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Emergency Planning and Response Damage Prediction Modeling to Mitigate Interdependency Impacts on Water Service Restoration

Serge Terentieff [1], Andrea Chen [2], Roberts McMullin[3], Yogesh Prashar[4], and Xavier Irias[5]

ABSTRACT

Interdependencies can significantly impact the time for the East Bay Municipal Utility District (EBMUD) to restore water service 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. The Association of Bay Area Governments (ABAG), in partnership with EBMUD and other utilities, has assembled a Regional Lifelines Council Workgroup to better understand impacts 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 of the study is to improve emergency planning and response efforts, including allocation of limited resources for post-disaster restoration purposes (repair crews, emergency pumps, generators, fuel, etc.).

EBMUD developed Marconi, a web-based application, to better plan, respond, and recover from various types of emergencies and hazards, such as a catastrophic earthquake event. Marconi computes rapid damage predictions using both readily available and facility specific customized fragility curves and real-time ShakeMap data to estimate potential damage to water facilities such as tanks, dams, pumping plants, and large diameter pipelines. Pacific Gas and Electric Company (PG&E), the utility that provides line power to EBMUD's service area, has also developed similar damage modeling capabilities for its power distribution system. EBMUD is actively working with PG&E to assess the water and power infrastructure systems interdependencies with a goal of using common input scenario earthquake events, overlaying damage prediction results, and setting common priorities for service restoration.

This paper discusses the importance of using an interdependencies-based regional risk assessment process to improve emergency preparedness. Damage prediction models can be used to both identify fragile components within the system as well as to assist in prioritizing emergency response efforts. A better understanding of interdependencies and associated vulnerabilities of critical facilities can help utility owners assess the need for additional pre-event mitigation or hardening of the system. Examples of proactive measures to reinforce the system are discussed and include adding electrical redundancy to critical facilities and making seismic improvements to reduce the risk of cascading failures resulting from collocated lifelines such as water and fuel. In addition, utility owners must be cognizant of public expectations by setting realistic timelines for service restoration and improving awareness at the local community and regional levels.

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INTRODUCTION

About EBMUD

The East Bay Municipal Utility District (EBMUD) provides drinking water to over 1.3 million people on the eastern side of the San Francisco Bay. The EBMUD water system comprises of 167 supply reservoirs, 132 pumping plants, 29 embankment dams, 7 water treatment plants, and approximately 4,200 miles (6,800 kilometers) of treated water distribution and transmission pipelines and 270 miles (435 kilometers) of raw water aqueducts. Figure 1 presents the EBMUD Location Map. The EBMUD service area encompasses a large and varying topography. With such a large water system to manage and operate in an area prone to destructive earthquakes, emergency response can be an overwhelming task in the minutes and hours following an earthquake. As a result, EBMUD created damage prediction models to prioritize field inspections of the water system and help accelerate emergency response and recovery time.

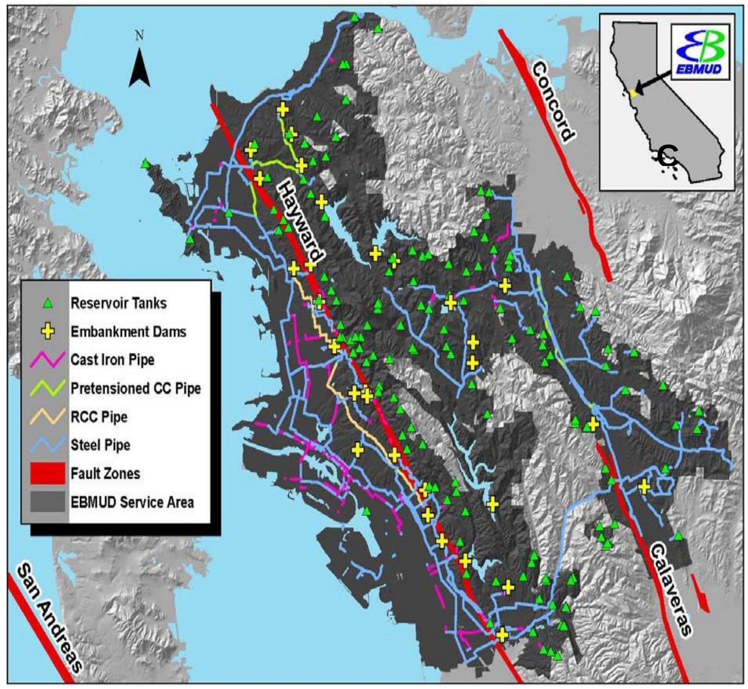

Figure 1. EBMUD Location Map

Background

The published documents entitled "Rapid Modeling of Seismic Damages to Water Infrastructure" [1] and "Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines" [2] provide the introductory framework to this paper. As discussed in these papers, the anticipated performance of EBMUD's facilities can be predicted using real-time ShakeMap data and customized fragility curves. Estimating the level of ground shaking (Peak Ground Acceleration [PGA]) at any particular facility is the critical input in developing rapid damage predictions. A better understanding of the specific interdependencies that can impact service restoration, in combination with the use of predictive models to estimate the level of water system damage, can be used for pre-event planning purposes, as well as to help prioritize inspections and deployment of limited resources immediately following a major seismic event.

Seismic Setting and Scenario Event for Damage Predictions

The highly active Hayward Fault dominates EBMUD's risk profile. This fault, capable of earthquakes of M7.25, has produced major earthquakes on average every 140 years, with the last damaging earthquake occurring in 1868. The economic losses from a similar earthquake occurring today have been estimated at up to $200 billion. According to the United States Geological Survey (USGS), the overall probability of a magnitude 6.7 or greater earthquake in the greater Bay Area in the next 30 years is 63%. The earthquake probability is highest for the Hayward Fault system, at 31%. As shown on Figure 1, dozens of EBMUD's critical facilities are located within a few hundred meters of the Hayward Fault.

