Implementing a Water System Seismic Resilience and Sustainability Program in Los Angeles

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ABSTRACT

The Los Angeles Water System is implementing a Seismic Resilience and Sustainability Program as part of a larger plan to improve the City's seismic resilience as outlined in the *Resilience by Design* report released by the Mayor [2]. The Water System Resilience and Sustainability Program comprehensively integrates into all aspects of water system business. The purpose is to continually improve the Water System seismic resilience in a manner that ensures its sustainability and improves the resilience and sustainability of Los Angeles. Water System resilience is critical for providing the water delivery, quality, quantity, fire protection, and functionality service categories, all necessary for supporting community resilience. The goal of a resilient Water System is to limit the total number of service losses and restore the water service categories as rapidly as possible while protecting property, life safety, and the regional social and economic stability. This paper reviews Water System resiliency and sustainability then provides brief descriptions of recommendations and potential tasks which may be implemented to accomplish the recommendations.

INTRODUCTION

The Los Angeles Department of Water and Power (LADWP) Water System (Water System) is undertaking a seismic resilient and sustainability program at the request of the Mayor [1]. Los Angeles City Mayor Eric Garcetti established a 1-year partnership in 2014 between his administration and United States Geologic Survey (USGS) seismologist Dr. Lucy Jones to develop earthquake resilient strategies for Los Angeles by focusing on three main components: water, communication, and building structures. The main focus for the water component is creating a seismically resilient and sustainable Water System which supports the resilience of Los Angeles.

The Water System Seismic Resilience and Sustainability Program (Program) purpose is to continually improve the Water System seismic resilience in a manner that ensures its sustainability and improves the resilience and sustainability of Los Angeles. This is viewed as an effort to make the implementation of resilience activities a standard of practice, building upon seismic improvements implemented over the past century.

Program development is being accomplished through a management team effort investigating three requisites: (1) defining characteristics of a seismically resilient Los Angeles Water System, (2) identifying the current status of Water System seismic resilience, and (3) recognizing aspects which may improve Water System seismic resilience. To proceed with the Program six initial

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recommendations are identified as follows:

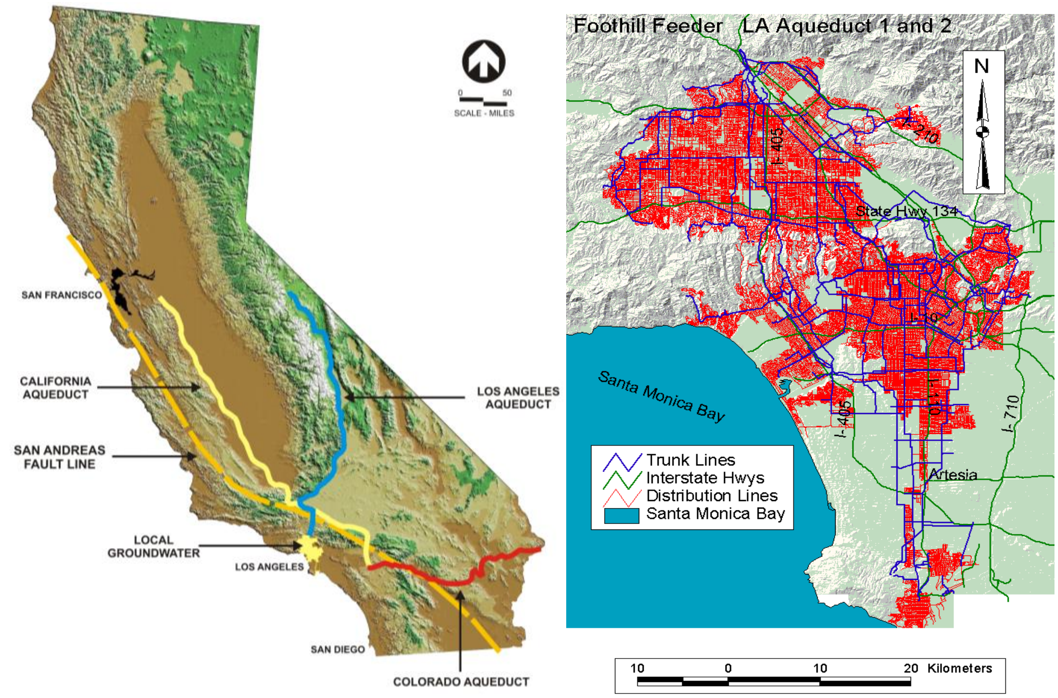
- Establish an LADWP-wide Resilience Task Force to oversee and provide resources to lead, support and ensure accomplishment of the Program.
- Prepare a plan for implementing the Program.
- Implement Water System seismic planning, evaluation, and monitoring to identify needed mitigations throughout the City and along the Los Angeles Aqueducts (LAA).
- Develop a seismically resilient pipe network.
- Increase water supply and storage reliability, including
    - Identify mitigation alternatives for LAA crossing the San Andreas Fault.
    - Enhance the Dam Safety Program using risk-based methods.
    - Identify alternative water supply sources for firefighting.
    - Develop local supply sources to reduce dependence on imported water and enhance water availability in emergencies.
- Enhance emergency response capabilities.

From this outline, the Mayor made some specific recommendations in the *Resilience by Design* report released in December 2014 [2]. This paper provides an overview of the Program purpose and implementation.

