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WATER SUPPLY DECISION SUPPORT FOR EARTHQUAKES

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ABSTRACT

This paper describes the response of the Los Angeles Department of Water and Power (LADWP) water distribution system to scenario earthquakes of 7.0 M_W on the Northridge Fault and 7.8 M_W on the southern San Andreas Fault. The simulations cover all 11,691 km of water trunk and distribution pipelines and related facilities (e.g., tanks, reservoirs, pressure regulation stations, etc.) in the LADWP system. The paper focuses on post-earthquake performance with and without the reservoirs removed from the system because of water quality requirements. The simulations show that opening the reservoirs immediately after a serious earthquake improves serviceability significantly, especially in the most highly populated areas of Los Angeles, and is therefore a favorable strategy for improved emergency performance.

Introduction

A decision support system was developed by using the LADWP water supply as a test bed. The system is intended to plan operations, emergency response, and new system facilities and configurations to optimize water supply performance during and after earthquakes (O'Rourke et al, 2008). The system is generic, and the architecture of its computer programs is adaptable to any water supply. The system works in conjunction with an easily accessible hydraulic network model, EPANET, which is available on-line from the U.S. Environmental Protection Agency (EPA, 2007) as well as a special program for damaged network flow modeling, known as Graphical Iterative Response Analysis for Flow Following Earthquakes (GIRAFFE). Detailed information about the development and evaluation of GIRAFFE is provided by Bonneau and O'Rourke (2009).

The paper describes the decision support system and its application in developing emergency response plans for a severe earthquake. System simulations were performed for the water supply response to both a 7.0 M_W earthquake on the Northridge Fault and a 7.8 M_W earthquake on the southern San Andreas Fault. The models for simulating pipeline performance under transient and permanent ground deformation are discussed, and the results of the earthquake/water supply simulations are summarized. The paper focuses on the post-earthquake performance of the water supply with and without

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reservoirs that were removed from service due to water quality requirements. The serviceability of the water supply, defined as the ratio of water available after an earthquake to the water supplied beforehand, is compared after two scenario earthquakes for water distribution system performance with and without the removed reservoirs.

Scenario Earthquakes

The ShakeOut Scenario earthquake is a 7.8 M_W earthquake on the southernmost 300 km of the San Andreas Fault (SAF), which ruptures from the Salton Sea towards Los Angeles (USGS, 2008a). The ShakeOut scenario strong ground motion model includes attenuation, site effects, directivity, and radiation patterns at different locations in southern California. This scenario was used as part of an earthquake preparedness exercise referred to as the Great Southern California ShakeOut, which was the largest earthquake preparedness drill in US history, with an estimated 5.47 million people participating.

Figure 1 shows the strong motions predicted by the Shakeout Scenario throughout the LADWP system. Figure 1 a) shows a regional map of the Los Angeles area in which the LADWP system is located relative to the SAF. Figure 1 b) presents the spatial distribution of PGA generated by the earthquake. The San Fernando Valley and the southern part of the service area are the locations of maximum PGA (approximately 0.3 g). Figure 1 c) presents the SAF rupture and distribution of PGV. The locations of maximum PGV correspond to deep sediment basins, which amplify the incoming ground waves to produce locally high PGV. There are two main locations of wave amplification in the northern part of the San Fernando Valley and the southeast part of the region, where PGVs approach 200 cm/sec. Shape files for the areal distribution of peak ground acceleration (PGA) and peak ground velocity (PGV) of both maps are available at the USGS web site (USGS, 2008b).

The M_w7.0 Northridge earthquake scenario is slightly stronger than its 1994 counterpart, but sufficiently similar to provide results that can be assessed relative to recent experience with system performance during the actual Northridge earthquake. As pointed out by Davis, et al. (2007), system simulations for a repeat Northridge earthquake provide a credible basis for assessing how water quality improvements affect the seismic performance and recovery capability of the LADWP water supply. As explained by Bonneau and O'Rourke (2009), strong motion simulation involves modeling the earthquake source, estimating rock motions throughout the LADWP system using four attenuation relationships with equal weighting, and using the GIS site-condition map for the Los Angeles region to determine the NEHRP site conditions to obtain surface strong motion parameters.

