Groundproofing a New Model for Estimating Earthquake Damage and Planning Recovery

Developed by the University of Colorado for USGS, the CUWNet model focuses on buried pipe.

By Keith Porter

THE U.S. GEOLOGICAL SURVEY'S (USGS) Science Application for Risk Reduction (SAFRR) program aims to innovate application of hazard science for the safety, security and economic well-being of the nation. SAFRR produced the ShakeOut earthquake scenario (Jones et al. 2008), ARkStorm winter storm scenario (Porter et al. 2010) and SAFRR Tsunami Scenario (Ross et al. 2013). USGS has long recognized the importance of water supply in earthquakes. For example, the magnitude 6.9 (M_W 6.9) 1989 Loma Prieta earthquake in the Santa Cruz Mountains south of the San Francisco Bay Area caused 761 pipeline breaks and leaks throughout the San Francisco Bay Area.

What Happens When Things Go Haywire?

SAFRR's HayWired earthquake scenario depicts a hypothetical but realistic earthquake sequence beginning with a M_W 7.0 rupture of the Hayward Fault in the eastern San Francisco Bay Area, followed by 16 aftershocks of magnitude five or greater at various locations in the Bay Area and Sacramento Delta region during the subsequent two years. Although approximately the same size as the Loma Prieta earthquake, the HayWired earthquake would produce much greater damage to water supply systems because of its location on arguably the most urbanized active earthquake fault in the United States. Moreover, HayWired takes place in a world where water agencies depend on Internet-based cellphones, web-based emergency operation centers and inventory management systems. What happens when an earthquake causes all these systems to go haywire?

The Model

Included in HayWired is the CUWNet (University of Colorado Water Network) model, developed at the University of Colorado for USGS and focused exclusively on buried pipe, which is where most water service restoration effort is concentrated. The model can be exercised deterministically (to produce expected values of number of breaks and leaks, repair time and average number of services available as a function of time) and stochastically (explicitly accounting for and propagating important sources of uncertainty). Most water industry users will probably want to use the simpler deterministic model, which involves coding (programming) 19 equations into a spreadsheet and using a geographic information system to calculate ground shaking and ground failure, landslide and liquefaction probability, and fault offset at each pipe segment of the water supply system.

The stochastic model involves six more equations and requires a slightly larger skillset, but water agencies can use it to calculate probability distributions of uncertain outcomes such as the number of pipe breaks and leaks, number of customers receiving water service in the hours, days and weeks after the earthquake, time required to restore service, number of service days lost and the value of economic activity lost because of water-service interruption.

Water agencies can use CUWNet and HayWired to assess their emergency response needs, understand how seriously any given earthquake could impair their systems and affect the regional economy and estimate quantitatively the benefits of remediation measures. For example, what would be the benefits in terms of faster service restoration and fewer service days lost if an agency replaced the most brittle pipe first or faster than current plans call for or focused on adding valves to pipe in areas of infirm soil? With an order-of-magnitude estimate of the economic loss associated with one service day lost (approximately $700 in 2018 currency, judging by economic analyses of the ShakeOut scenario), a utility can convert those service days lost to economic impacts to the community and thereby provide a richer monetary depiction of the benefits of mitigation in rate filings.

The model was applied to HayWired using maps of the East Bay Municipal Utility District (EBMUD) and San Jose Water (SJW) pipeline systems provided by the utilities with USGS maps of ground shaking, land sliding, liquefaction, fault offset and aftershocks from a simulated earthquake in the San Francisco Bay Area.

But Is It Accurate?

A model is only as good as it is accurate. With support from the Water Research Foundation (WRF), the University of Colorado worked with EBMUD and SJW, the City of Napa, Contra Costa Water District, Alameda County Water District and the Bay Area Center for Regional Disaster Resilience to compare model estimates with the actual outcomes of the magnitude 6 (Mw 6.0) quake that struck south Napa County on August 24, 2014 causing heavy damage to the City of Napa's municipal water system. (Porter, K. A. Forthcoming "Validating a Water Network Resilience Model." Project #4709. Denver, Colo: Water Research Foundation WRF). If CUWNet could realistically hindcast that damage, that is, estimate the damage that actually occurred based solely on the map of ground shaking and the layout of the City of Napa's system, the model's predictability could be assumed to be reasonably accurate.

Such evidence of accuracy would give utility planners and operators a level of confidence that would be in some sense proportional to the fraction of performance metrics that the model accurately estimated for the test case. If, for example, only a few of the actual performance outcomes in the 2014 Napa earthquake fell near the model's estimated values, say near its median estimates plus or minus one standard deviation (i.e., the 68 percent confidence interval), then utilities would get minimal value. If most or all of the actual outcomes fell near the model's estimated values, utilities would get significant value from the model's findings for this or other earthquakes or water systems when combined with planning with other critical infrastructure dependent on system water supplies for response and recovery.