Beyond the Hayward Fault, several other faults threaten EBMUD's system, ranging from the larger San Andreas Fault west of the service area, to the Calaveras and Concord Faults in the eastern portion of the service area. While the San Andreas, Calaveras, and Concord Faults could also have a significant impact on EBMUD's distribution system, the discussions on interdependencies and damage predictions presented in this paper are based on an assumed moment magnitude 7.05 (M-7) scenario event on the Hayward fault.

Goals of the Paper

This paper discusses different types of interdependencies that could impact service restoration for a water utility and includes examples of cascading outages and failures. Damage estimates, including results of a seismic evaluation of PG&E's substations and power outages for EBMUD's pumping plants, and estimates of the overall level of damage to water distribution mains, are presented.

This paper also presents results of recent rapid damage prediction modeling efforts for Large Diameter Pipelines (LDP), highlighting fragile components within the transmission system. Rapid damage modeling can assist in identifying vulnerable components of the system where physical improvements may be needed to promote resiliency. Similar damage prediction modeling efforts, using ShakeMap data, have been undertaken by PG&E for its power distribution system. EBMUD is working with PG&E to study the interdependencies between water and power infrastructure systems in more detail. The goal is to use common input scenario earthquake events, overlay damage prediction results, and develop common priorities for service restoration based on facility criticality and customer impacts.

A better understanding of interdependencies and associated vulnerabilities of critical facilities will help utility owners with emergency planning and response efforts. These efforts include the allocation of resources for post-disaster restoration purpose and assessing the need for additional pre-event mitigation or hardening of their system.

Based on damage predictions results and associated vulnerabilities, EBMUD is taking steps to mitigate impacts of interdependencies by improving robustness and/or adding redundancy to its critical facilities. These steps include adding flexible joints on large diameter mains located at fault crossings with collocated lifelines to reduce the risk associated with cascading failures, replacing critical estuary crossings that supply water to areas with no storage, adding electrical redundancy at water treatment plants, upgrading facilities, replacing large diameter pipelines, and installing new parallel transmission pipelines.

Finally, this paper discusses the need for utility owners to be cognizant of public expectations for service restoration following a catastrophic earthquake event. Despite making improvements to their systems, service restoration may take weeks or months. It is important to communicate realistic timelines by improving awareness and coordination at the local community and regional levels. The need for having an emergency drinking water distribution plan is also discussed, in the event of prolonged service disruptions.

INTERDEPENDENCIES

In a study published in 2014 [3], the City and County of San Francisco's (CCSF) Lifeline Council defined the interdependence between twelve important systems showing significant interactions with the fuel sector, and significant reliance by others on water, electricity, roads, and telecom (see Figure 2).

While there are many types of interdependencies, they can generally be categorized into four main types as defined in the Association of Bay Area Governments' (ABAG) recent study entitled "Cascading Failures: Earthquake Threats to Transportation and Utilities" [4]. Specific examples of cascading outage and cascading failures that apply to EBMUD's water distribution system are discussed in more detail in the following sections. These categories, and corresponding examples for EBMUD's water system, include:

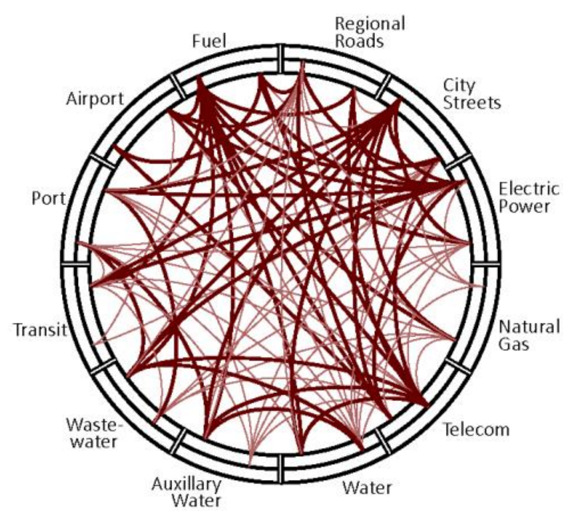

Figure 2. CCSF Matrix Information Illustrating Interdependencies of Infrastructure Systems

Cascading outages, when failure of one system causes another to shut down until the system is restored, such as the impacts of electrical outages on pumping plants, which – depending on the scale and duration of the outage – could impact service to a large number of customers.

Cascading failures, when a failure results in physical damage to another, such as the impacts a catastrophic break on a water main could have on another adjacent lifeline, such as a gas or petroleum line.

Influence on recovery, when a system outage slows the repair of other systems, such as impassable roadways preventing repair crews from reaching a damage pipeline or pumping plant site.

Multi-system process, when a process requires two functional systems, such as a water treatment plant requiring the operation of an emergency generator to supply power during an outage, and the generator relying on fuel supply which can't be replenished if transportation does not work or fuel supplies run out.

Cascading Outages

EBMUD's distribution system includes over 120 different pressure zones delivering water to elevations that range from sea level to about 1,500 feet (460 meters). Nearly half of EBMUD's services rely on EBMUD's 132 pumping plants to deliver water to higher elevations, such as the Oakland-Berkeley Hills located along the Hayward Fault (see Figure 1). The average winter water consumption and number of services supplied by gravity zones and pumped zones are summarized in Table 1, with corresponding pressure zones illustrated on Figure 3.