System Simulation

As described by O'Rourke, et al. (2008), the decision support system uses a hydraulic network model that accounts for all 11,691 km of water trunk and distribution pipelines and related facilities (e.g., tanks, reservoirs, pressure regulation stations, etc.) in the

LADWP system. The system also accounts for the aggregated seismic hazard in Los Angeles through an ensemble of 59 scenario earthquakes. The 59 scenario earthquakes provide a library of seismic scenarios, from which engineers can select specific scenarios or combinations of scenarios to assess system performance. The decision support system works with risk and reliability assessment tools to provide metrics of system performance. The computer simulations account for the interaction of the water and electric power supplies, and model output can be used to evaluate the regional economic and community impacts of water losses. All system input and output can be visualized through GIS with advanced query logic and web-based features. The simulations are dynamic in time, and can account for loss of service as tanks and local reservoirs lose water over time through leaks and breaks in pipelines.

Pipeline damage caused by permanent ground deformation (PGD) is accounted for explicitly by locating the area of the system subjected to large ground movements and estimating the damage by various methods, such as expert judgment, simplified models, and finite element simulation of soil-pipeline interaction.Transient ground deformation (TGD), or seismic wave, effects are estimated by means of regressions developed from previous earthquake records that correlate pipeline repair rate (RR), defined as the number of repairs per km, with PGV. Regressions developed by Jeon and O'Rourke (2005) and Wang and O'Rourke (2008) for water distribution and trunk lines, respectively, are used. Because it is not possible *a priori* to know the damage locations, multiple system response analyses, known as Monte Carlo simulations, are run and the statistics of the simulated performances are summarized. As explained by Bonneau and O'Rourke (2009), Monte Carlo simulations are run according to an algorithm that uses a Poisson process to select pipeline damage locations. The number of simulations is either set by the user or determined by the program according to specified convergence criteria. Typically, 15 simulations were required to meet convergence requirements.

In addition to modeling pipeline damage, it is important to account for the vulnerability of other facilities in the system. For example, tank damage was modeled by fragility curves developed for different types of tanks used by LADWP. The simulations incorporate fragility curves proposed by O'Rourke and So (2000) for steel tanks and fragility curves used in HAZUS (FEMA, 2006) for concrete tanks.

As described by Bonneau and O'Rourke (2009), the PGD effects for a 7.0 M_W earthquake on the Northridge Fault were assumed to be similar to those observed after the 1994 Northridge earthquake. As described by Romero, et al (2010), the magnitudes and locations of PGD from the ShakeOut Scenario were used to estimate damage to the trunk line system according to a decision process developed with LADWP that accounts for the predicted magnitude of movement and type of pipeline (Romero et al, 2010). For both the 7.0 M_W Northridge Fault and 7.8 M_W San Andreas Fault earthquakes, disruption of the Los Angeles Aqueducts (LAAs) was assumed. The 3.3-m rupture of the San Andreas Fault at the LAA crossings predicted by the ShakeOut scenario earthquake would cut off the aqueduct supply. Slope instability and severe shaking effects would locally damage the LAAs during a 7.0 M_W Northridge earthquake. Thus, the simulations were run without supply from the LAAs in the hydraulic network model.

Reservoirs and Water Service Areas

The LADWP is presently undertaking an extensive capital improvement program to meet the requirements of the U.S. Environmental Protection Agency and California State Department of Health Services requirements with respect to surface water treatment and disinfection byproducts. Significant water system changes are necessary to meet the requirements. System changes include the removal of Encino, Hollywood, and Lower Stone Canyon Reservoirs from normal operating service, which places a much greater importance on the Los Angeles Reservoir and Van Norman Complex for reliable water distribution. Figure 2 shows the locations and approximate water storage capacities of the Los Angeles, Encino, Lower Stone Canyon, and Hollywood Reservoirs. The removal of these reservoirs represents a loss of about 34 million m^3 of water from immediate use in the system.