The City of Napa operates 337 miles of distribution pipe. Fifty percent is cast iron or asbestos cement, which has repeatedly been demonstrated to be especially susceptible to earthquake damage both when shaken and when subject to ground failure in the form of liquefaction, landslide and fault offset. Napa is not unusual in its large inventory of aging brittle water supply pipe, and since approximately 22 percent of the U.S. population lives in highly seismically active areas, and almost all damaging U.S. earthquakes in the past two decades have measured M_W 6.9 or smaller, the Napa event provides a meaningful case study.

Methodology

In applying the USGS map of estimated shaking in the 2014 Napa earthquake, its values were factored up slightly (multiplied by a scalar quantity greater than 1.0) to account for the fact that the map underestimates recorded ground motion on average at 12 strong motion instruments within and near the City of Napa. Local under- and overestimation of ground motion is not uncommon. USGS ShakeMaps attempt to estimate the median motion, that is, motion with a 50 percent chance of over- or underestimation, by adjusting the estimated ground motion up or down to minimize the error with all the instruments in a large geographic area. In the case of the 2014 South Napa earthquake, the USGS adjusted its median ground motion estimates to better match recordings over a geographic area that is much larger than the City of Napa's water supply system. When one considers only the USGS's adjusted ground motions near and within the City of Napa, the USGS's adjusted values underestimated motion at those locations. The project team therefore further adjusted the USGS's estimated motions to better match the values recorded by 12 strong motion instruments near and within Napa.

Once corrected for the local underestimation bias, estimated Napa earthquake ground motion values were assigned to each segment of pipe in the city's system using ESRI's ArcGIS version 10.5. Ground-shaking values, pipe lengths and pipe materials were entered on a Microsoft Excel spreadsheet together with Napa's electrical service interruption, telephone service interruption and repair crew availability over time after the earthquake. Fuel, roads, supplies and other necessary inputs to pipe repairs did not impose significant hindrances to repairs and so were ignored for purposes of the CUWNet analysis, which would otherwise have used them to calculate service restoration.

The stochastic version of the CUWNet model was also applied to estimate several performance measures of water service damage and restoration. Among these were the initial level of service, the speed with which repairs were performed, the time required to complete repairs and the area above the curve of service restoration versus time (the area has a technical name, "loss of resilience"). Since each CUWNet output in the stochastic version comes in the form of a probability distribution (bell-shaped curves), one can express Napa's actual experience with CUWNet estimates in terms of percentiles: anything near the middle of the modeled distribution, say within one standard deviation of the median—i.e., between the 16th and 84th percentiles—suggests agreement between the model and reality. Anything outside those bounds suggests poorer agreement.

Figure 1 compares a number of simulations of Napa water restoration (dotted lines) along with actual service restoration (solid red line). The solid red line lies in the middle of the cloud of simulations, which is a good sign. There is a lot of variability between those dotted black lines because of all the uncertain quantities that go into the model, such as how long it takes to complete one pipe repair. In practice, it is easy to perform 1,000 or more such simulations, which was actually done but would be hard to see on a plot like Figure 1. Figures 2, 3 and 4 (next page) show the distributions of several performance measures. The height of

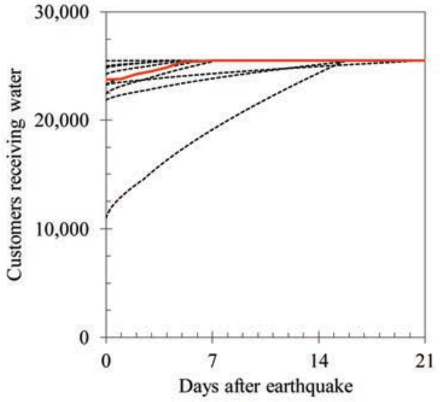


Figure 1. Simulations of Napa water restoration (dotted lines) and actual service restoration (solid red line)

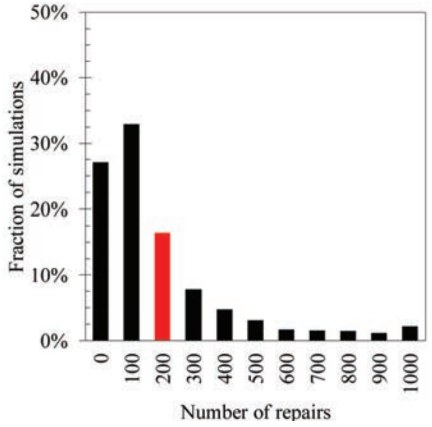


Figure 2. Simulated number of post-earthquake repairs. The number below each bar indicates the lower bound of the range, e.g., 0 to 99 for the first bar. Red bar shows Napa's actual experience.