Table 1. EBMUD Gravity vs. Pumped Zones

Pressure Zones	Avg. Winter Demand Consumption	Service Count
Gravity	65 MGD*	204,000
Pumped	52 MGD*	176,000
* MGD = Millions of Gallons/Day		

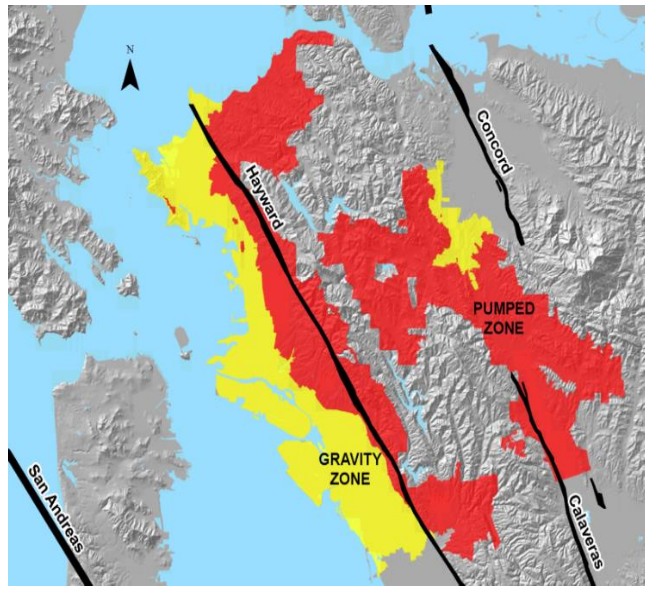

Figure 3. EBMUD Gravity vs. Pumped Pressure Zones

The impacts of power outages on EBMUD's water distribution system are discussed in more detail in the next section of this paper, titled "Damage Predictions". ABAG's 2014 report [4] provides an estimate of the potential impact of interdependencies on expected utility restoration as part of an exercise completed in 2008 with Southern California Edison (SCE), the power provider for Los Angeles, Riverside, and San Bernadino Counties. SCE held two panel discussions and concluded that "power restoration times are strongly interdependent with other lifelines and are particularly affected by damage to the water system, natural gas delivery, transportation network, telecommunication overload, and post-earthquake fires."

In their second panel discussion to estimate the potential time frame for restoration of their system after a massive Southern California M-7.8 San Andreas scenario, which took into account the impacts of external interdependencies, SCE estimated that the time it would take to restore service to 90% of its customers would increase from an estimated two weeks to over one-year after the scenario event, as illustrated in Figure 4 [4].

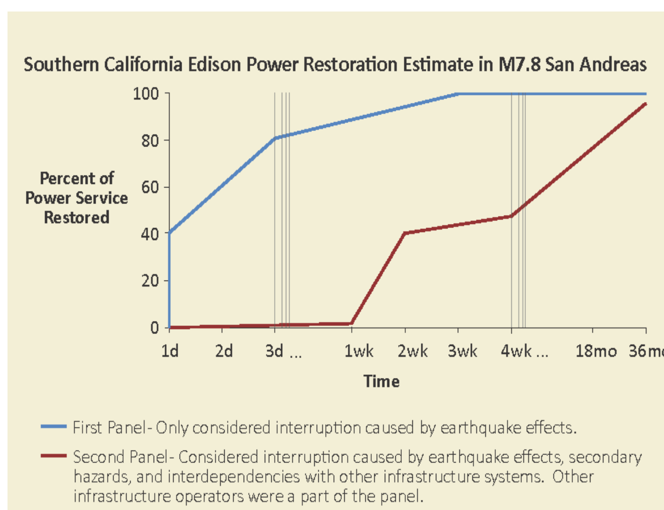

Figure 4. Power Restoration Estimate in M-7.8 San Andreas

Cascading Failures

One of EBMUD's 60-inch (1.5-meter) diameter LDP, located in El Portal Road in Richmond, failed in 2011 due to creep along the Hayward Fault. Resulting tensile stresses accumulated in the pipe. The ensuing sinkhole closed the road and resulted in significant damage to the roadway, adjacent utilities, and a creek bank. An adjacent 6-inch diameter petroleum product line operated by the Conoco Phillips Pipeline Company was damaged as well. The petroleum line had to be shut down and repaired prior to EBMUD crews being able to start repairs on the transmission main, which increased recovery time. Figure 5 shows the large sinkhole created by this break, with both the 60-inch (1.5-meter) pipe (seen in foreground) and 6-inch (0.15-meter) petroleum pipe exposed (in background). EBMUD was able to avoid any level of service impacts associated with this break by relying on an adjacent 24-inch (0.6-meter) diameter High Density Polyethylene (HDPE) bypass pipeline that had been installed at this location in 1997, as part of EBMUD's Seismic Improvement Program.

Figure 5. El Portal Main Break/Sinkhole and Mitigation Project
Example of Cascading Failures Associated with Collocated Utilities

Had the damage to the petroleum pipeline been more significant, the break in this water main could have caused more significant impacts on a nearby petroleum refinery as well as significant environmental damage. These collocated utilities also significantly slowed EBMUD's restoration efforts, as repair crews were delayed in order to first address safety concerns, and to allow Conoco Phillips time to repair its pipeline.

Due to the relentless creep of the Hayward Fault, it was estimated that a similar break could occur every few years. To reduce the risk associated with another break and the potential for damage to the adjacent petroleum pipeline, EBMUD recently installed a 48-inch (1.2-meter) diameter flexible expansion joint (Flex-Tend®), as shown in the right photo of Figure 5. The Flex-Tend® was installed with equipment to periodically monitor the creep displacement in the flexible joint and determine when the Flex-Tend® will require resetting. The San Francisco Public Utilities Commission recently installed a modified 72-inch (1.8-meter) diameter Flex-Tend® in Fremont, designed to absorb a large offset over a very short duration on the Hayward Fault.

Regional Lifelines Council Working Group

ABAG, in partnership with EBMUD, PG&E, and other local leaders and regional disaster resilience planners, recently assembled a Regional Lifelines Council Workgroup to better understand the impacts that interdependent lifelines would have on 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 of the study is to improve emergency planning and response efforts, including allocation of limited resources for post-disaster restoration purposes (repair crews, emergency pumps, generators, fuel, etc.).