The system response was evaluated for 15 water service areas, shown in Figure 3. Water service areas are geographic groupings of pipelines, pumps, valves, tanks, reservoirs, and demands that can be analyzed individually. From north to south the water service areas are: Granada Hills (GH), Foothills (FH), Sunland-Tujunga (ST), Valley Floor A, B and C (VF A, VF B, VF C), Encino Hills (EH), Santa Monica (SM), Hollywood Hills (HH), Mount Washington (MW), Highland Park (HP), Santa Ynez (SY), Westside (WS), Central City (CC), and Harbor (H). The Valley Floor, Central City, and Westside water service areas are at relatively low elevations. They involve some of the highest demands in the system, delivering water to the San Fernando Valley, downtown Los Angeles, and western Los Angeles communities. The Harbor water service area is located at the southern end of the system, and the remaining water service areas are situated at higher elevations and in the mountains.

By showing the results for the 15 water service areas, one is able to understand the spatial variability of the system performance as expressed in terms of serviceability index (SI), which is the percentage of post-earthquake flows relative to pre-earthquake flows at all demand nodes within a water service area. The system serviceability index (SSI) is the same percentage for the entire system.

All simulations discussed herein were run for the average 24-hr summer water demand, which is the largest average usage during the year. Choosing the largest usage is a reasonable estimate of demand. Even though the occupants of damaged buildings may use less than normal quantities of water, service line leakage and damage to the interior piping of buildings will draw significant amounts of water from the system.

Shakeout Scenario Earthquake Effects

Figure 4 shows the flow conditions in the trunk line system at 0 and 24 hrs after the earthquake for a single network analysis representing the median results of the Monte Carlo simulations. This figure provides information about the spatial distribution of flows and the way they diminish with time. The deterioration in performance is generated by losses from leaking pipelines that draw down tanks and reservoirs, causing some sections of the system to lose all local sources of water. Following such a large event, it will take considerable time to isolate and repair leaking pipelines. A period of 24 hrs was chosen in consultation with LADWP personnel as a representative interval for showing time-dependent losses before significant repair and restoration can be initiated. The decrease in pipelines with reliable water flow and the increase in unsatisfied demand nodes are clearly shown by comparison of the 0 and 24 hr conditions. The mean SSI declines from 76 to 34 % over 24 hrs, which indicates that 66% of the normal water demand cannot be met one day after the main shock.

Figure 5 provides a graphical display of the LAWDP system response to the ShakeOut earthquake scenario with and without the disconnected reservoirs. The SSI statistics for 24 hrs after the earthquake are summarized in the histogram. The number of Monte Carlo simulations, which contribute to a particular SSI, was divided by the total number of simulations to provide an approximate probability index. The histograms of "probability" allow one to compare performance outcomes when the Encino, Lower Stone Canyon, and Hollywood Reservoirs are closed and open. The median SSI increases by about 6% when the reservoirs are open as opposed to closed. The shift in the probability distributions can be seen clearly in the figure.

Figure 6 provides a similar display in which service area SIs associated with the most populated areas of Los Angeles are represented. These areas include water service areas, WS, CC, HP, and MW, which are geographically close to the Encino, Lower Stone Canyon, and Hollywood Reservoirs. Because of the locally high populations, these areas of Los Angeles are likely to have the greatest need for water to fight post-earthquake fires.

The probability distributions for the most populated areas are substantially different from those for the entire system. The median SI decreases from 38% with reservoirs open to 21% with reservoirs closed. Not only does the mean SI increase by nearly 50% with reservoirs open, but the variance in outcomes decreases so that worst case possibilities are less likely. Perhaps the most important finding is that the worst case outcomes with reservoirs closed vary from SI of 5% to 15%. Such low levels of water service would expose the most populated areas of Los Angeles to exceptionally high risk.