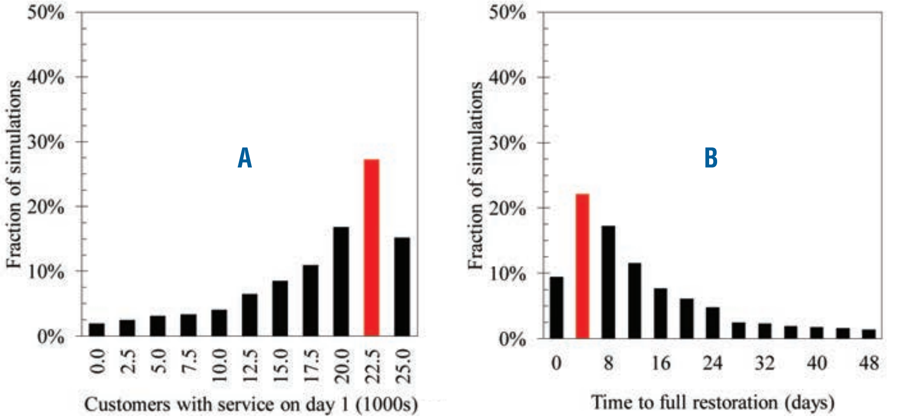


Figure 3. (A) Simulated number of customers receiving water service on the day of the earthquake; (B) Simulated days to finish service restoration. Red bars show Napa's actual experience.

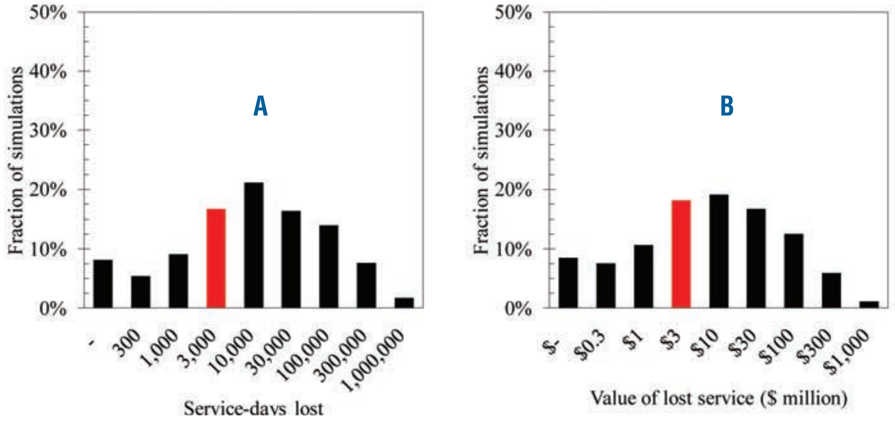


Figure 4. (A) Simulated number of service-days lost; (B) Simulated value of lost service. Red bars show Napa's actual experience.

each bar in each figure indicates the fraction of simulations producing a particular narrow range of outcomes. The red bar in each figure represents Napa's actual experience. A red bar at or near the tallest bar indicates good agreement between the model and what happened on the ground.

Figure 5 shows most of these charts and the restoration curve together, with one chart rotated to align its x-axis (showing initial service level) with the y-intercept of the chart of restoration curves, which measures the same thing. That is, the red bar in the chart on the left aligns with the left end of the red restoration curve. Table 1 (opposite page) presents all the performance measures together. Fourteen out of 15 performance measures estimated by CUWNet fall within the one standard deviation bounds of the true values, i.e., between the 16th and 84th percentiles. The 15th measure falls just outside these bounds.

While Table 1 shows that the total numbers of repairs and other measures agree with the actual experience, the spatial correlation of where one would expect damage versus where it actually occurred is poorer, but still fair. (Mathematically, the Pearson correlation coefficient between actual and estimated number of repairs per km^2 is $\rho \approx 0.4$. A value of $\rho = 1.0$ would indicate perfect agreement. Though 0.4 is smaller than one would prefer, it is still large enough to say that with at least 99 percent confidence, the model reflects a real spatial relationship.) See *www.sparisk.com/pubs/Porter-2017-WRF-CUWNet-Validation.pdf* for details of the validation work.