One of the main goals for this working group, which was formed in early 2015, is to provide guidance for communities and regional government agencies to better plan for emergencies and improve the resiliency of energy and water systems. This working group will build on the efforts from the CCSF Lifelines Council Interdependency Study [3], which was formed to better understand system interdependencies, help expedite response and restoration planning among agencies, identify key assets and restoration priorities, and develop a set of lifelines performance expectations.

DAMAGE PREDICTIONS

Following the 1989 Loma Prieta Earthquake, EBMUD completed a Seismic Evaluation Program (SEP) to examine the performance of its water distribution system [5]. As part of this SEP, which was the basis for EBMUD's 10-year, $189-Million Seismic Improvement Program that was completed in 1994, EBMUD also completed several studies to estimate the level of damage that would result from various scenario earthquake events. The results of these prior studies, as well as results from EBMUD's more recent damage prediction modeling efforts, are discussed below.

Power Outages

The SEP predicted a loss of power to a significant number of the District's 132 pumping plants serving the higher elevation pumped zones [5]. A vulnerability assessment was performed to estimate the availability of offsite power following various scenario events and included an estimate of the extent of damage to PG&E equipment, duration of outages, and number and location of impacted EBMUD facilities [6]. This assessment included an analysis using a model entitled "System Earthquake Risk Assessment" (SERA) that reflected actual substation equipment used by PG&E at the time (circa 1994). Some of the results from this study are summarized in Table 2, and indicate that over half of EBMUD's pumping plants may be out of power for 3 days or longer following a Hayward M-7 scenario event.

The specific pumping plants that are predicted to be out of service and the pressure zones that they serve are shown on Figure 6. These estimates suggest that on the order of 25% of EBMUD's services could be impacted by power outages as a result of a Hayward M-7 event. This estimate does not take into account service disruptions due to main breaks. The combined impact from both power outages and main breaks is likely to be significantly higher, on the order of 50% or more.

Table 2. Estimate of Pumping Plants that will Lose Power

Scenario Earthquake	Number of Pumping Plants Losing PG&E Power	Time to Restore PG&E Power to 95% of Pumping Plants (Days)
Hayward M-7	73-84	2.8-3.3
Hayward M-6	24-33	1.2-1.5
Calaveras M-6.75	11-22	0.9-1.2
Concord M-6.5	12-22	0.6-0.8

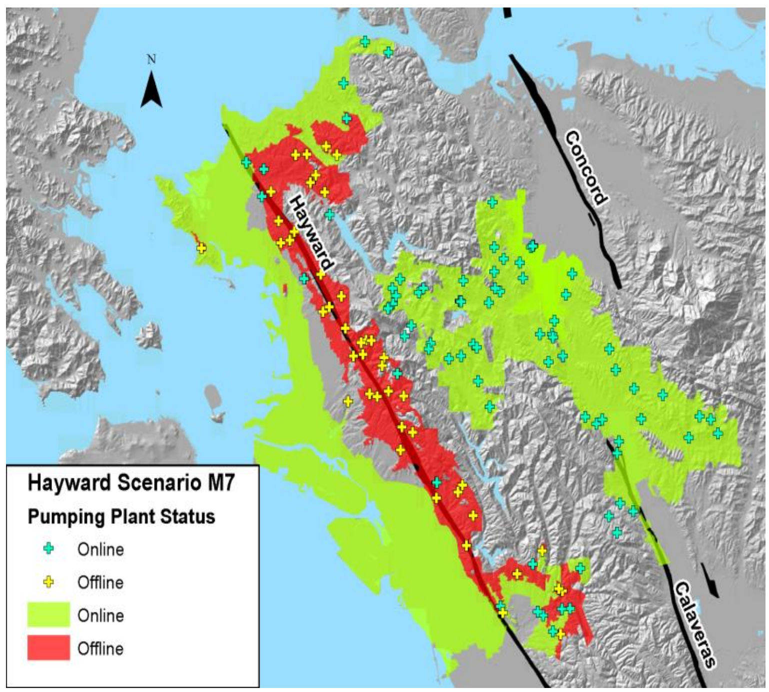

Figure 6. Pumping Plants with Power Outages and Impacted Pressure Zones

However, this prior study [6] may not have fully accounted for the interdependencies that may impede PG&E's ability to repair damaged substations. PG&E has a total of 17 substations that serve EBMUD's facilities, which have an estimated probability of power outage – based on the 1994 SERA model results – ranging from 4% to 78% as a result of a Hayward M-7 scenario event (11 substations with a probability of power outage ranging from 54%-78%, and 6 substations with a probability ranging from 4%-47%).

As previously discussed, recent studies suggest that power service interruptions as a result of a major earthquake – when accounting for other interdependencies – could last much longer (several weeks or more). Power outages as a result of a Hayward M-7 event may therefore be much longer than the estimated 2.8-3.3 days noted in Table 1, when taking into account interdependencies with other infrastructure systems and secondary hazards such as post-earthquake fires.

Assuming a winter or early-spring demand scenario, as summarized in Table 1, EBMUD could supply its customers for approximately 48 hours on a gravity-fed supply (using distribution reservoirs, with pumping plants out of service). After about 48-72 hours, only customers in pure-gravity zones shown on Figure 3 would be able to get water. Since only 2 of EBMUD's 132 pumping plants currently have permanent standby power, a majority of pumping plants impacted by prolonged power outages would therefore need to rely on emergency backup generators and portable pumps for operation.

EBMUD has a limited number of emergency backup generators (13) and portable pumps (22), which would be deployed as needed at pre-designated priority pumping plants locations shown on Figure 7. EBMUD, however, only has a limited amount of emergency fuel supply needed to power its emergency generators and portable pumps – only enough to last on the order of 24 to 48 hours. The same issue also applies to EBMUD's water treatment plants, which only have about 24-48 hours of fuel to power its backup generators. Depending on the extent and duration of PG&E power outages, EBMUD would therefore depend on external sources of fuel supply to keep its emergency backup generators and portable pumps in operation.