With reservoirs open the probability distributions shift markedly to the right such that the worst case scenarios have SIs higher than the mean SI for reservoirs off. In some cases, water is available at nearly 50% of the demand nodes after 24 hrs. The results show that opening the reservoirs immediately after a serious earthquake improves serviceability so significantly that it is a plausible strategy for optimal emergency response.

7.0M_W Northridge Earthquake Scenario Effects

For the 7.0M_W Northridge earthquake the mean SSI decreases over 24 hrs to 43%, which indicates that 57% of the normal water demand cannot be met one day after the main shock. Figure 7 provides a graphical display of the LAWDP system response to the

7.0 M_W Northridge earthquake scenario, similar to that in Fig. 5. The median SSI increases by about 11% when the reservoirs are open as opposed to closed. Figure 8 provides a similar display in which service area SIs associated with the most populated areas of Los Angeles are represented. Again, the probability distributions for the most populated areas are substantially different from those for the entire system. The median SI decreases from about 60% with reservoirs open to 36% with reservoirs closed. Not only does the median SI increase by nearly 68% with reservoirs open, but the variance in outcomes decreases so that worst case possibilities are less likely. The worst case outcomes with reservoirs closed are for SI = 15–20%. As was the case for the ShakeOut Scenario earthquake, such low levels of water service would expose the most populated areas of Los Angeles to elevated risk.

Conclusions

Select results of simulations of the LADWP water supply response to 7.0 M_W Northridge and 7.8 M_W ShakeOut scenario earthquakes are presented. The simulations covered all 11,691 km of water trunk and distribution pipelines and related facilities (e.g., tanks, reservoirs, pressure regulation stations, etc.) in the LADWP system, plus the performance of the Los Angeles Aqueducts. The effects of seismic ground waves and of permanent ground deformation associated with fault rupture, liquefaction, and landslides, were modeled.

Post-earthquake performance is quantified by means of a system serviceability index (SSI) and local serviceability index (SI) defined as the ratio of water flow after to water flow before the earthquake on both a system-wide and local level, respectively. The simulations show serious deterioration in the ability to deliver water 24 hrs after the earthquake, which is generated by losses from leaking pipelines that draw down tanks and reservoirs. For the 7.8M_W ShakeOut Scenario earthquake the mean SSI declines from 76 to 34% over 24 hrs, which indicates that 66% of the normal water demand cannot be met one day after the main shock. For 7.0M_W Northridge earthquake the mean SSI decreases over 24 hrs to 43%, which indicates that 57% of the normal water demand cannot be met one day after the main shock.

The LADWP system was modeled with and without several key reservoirs, which have been removed from normal operating service to meet water quality standards. The results show that opening the disconnected reservoirs immediately after a serious earthquake improves serviceability so significantly that it is a plausible strategy for optimal emergency response, even though such action will require tap water safety notices to be issued for the entire system. Work, such as this, that links emergency response with public health decisions provides a good example of how system modeling supports decisions about geotechnical effects on a regional scale and the complex performance of critical lifeline networks.

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References

Bonneau, A.L. and O'Rourke, T.D. (2009) "Water Supply Performance During Earthquakes and Extreme Events", Technical Report *MCEER-09-0003,* University of Buffalo, State University of New York, New York.

Davis, C.A., J. Hu, T.D. O'Rourke, and A. Bonneau, (2007) "Seismic Performance Evaluation of LADWP Water System Using GIRAFFE" Proceedings, 5th U.S.-Japan Workshop on Seismic Performance of Water Supplies, Oakland, CA, AWWA.

Environmental Protection Agency, EPA (2007). "EPANET". <http://www.epa.gov/nrmrl/wswrd/dw/epanet.html>

Federal Emergency Management Agency, FEMA (2006). *HAZUS-MH MR2 Technical Manual*. FEMA, Washington, D. C.