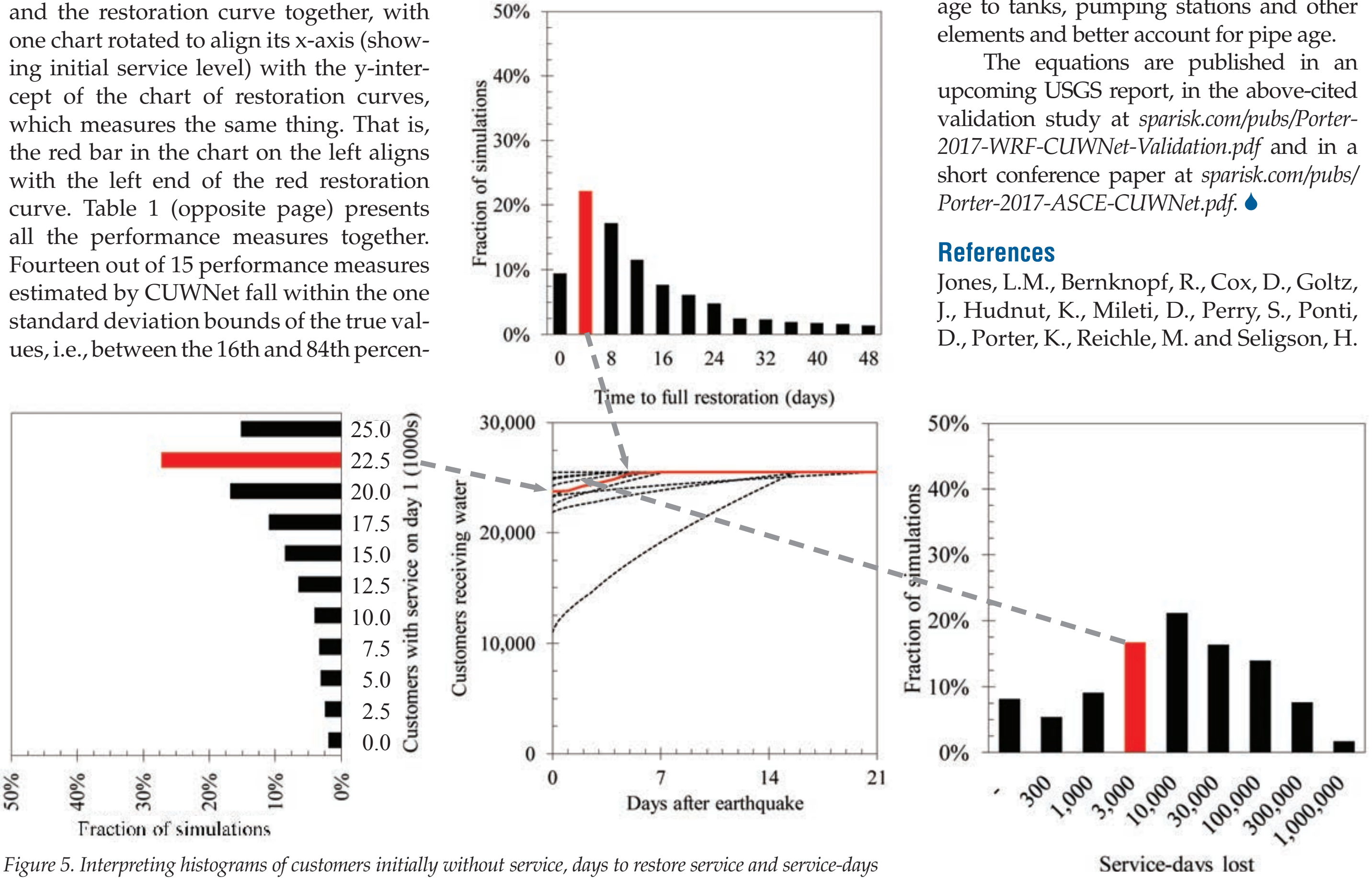


Figure 5. Interpreting histograms of customers initially without service, days to restore service and service-days lost in terms of the uncertain restoration curve