Main Breaks

Estimates of the extent of damage to EBMUD's distribution pipelines were also made as part of the SEP, and as summarized by pipe material type in Table 3. As indicated, it is estimated that EBMUD's distribution system would experience in excess of 4,000 leaks/breaks as a result of a Hayward M-7 event. Nearly 90% of pipe damage will result from breaks in the cast iron and asbestos cement pipe, which make up over 60% of the system. These pipes are generally older and more brittle pipe types when compared to other pipe materials [7]. This estimate is consistent with actual pipe damage observed during the Christchurch earthquake in New Zealand, where asbestos cement pipes had the highest break rate in liquefaction areas and cast iron pipes had the highest break rate in non-liquefaction areas [8].

This large number of breaks would quickly overwhelm EBMUD's four service centers and would require that aid be provided from outside sources. To address this emergency response issue, EBMUD has taken a number of steps including use of regional interties with adjoining water agencies and inter-agency cooperation and agreements, which are discussed in more detail in the next section of this paper, under "Steps to Improve Resiliency".

Results of a more recent analysis, using EBMUD's rapid damage prediction model, are also summarized in Table 3. As noted, this recent analysis focused on predicting damage to LDPs, which represents only 9% of EBMUD's distribution system but would have a more significant impact on EBMUD's system. The results of this more focused analysis are discussed in more detail below.

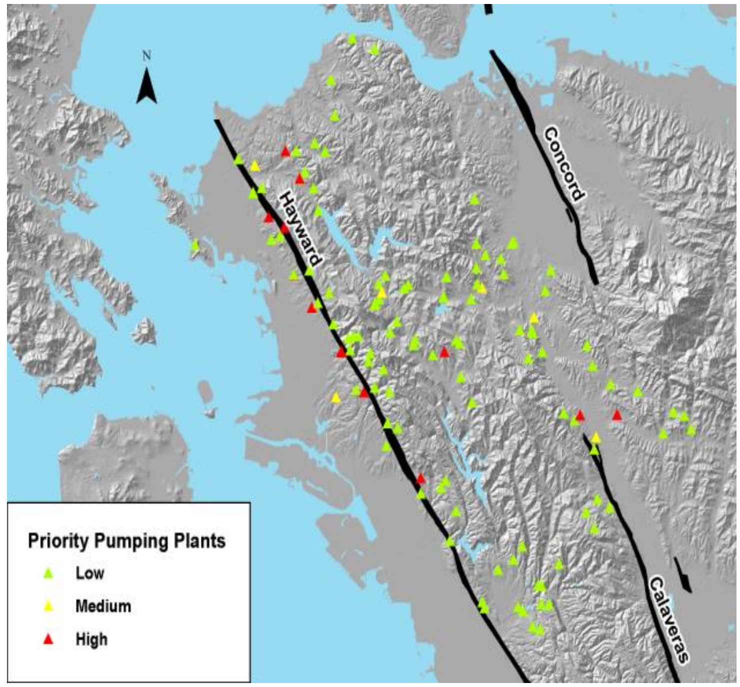

Figure 7. Priority Pumping Plants for Immediate Pumping, Hayward M-7 Earthquake

Table 3. Pipe Damage Predictions, Hayward M-7 Event

Pipe Material	Miles	% of System	Projected # of Breaks
1997 Estimates [6]			
Steel pipe	1,246	30	264
Cast iron pipe	1,357	33	2,451
Asbestos cement pipe	1,145	28	1,113
PVC	369	9	16
Other pipe (HPDE, copper, ductile iron, wrought iron, etc.)	11	<1	21
Large diameter pipe (reinforced, unreinforced, and pre-tensioned concrete cylinder pipe only)	21	<1	13
Total, all pipe materials	4,149		4,054
2015 Estimates – Based on Damage Prediction Model for Large Diameter Pipelines, using HayWired M-7 Scenario Event			
Steel (≥20-inch or 0.5-meter in diameter)	298	83	112
Cast Iron (≥16-inch or 0.4-meter in diameter)	37	10	164
Reinforced Concrete Cylinder (>24-inch or 0.6-meter)	14	4	54
Pre-tensioned Concrete Cylinder(>24-inch/0.6-meter)	10	3	4
Total, large diameter only	358		334

Rapid Damage Prediction Modeling and Marconi

Rapid modeling of seismic damage remains a very important area for water utilities seeking to maximize their reliability. It can greatly improve emergency response by allowing resources to be focused on the most important damage areas. Especially for large agencies that may have major assets spread over hundreds of square kilometers, timely estimates of earthquake damage can be invaluable since damage may vary substantially over a large area. For example, model results that show possible damage to key pipelines might prompt an agency to operate isolation valves immediately even before inspections can be completed.

Recent modeling efforts completed by EBMUD focused on estimating the extent of damage to LDPs as a result of a Hayward M-7 event. The subset of pipes that were included in this analyses includes approximately 358 miles (576-kilometers) of pipelines consisting of 20-inch (0.5-meter) and larger welded steel pipe, 36-inch (0.9-meter) and larger reinforced concrete cylinder pipe, 16-inch (0.4-meter) and larger diameter cast-iron pipe, and 20-inch (0.5-meter) and larger pre-tensioned concrete cylinder pipe (as summarized in Table 3).

This assessment is important for EBMUD to clearly identify areas in its pipeline network that are unlikely to perform adequately during a seismic event. The assessment also allows EBMUD to have a better understanding of various hazards including liquefaction-induced settlement, landslides, and fault crossings and how these hazards will affect EBMUD's water distribution capabilities.