Jeon, S.-S. and O'Rourke, T.D. (2005). "Northridge Earthquake Effects on Pipelines and Residential Buildings." *Bulletin of the Seismological Society of America*, Vol. 95, No.1, 294-318.

O'Rourke, M.J. and So, P. (2000). "Seismic Fragility Curves for On-Grade Steel Tanks." *Earthquake Spectra*, Vol. 16, No. 4, 801-815.

O'Rourke, T.D., J.M. Jezerski, N.A. Olson, A.L. Bonneau, M.C. Palmer, H.E. Stewart, M.J. O'Rourke, T. Abdoun (2008) "Geotechnics of Pipeline System Response to Earthquakes", *Keynote Paper, Proceedings, Geotechnical Earthquake Engineering and Soil Dynamics IV (GEESD)* Sacramento, CA, May.

Romero, N, T.D. O'Rourke, L.K. Nozick, and C.R Davis (2010) "Seismic Hazards and Water Supply Performance", *Journal of Earthquake Engineering* (accepted for publication, 2010)

USGS (2008a). "The ShakeOut Scenario." *USGS Open File Report 2008-1150, CGS Preliminary Report 25.* U.S. Geological Survey, California Geological Survey, 2008. < http://pubs.usgs.gov/of/2008/1150/>.

USGS (2008b). "ShakeMap for ShakeOut Scenario." *Earthquake Center ShakeMap, southern California.* U.S. Geological Survey. http://earthquake.usgs.gov/eqcenter/shakemap/sc/shake/ShakeOut2_full_se/.

Wang, Y. and T. D. O'Rourke (2008). "Seismic Performance Evaluation of Water Supply Systems." Technical Report *MCEER-08-0015,* University of Buffalo, State University of New York, New York.

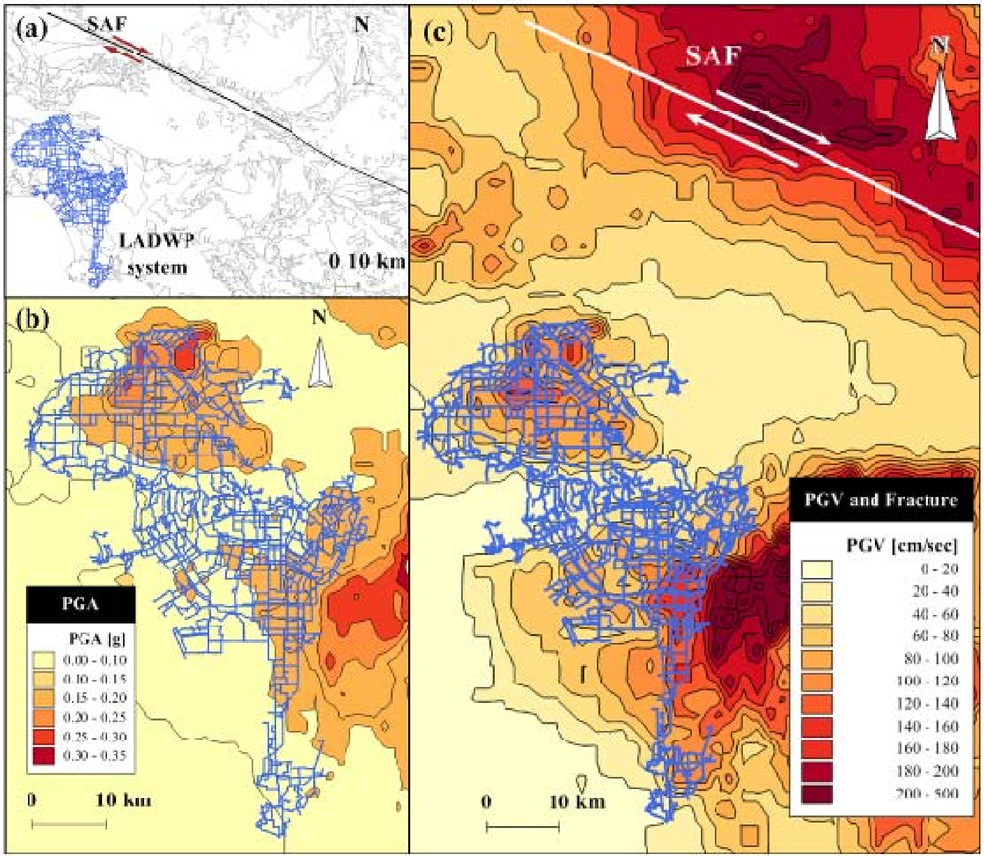
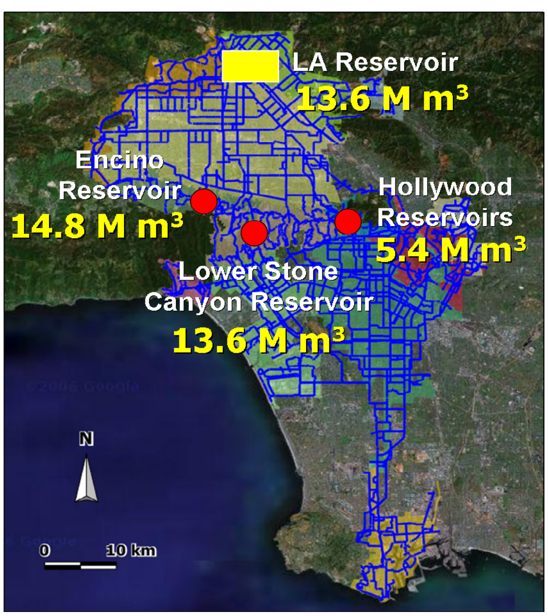