Conclusions

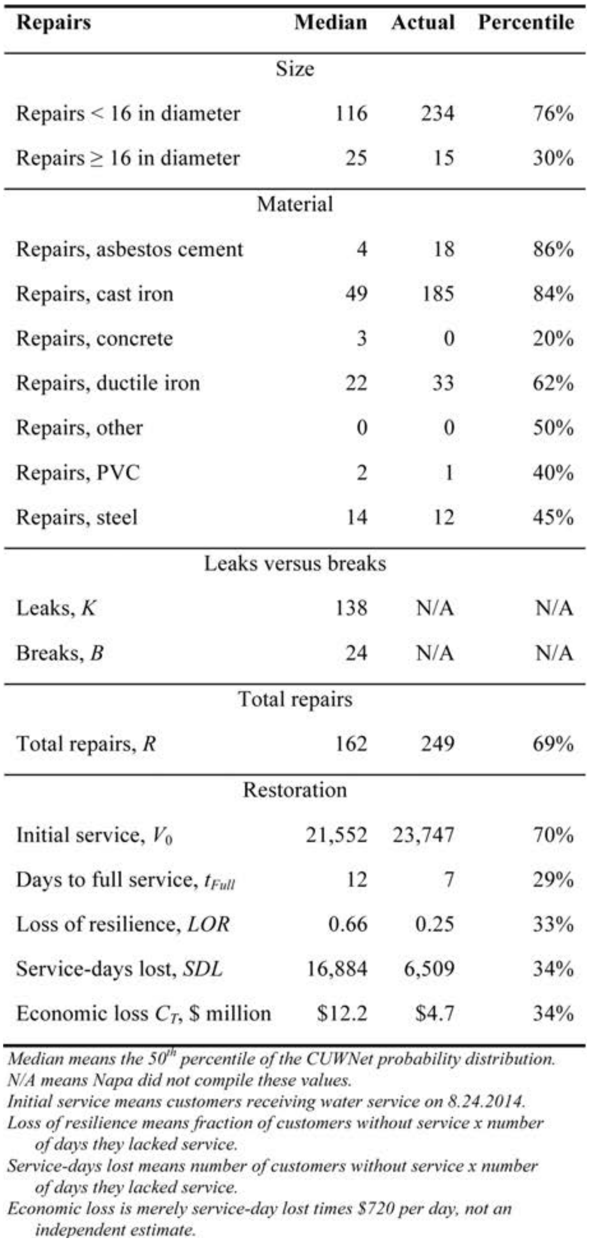
HayWired is a useful approximation of what could happen in a large metropolitan earthquake. CUWNet is a potentially useful approximation of water supply damage and restoration. Both are freely available to engineers interested in the effects of earthquakes on water supply. CUWNet is particularly useful to a water agency whose engineers can use a geographic information system and can read and code equations into a spreadsheet. The hope is to further enhance the model to better address damage to tanks, pumping stations and other elements and better account for pipe age.

The equations are published in an upcoming USGS report, in the above-cited validation study at *sparisk.com/pubs/Porter-2017-WRF-CUWNet-Validation.pdf* and in a short conference paper at *sparisk.com/pubs/Porter-2017-ASCE-CUWNet.pdf.* 💧

References

Jones, L.M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M. and Seligson, H.

Table 1. Comparison of modeled damage and restoration variables with Napa's actual experience



Repairs	Median	Actual	Percentile
Size			
Repairs < 16 in diameter	116	234	76%
Repairs ≥ 16 in diameter	25	15	30%
Material			
Repairs, asbestos cement	4	18	86%
Repairs, cast iron	49	185	84%
Repairs, concrete	3	0	20%
Repairs, ductile iron	22	33	62%
Repairs, other	0	0	50%
Repairs, PVC	2	1	40%
Repairs, steel	14	12	45%
Leaks versus breaks			
Leaks, K	138	N/A	N/A
Breaks, B	24	N/A	N/A
Total repairs			
Total repairs, R	162	249	69%
Restoration			
Initial service, V_0	21,552	23,747	70%
Days to full service, t_{Full}	12	7	29%
Loss of resilience, LOR	0.66	0.25	33%
Service-days lost, SDL	16,884	6,509	34%
Economic loss C_T, \$ million	\$12.2	\$4.7	34%

Median means the 50th percentile of the CUWNet probability distribution.
N/A means Napa did not compile these values.
Initial service means customers receiving water service on 8.24.2014.
Loss of resilience means fraction of customers without service x number of days they lacked service.
Service-days lost means number of customers without service x number of days they lacked service.
Economic loss is merely service-day lost times \$720 per day, not an independent estimate.

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Ross, S. L., Jones, L. M., Miller, K., Porter, K. A., Wein, A., Wilson, R. I., & Bwarie, J. T. (2013). The SAFRR (Science Application for Risk Reduction) tsunami scenario. US Geological Survey Open-File Report, 2013-1170, p897. *pubs.usgs.gov/of/2013/1170/pdf/of2013-1170_all.pdf.*

Applying the Model

East Bay Municipal Utility District and San Jose Water are using the results of HayWired in their seismic resiliency programs and to improve emergency response plans, including determining resource needs and assumptions for pipeline repair crews, employee training and community outreach and earthquake exercises.