The approach and analysis used to predict the number of LDP breaks summarized in Table 3 is discussed in more detail in EBMUD's paper entitled "Pipeline Fragility Assessment Against Liquefaction Induced Differential Settlement in City of Alameda, and Oakland, California" [9]. The spatial distribution of the projected LDP breaks within EBMUD's service areas, resulting from liquefaction, landslides, and fault crossings hazards as a result of an M-7 scenario event is illustrated on Figure 8.

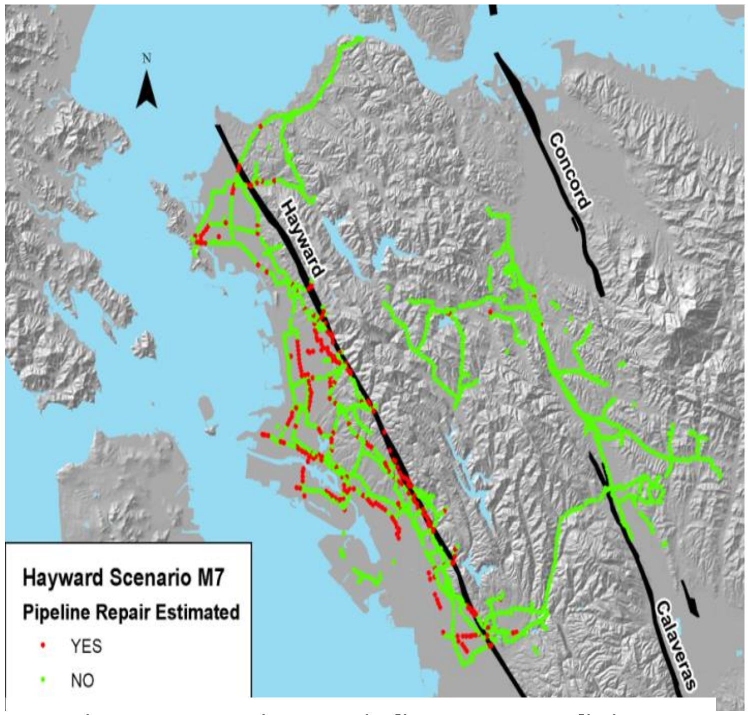

Figure 8. Large Diameter Pipeline Damage Predictions

Integration of Model Results with Emergency Response

As described previously, EBMUD uses an emergency response software called *Marconi* that integrates seismic model results with emergency response. Among its many capabilities is the ability to easily model historic or possible future earthquakes and quickly export damage prediction results. Marconi can also present actual damage reports on a map. However, rapid modeling, even at its best, remains an approximate prediction that might inform more detailed investigations. It is vital that the model results not be assumed true, but rather be interpreted in the light of real data as the data develop in the first hours and days after an earthquake.

In addition, the Marconi software has been licensed for open-source use and is being used by agencies besides EBMUD. This multi-agency use presents opportunities for collaboration in many areas, including seismic modeling and emergency response.

Damage Prediction Modeling and Interdependencies – Next Steps

PG&E has developed similar damage modeling capabilities for its power distribution system, using ShakeMap data to evaluate the likely level of damage to its substations and electric distribution system. In the near future, EBMUD will be working with PG&E to overlay its damage prediction scenarios for its water infrastructure system with PG&E's

electric distribution system. The goal is to use common ShakeMap data to estimate potential damage of the combined water and power infrastructure systems. As part of this effort, EBMUD is hoping to develop common priorities for service restoration based on customer criticality and other criteria. Being able to compare EBMUD's priorities for service restoration with PG&E's priorities for restoring gas and electric service and power generation, and critical business functions will be key to better understanding the interdependencies between the two systems.

STEPS TO IMPROVE RESILIENCY

While EBMUD completed a comprehensive, $189 Million Seismic Improvement Program (SIP) that included significant seismic upgrades to critical links to improve overall system performance, these improvements did not fix every component of the system that could be damaged in a major earthquake. Despite completing the SIP in 2004, it is predicted that the impacts on EBMUD's distribution system from a Hayward M-7 scenario event would still be significant, with an estimated number of leaks/main breaks on the order of 4,000. This damage includes over 300 breaks on LDPs and over 70 pumping plants potentially without line power for several days or longer. The additional steps that EBMUD is taking to further improve the resiliency of its distribution system are discussed below and include near-term projects to improve reliability as well as long-term improvements to improve robustness of EBMUD's distribution system.

Efforts to Improve System Reliability and Robustness

EBMUD has a large, ongoing capital improvement program that continues to improve the seismic reliability and robustness of its distribution system. Upcoming near-term projects include replacement of a vulnerable cast iron transmission pipeline and estuary crossing that supplies the island of Alameda, mitigation of liquefaction hazards, and electrical improvements at treatment plants to improve system redundancy and reliability. Longer-term improvements program also include:

- **Infrastructure Renewal Program:** In 2014, EBMUD initiated a new program to increase its rate of pipeline replacements from approximately 10 miles (16-kilometers) to a goal of as high as 40 miles (64-kilometers) per year. This program focuses on replacement of smaller diameter cast iron and asbestos cement distribution pipeline (pipes that are most likely to break as a results of an earthquake), and will gradually improve the earthquake resiliency and robustness of EBMUD's distribution system.
- **LDP Replacement Program:** A few years ago, EBMUD developed a new capital program to start replacing its LDPs at a rate of approximately 3 miles (4.8-kilometers) per year. Recent progress under this new program includes the Lincoln Avenue Pipeline Replacement Project in Alameda and the Dingee Pipeline and Claremont Center Aqueducts Replacement Project in Oakland, which included the replacement of over 5 miles (8-kilometers) of old LDPs. These recent improvements, and future projects under this new capital program will gradually improve the reliability of EBMUD transmission pipelines, which – as discussed in this paper – may experience a significant number of breaks as a result of a Hayward M-7 scenario event.
- **Other Capital Programs:** EBMUD has a number of other long-term and also recurring capital programs that will, over time, further improve the earthquake performance and reliability of its distribution system. These include open-cut, steel reservoir, and pumping plant rehabilitation projects (on the order of 6 facilities rehabilitated each year), as well as pther capital improvements including over $100 Million in transmission improvements, with over 23 miles (37-kilometers) of new LDPs scheduled to be completed in the next 15 years.