Figure 1. (a) Location of San Andreas Fault and LADWP system, (b) PGA contours, (c) PGV contours and SAF.



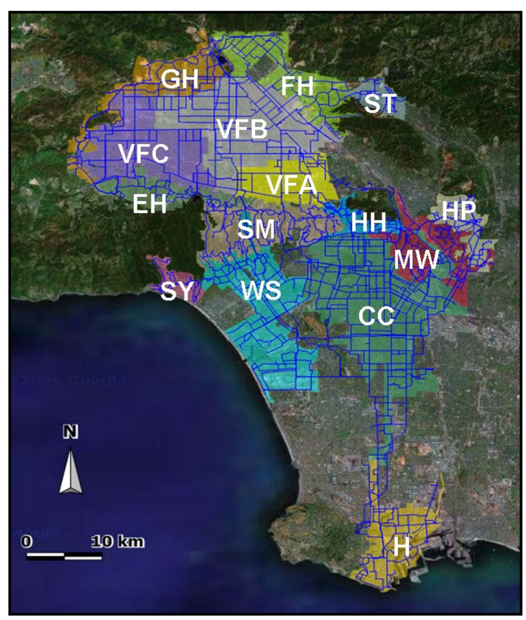


Figure 2. LADWP Reservoirs

Figure 3. LADWP water Service Area

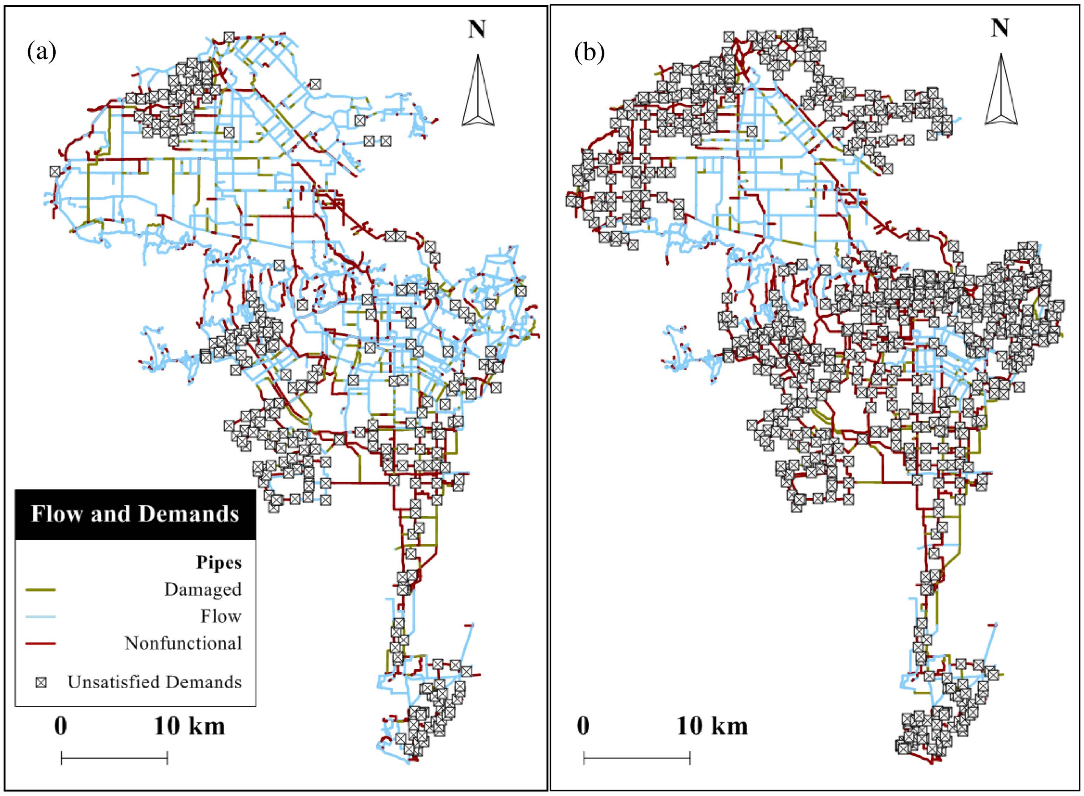