By Keith Porter, Roberts McMullin, Serge V. Terentieff, Jim Wollbrinck and Xavier J. Irias

AS A RESULT OF PARTICIPATING IN THE DEVELOPment of the U.S. Geological Service's HayWired scenario, East Bay Municipal Utility District (EBMUD) and San Jose Water (SJW) confirmed that ongoing capital programs to improve the resiliency of our infrastructure and emergency planning efforts are well-founded. We also determined that we can expect significant damage to our systems as a result of this hypothetical large earthquake on the Hayward Fault, and that mutual assistance and regional collaboration will be essential to restoring service to the Bay Area.

Background

For at least 25 years, engineers have performed computerized risk analyses of earthquake damage to water supply systems to estimate earthquake damage and predict restoration timelines. HayWired's CUWNet model (University of Colorado University Water Network) enhances the traditional loss estimation approach in a number of ways:

- It directly models how individual repairs are slowed by limitations in upstream lifelines including electricity, fuel and transportation.
- It quantifies damage and restoration over the entire earthquake sequence, i.e., the main shock, aftershocks and afterslip.
- It offers an empirical model of service restoration as a function of the number of pipeline repairs performed (as opposed to more rigorous, but computationally demanding, hydraulic analysis).
- It offers a procedure to adjust estimates of restoration to account for an earthquake sequence and lifeline interaction and corrects for assumptions about the number of available repair crews.
- Combining results with GIS modeling, it provides utilities reliable scenarios with which to determine system leak outage effects on Critical Infrastructure and Key Resources (CIKR) throughout their service areas.
- It provides valid data for developing realistic exercise scenarios.

The model quantifies system damage, recovery, delays due to fuel and other lifeline limitations and setbacks in restoration because of aftershocks. It estimates the benefit of a fuel management plan and increased pipe replacement rate in order to reduce the time is takes to restore service. In addition, it helps utility owners understand the importance of interdependencies and how service may depend greatly upon other providers.

The Event and Its Effects

The main shock of the hypothetical HayWired earthquake occurs at 4:18 p.m. on Wednesday, April 18, 2018, rupturing the north and south segments of the Hayward Fault, which runs for approximately 74 miles in the San Francisco Bay Area. The damage mode begins with the following assumptions (based on utility owner judgment): 1) it takes approximately two weeks to restore electricity to critical facilities, 2) fuel is limited for a week and 3) other utilities and contractors can send additional crews under mutual assistance agreements to augment EBMUD's and SJW's crews for approximately one month.

As applied by the University of Colorado, Haywire's CUWNet computer model estimates that the earthquake sequence would cause approximately 5,500 breaks and leaks, mostly in older and more brittle cast iron and asbestos cement pipes and in areas of softer soil, liquefaction-prone soil and where the network is densest. The model further estimates that it could take about six months to restore all services. The timeline relies on a number of assumptions, e.g., that EBMUD has 20 crews actively working on repairs and could only accommodate an additional 15 repair crews through mutual assistance agreements for a relatively brief time.

Figure 1 presents a damage heat map for EBMUD's system showing the mean number of repairs per one square kilometer (1 km2) following the main shock event. Warmer colors indicate greater concentration of damage, such as in parts of Berkeley and Alameda. The model further estimates that:

- Water service damage would cost on the order of 19 million service days (days to restore service times the number of customers out of service).
- The average customer would lose service for seven weeks.
- Damage to the local economy would be on the order of $14 billion, exclusive of fire losses.