Figure 10 shows some of the transmission system improvements planned for EBMUD's "West of Hills" area, located along the Hayward fault. The new Wildcat Aqueduct South pipeline is currently being designed and will include approximately 1.7 miles (2.7-kilometers) of new 48-inch diameter transmission

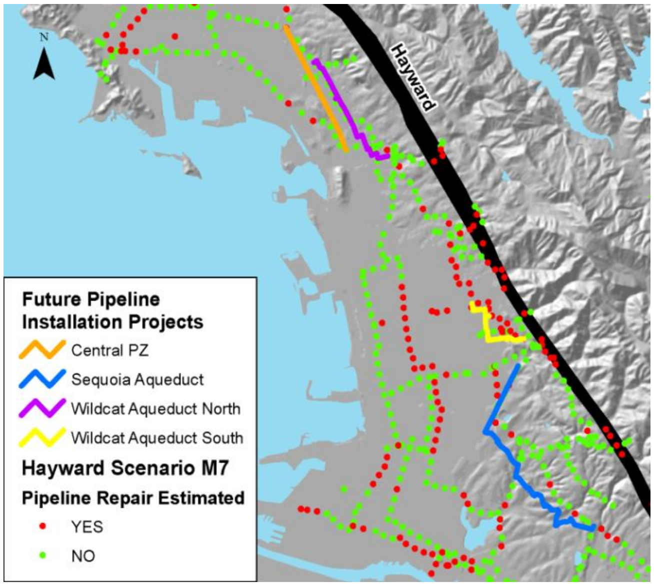

Figure 10. West of Hills Pipeline Improvement Projects

pipeline. This and other future improvements will not only improve transmission capacity for EBMUD but will also facilitate repairs on the existing parallel LDPs including the Wildcat Aqueduct, a reinforced concrete cylinder pipe projected to have a significant number of leaks as a result of a Hayward M-7 scenario event (as illustrated on Figures 8 and 10).

Emergency Response

General: EBMUD has a very well developed emergency preparedness program, including an Emergency Operations Plan (EOP). EBMUD recognizes that despite a high level of investment to harden its facilities, there will still be a significant level of damage following a major earthquake. For that reason, EBMUD has an overall EOP that describes how to respond to a major incident, trains staff to use the plan, and has regular exercises and drills to ensure staff understands the plan while providing an opportunity to identify where the program can be improved.

EBMUD also has hazard specific appendices to its EOP that describe how EBMUD would respond to specific types of incidents. Examples include a failure of a raw water aqueduct or threat to one of EBMUD's dams. In addition, there are functional appendices which describe specific tasks such as deployment of EBMUD flexible hose to temporarily restore service at fault crossings. EBMUD recommends to its customers to be self-sustaining for 3 to 7 days until water and food distribution centers can be set up.

EBMUD is also currently developing a pipe repair mitigation plan that includes improving its welding shop's capabilities to fabricate custom parts for repair, such as buttstraps, reducers, and manholes, and stockpiling limited quantities of LDPs with a pre-set reorder point to keep turnover in stock.

Regional Interties: EBMUD has 10 emergency interties with other local water agencies, which would allow for potable water to be shared if available, following a significant earthquake event that would affect one agency more than another. Figure 11 shows the approximate location and flow capacities that could be provided to or by EBMUD using these interties.

Inter-Agency Cooperation and Agreements: EBMUD is one of the original founding members of the California Water/Wastewater Agency Response Network (CalWARN), which was started in 1994 to increase planning and coordination between agencies, reduce administrative conflicts, and increase community and customer assistance. In response to the recent Napa earthquake, EBMUD sent crews to Napa via the CalWARN agreement, along with Alameda County Water District, Contra Costa Water District, and the City of Fairfield. EBMUD crews were in Napa the Monday morning after the earthquake, which occurred on a Sunday. EBMUD sent 5 crews, who repaired 56 leaks out of 144 total leaks, as well as an Incident Commander, Safety Officer, Logistics Chief/Liaison, and a Finance Chief (Accountant).

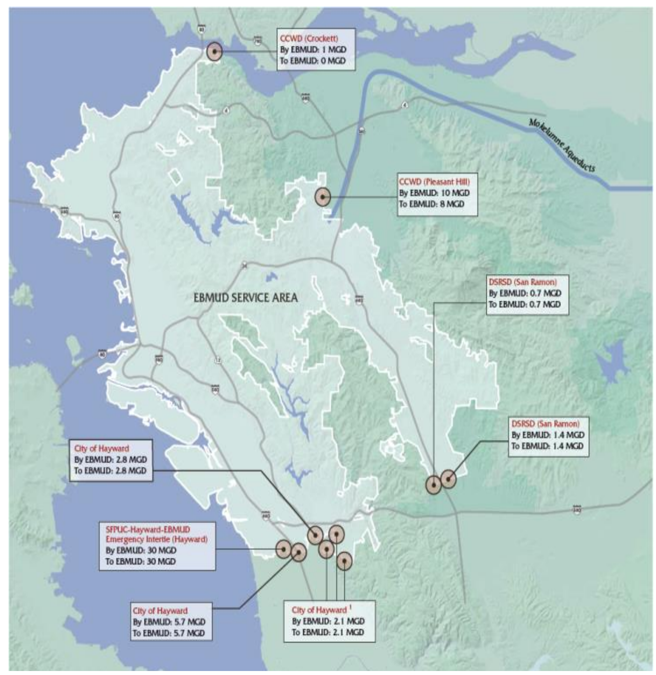

Figure 11. EBMUD Interties with Other Bay Area Water Agencies

In addition to being part of the CalWARN system, EBMUD has also entered into mutual assistance agreements with the Los Angeles Department of Water and Power (LADWP) and the Las Vegas Valley Water District (LVVWD), two other large water agencies that are not exposed to the same earthquake risk as EBMUD (i.e. geographically distant agencies, exposed to different sets of faults). This was done in recognition that a Hayward M-7 scenario event would likely overwhelm other local water/wastewater agencies that would be called to first respond to their own emergencies, before they could assist EBMUD.

