources Planning and Management,* vol. 134, no. 6, pp. 556-568, 2008.