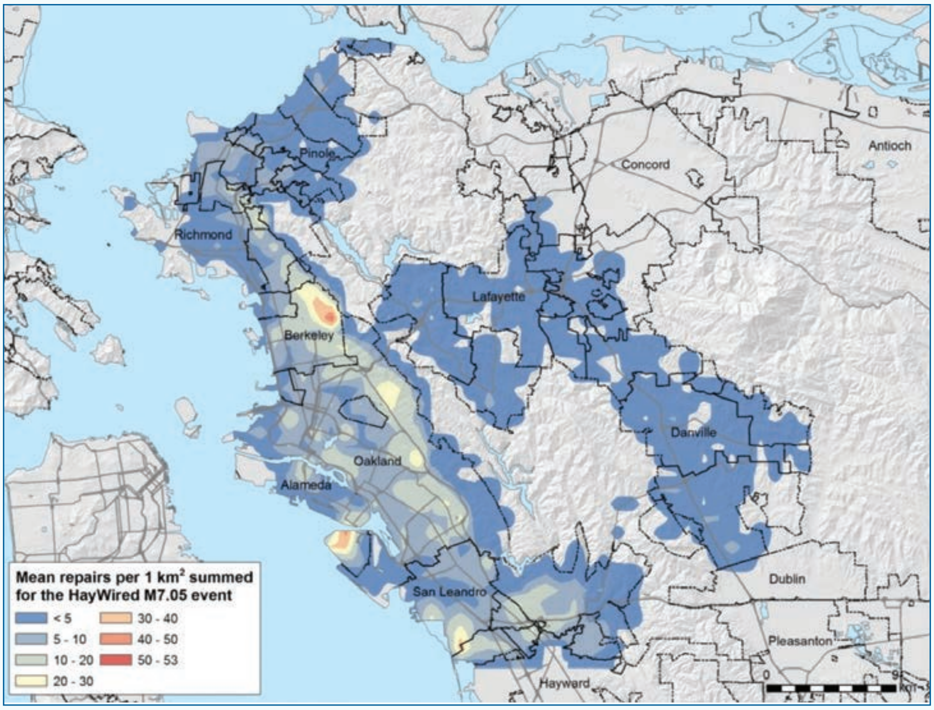

Figure 1—Buried water pipeline damage heat map for the HayWired main shock in EBMUD's service area

The model also suggests that instituting resilience measures could reduce the economic loss by $8 billion and restore service four weeks earlier if EBMUD replaced all of its cast iron and asbestos cement pipe, an effort that would cost ratepayers an estimated $6 billion (assuming a replacement cost of $2.5 million per mile to replace 2,400 miles of cast iron and asbestos cement pipe). The model also indicates that implementing a fuel plan could save the economy $200 million and restore water service an average of one day sooner. Figure 2 presents the estimated service restoration curve and repairs remaining for EBMUD in the earthquake sequence.

SJW Damage Estimates

Based on the model, SJW is expected to experience upward of approximately 2,000 breaks and leaks on its buried pipeline system during the main shock and aftershocks sequence. Similar to EBMUD, SJW's more brittle pipe materials are expected to have the highest densities of

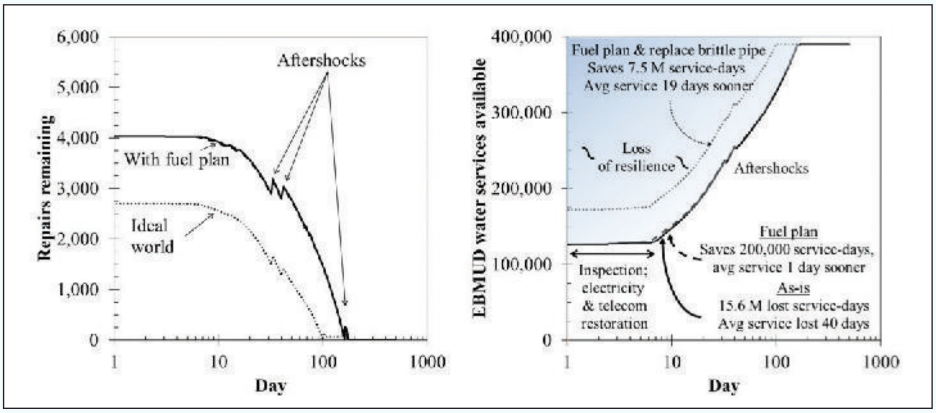

Figure 2—EBMUD Restoration curves in HayWired sequence.