Figure 4. System flow state and unsatisfied demands for: (a) 0 and (b) 24 hours after the 7.8 M_W ShakeOut scenario earthquake.

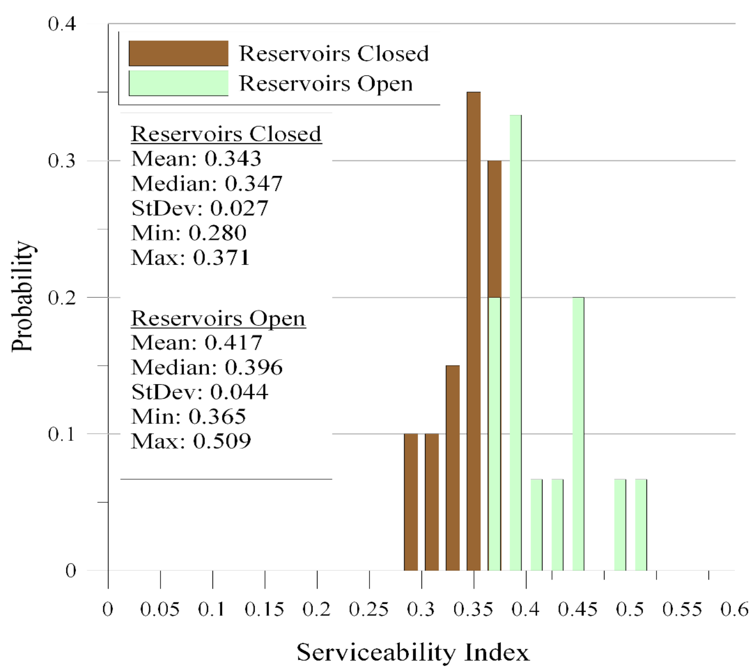


Figure 5. SSI at 24 hours for ShakeOut scenario earthquake.