In addition to these inter-agency agreements, EBMUD has also worked with other water agencies and the state to develop a statewide plan for emergency drinking water procurement and distribution. This is an important component of EBMUD's emergency response plan, and includes working closely with local cities and/or the counties to seek their assistance in procuring and distributing drinking water in the event that EBMUD cannot supply drinking water following a catastrophic earthquake event.

PLANNING FOR PROLONGED UTILITY SERVICE DISRUPTIONS

In the 2011 earthquake that devastated Christchurch in New Zealand, around 80% of residents were without a fully operational water supply for the first few days after the earthquake. Within a week, 50% of Christchurch had basic water supply and 75 per cent of the city had power, but people were still asked to conserve water and boil it before drinking. Progress to fully restore services was slow due to damage to roads and to the electric network, much of it underground.

Prior case studies for water system restoration following the 1995 M-6.9 earthquake in Kobe, Japan, and the M-8.8 earthquake in Concepcion, Chile, indicate that the time to restore service to 90% of customers took approximately 5 to 6 weeks, as illustrated on Figures 12 [4]. And based on the results from CCSF's study, the time to restore 90% of water service in San Francisco could take approximately 3-4 weeks, as illustrated on Figure 13 [3]. However, large-scale disasters such as Hurricane Katrina, the 2010 earthquakes which devastated Haiti, Chile, and Pakistan have demonstrated that recovery periods can be considerably greater than 3 weeks [10].

The time to restore service to 100% of EBMUD's customers, following an M-7 Hayward scenario event, will depend on a number of factors. A catastrophic earthquake in the San Francisco Bay Area may require innovative solutions such as scaling up mobile water treatment units, or developing temporary distribution systems.

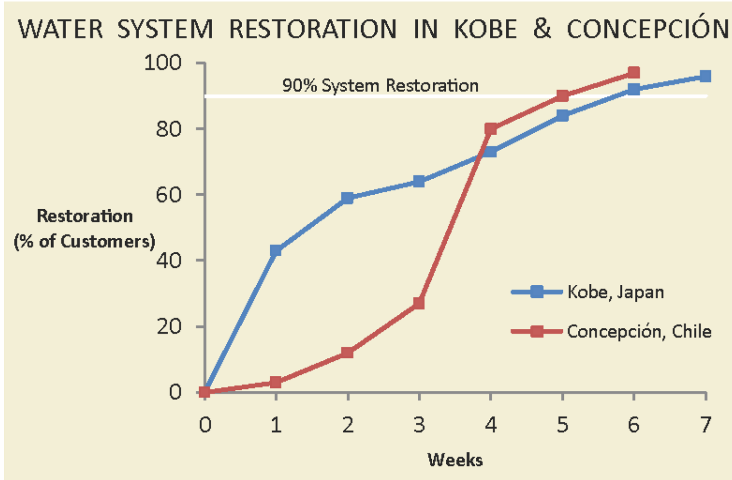

Figure 12. Water System Restoration Timelines in Kobe, Japan, and Concepcion, Chile [4]

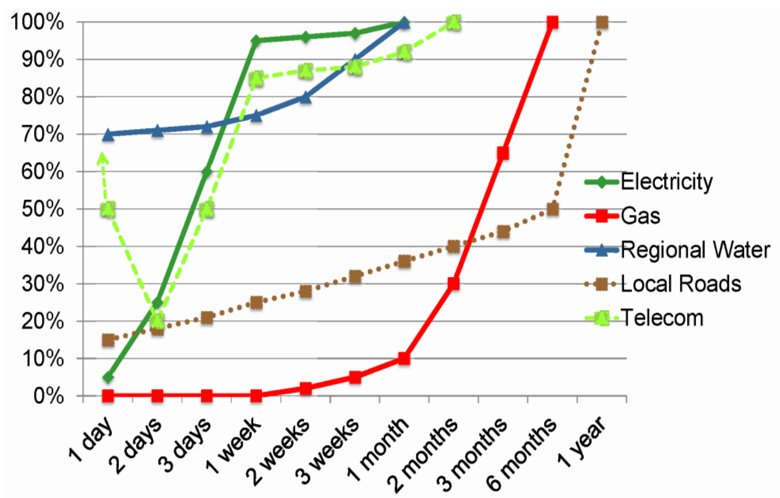

Figure 13. Timelines for System Restoration, CCSF Lifelines Council Interdependency Study, AICP Consulting | Research, January 2013 Progress Report [3]

SUMMARY

In summary, despite water utilities' ongoing efforts to improve their distribution systems, not every component of the system can be hardened. Interdependencies significantly increase the potential for prolonged system outages following a major seismic event. AWWA's 2011 study entitled *Planning for an Emergency Drinking Water Supply* [10], illustrates how water from various sources could be distributed either through an existing, partially-operating distribution system, or via distribution sites. This study notes that depending on the nature of the damage and the ability of a utility to make functioning pipe connections, it may be impossible to transport water from functioning to non-functioning portions of the distribution system. If uncontaminated water is available in sufficient supply within the existing system but cannot be distributed as needed, the water may need to be tapped at fire hydrants or other locations within the functioning system for local distribution, and/or moved in bulk water tankers that would be accessible to local residents [10]. EBMUD has a water bagging station that could be deployed, to assist with distribution of water after an earthquake.

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