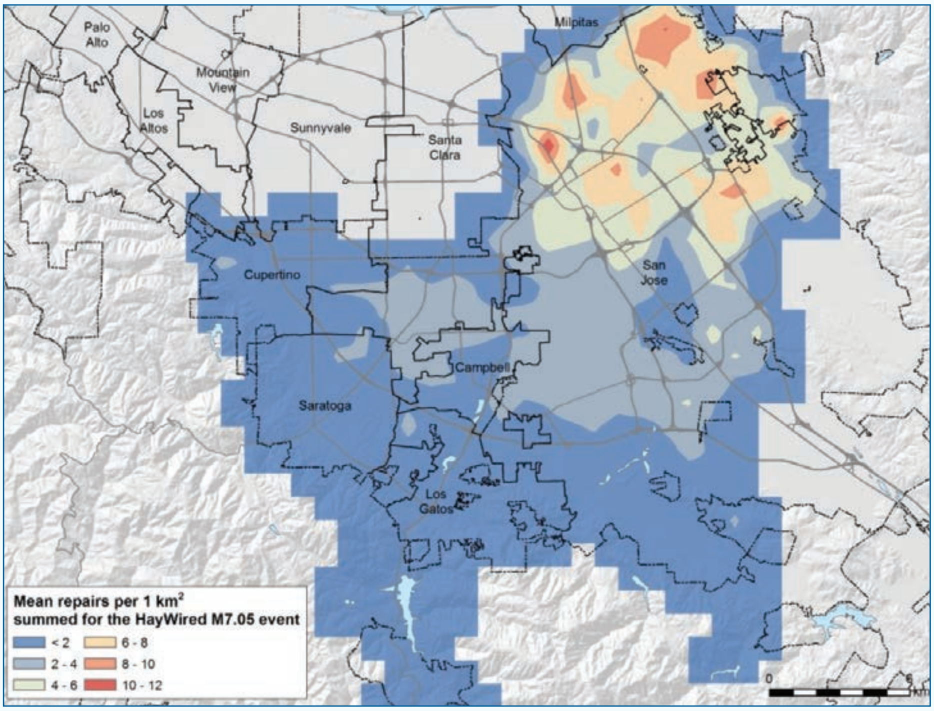

Figure 3—Heat Map of Break Rate in SJW Service Area

breaks and leaks. Figure 3 presents a heat map of break rate in the HayWired main shock. Colors indicate mean breaks per kilometer squared. Warmer colors indicate greater concentration of damage.

SJW estimated that the utility could realistically mobilize between 20 and 25 crews on a work basis of 12 hours on and 12 hours off. Damage would cost 940,000 service days. The average customer would lose service for four days. Figure 4 shows the repair timeline for SJW before and after implementing the fuel management plan and the simulated restoration curve. From this research, SJW has initiated numerous planning efforts. These include:

1. Using data from the model to evaluate whether current main replacement models should be evaluated to determine whether current lower priority leak locations should be elevated.
2. Evaluating leak detection technology that shows promise in detecting non-surfacing leaks, which would be of significant value after a Haywired event because historically 50 percent of post-earthquake leaks don't surface until four to 10 months after the event. This is well after many response and recovery agencies allow recovery funding related to the event.
3. Additional planning related to increased response resources (contractors and water utility mutual assistance) and the logistics to keep these resources stocked with repair material, fuel and housing.

Interdependencies

Interdependencies could significantly impact the time that it would take for a water agency to restore service to its customers following a major earthquake. Knowing the types of interdependencies that are most likely to impact a utility's ability to quickly restore service to its disrupted lifelines is critical. For example, EBMUD's 130 pumping plants rely on line power to serve almost half of its customers in the higher elevation pumped zones. Power restoration times are also strongly interdependent with other lifelines and could be particularly slowed by damage to the water system, natural gas delivery, transportation network, telecommunication overload and post-earthquake fires.

The Association of Bay Area Governments (ABAG), in partnership with EBMUD, SJW and other utilities, has assembled a Regional Lifelines Council Workgroup to better understand impacts that interdependent lifelines would have on expected utility restoration. As part of this effort, EBMUD is studying interdependencies between its water system and other critical lifelines such as line power and fuel. The goal is to improve emergency planning and response efforts where significant interdependencies are present, including allocation of limited resources for post-disaster restoration purposes (repair crews, emergency pumps, generators, fuel, etc.).

In 1995, EBMUD launched its 10-year $189 million Seismic Improvement Program (SIP) to retrofit facilities and minimize earthquake impact. The HayWired study has validated EBMUD's efforts to incorporate resiliency into its ongoing capital planning program for water pipeline rehabilitation and replacement. As part of this effort, EBMUD is installing earthquake-resilient pipe materials and developing programs to improve reliability of service to critical customers and reduce overall service downtime following an earthquake event. 💧

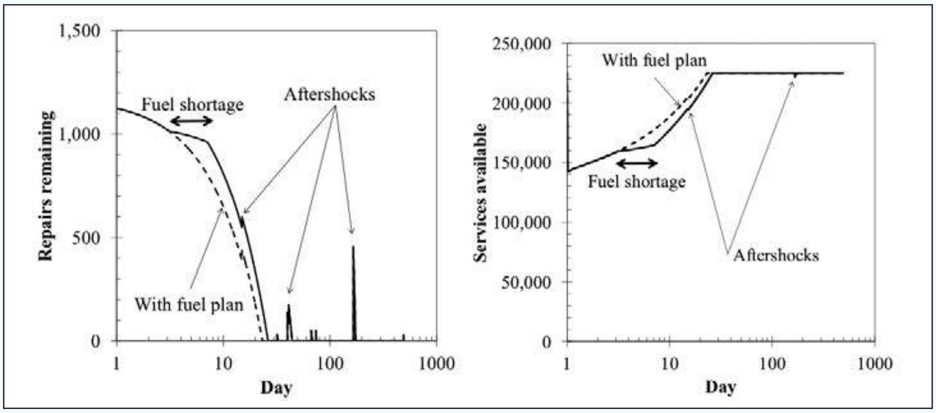

Figure 4—SJW Restoration curves in HayWired sequence.