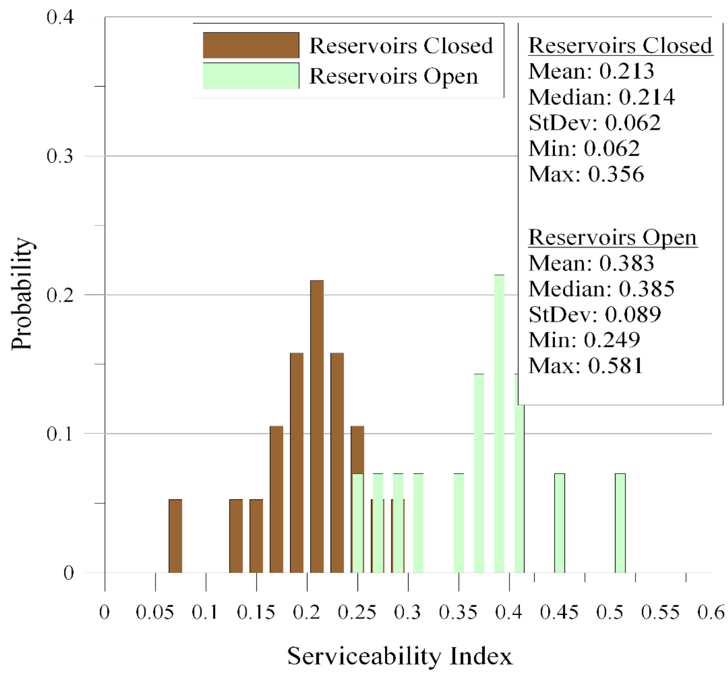


Figure 6. SI for most populated areas 24 hours after ShakeOut scenario earthquake.

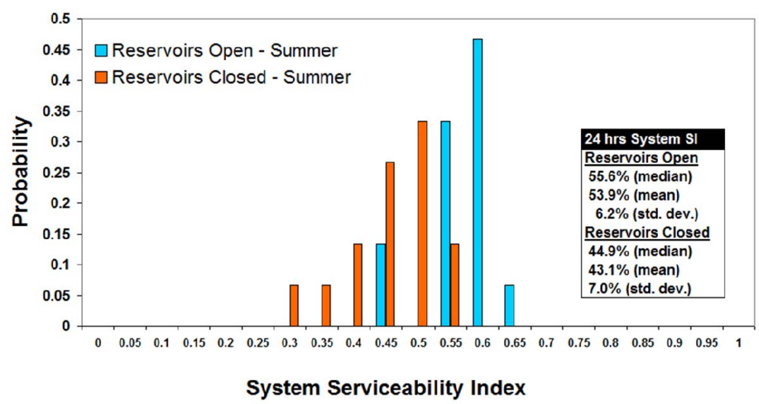


Figure 7. SSI at 24 hours for Northridge scenario earthquake.

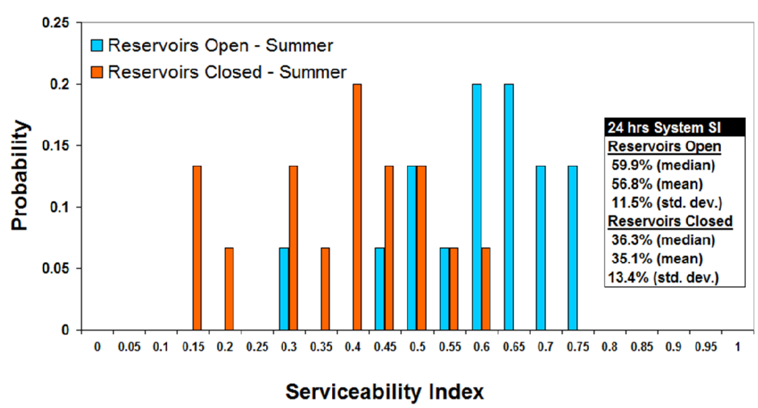


Figure 8. SI for most populated areas 24 hours after Northridge scenario earthquake.