LOS ANGELES WATER SYSTEM OVERVIEW AND SEISMIC HAZARDS

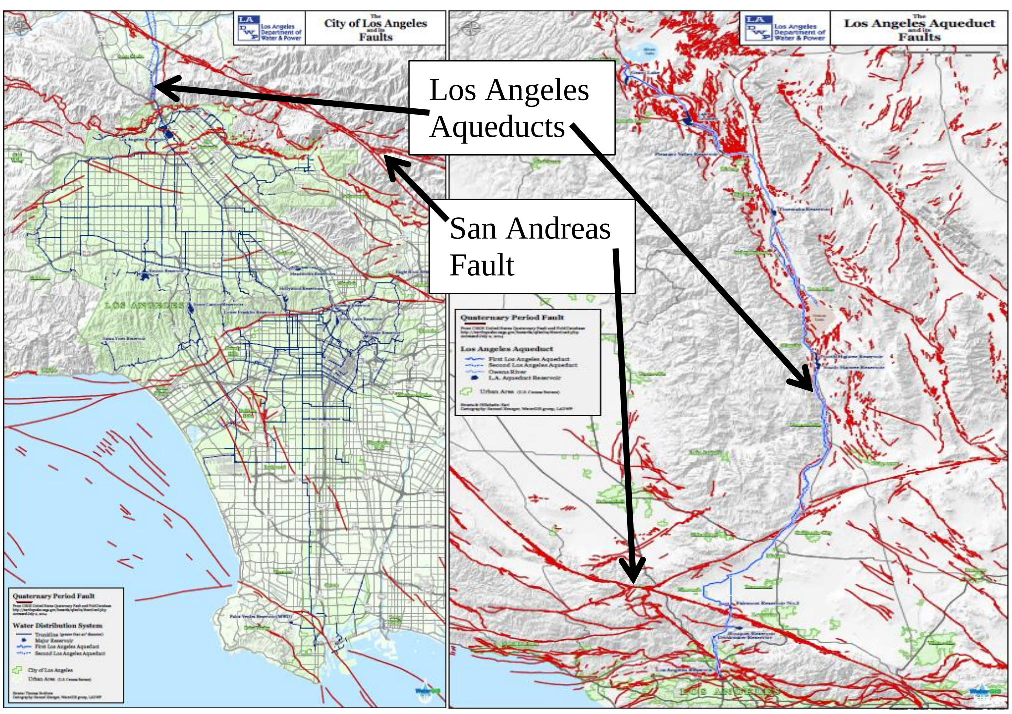
The Los Angeles Department of Water and Power (LADWP) is the largest municipal utility in the United States, and provides critical water and power services to support the local economy and wellbeing as well as in support of the supply of goods and products throughout the United States and the Pacific rim. The LADWP was founded in 1902 and is a primary reason for the growth and expansion of Los Angeles. Los Angeles covers an area of 1,214 km^2 with a population of about 4 million people. Figure 1 shows the approximate 12,000 km of pipe within the city used to transmit and distribute water to customers. The transmission and distribution networks also contain numerous tanks, reservoirs, pump stations, and regulating stations. Water quality is maintained with treatment plants, chloramination stations and chlorination stations.

The Los Angeles Water System has annual water sales of about 678 billion liters. As shown in Figure 1, Los Angeles receives water from multiple sources including local groundwater, the Los Angeles Aqueducts, The Metropolitan Water District of Southern California (MWD), and recycled water. The great majority of supply, about 88% on average for the five years 2008 to 2013, for Los Angeles is imported through the Los Angeles, Colorado River, and California Aqueduct systems. The Los Angeles Aqueduct (LAA) System [consisting of the First and Second Los Angeles Aqueducts], is owned and operated by the LADWP. The Colorado River Aqueduct (CRA) is owned and operated by the MWD. The California Aqueduct is owned and operated by the California Department of Water Resources and constructed as part of the California State Water Project (SWP). The MWD is a state-created regional water wholesaler that receives water from the SWP. The majority of local ground water comes from the San Fernando basin (SFB). The usable ground water volume has dwindled over the past several decades from contaminants in the SFB.



(a) (b)

Figure 1. (a) Water supply sources for Los Angeles. (b) Los Angeles Water System transmission and distribution pipe networks.



(a) (b)

Figure 2. Fault lines: (a) within the city of Los Angeles, (b) along the Los Angeles Aqueducts.

California is riddled with earthquake faults. Figure 2 shows the known 20 faults which can rupture the ground surface within the Los Angeles city boundaries and the nearly countless faults along the LAA. Additional blind faults not identified in Figure 2 do not rupture the ground surface. Earthquakes generated from these and other surrounding faults can cause severe ground shaking, and permanent ground deformations from liquefaction, landslides, differential settlement, etc. These movements threaten the Water System's capability to maintain service provision following an earthquake. The San Andreas Fault shown in Figures 1a and 2 poses the greatest risk to a regional disaster or catastrophe.

The combination of significant earthquake threats, major regional economy important to the USA and the Pacific rim, and Los Angeles' reliance on the Water System warrants the development and implementation of the Program.

RESILIENCY AND SUSTAINABILITY

Seismic resiliency and sustainability are achievable when the Water System:

- Has the systemic ability to provide water services in a manner allowing the community to effectively respond to earthquake events, recover quickly from them, and adapt to changing conditions, while also taking measures to reduce future seismic risks, and
- Is prepared to manage all threatening seismic hazards in a manner that minimizes and contains the hazard impacts while continuing a comprehensive approach to natural resource conservation and maintaining environmental quality.

To understand the inter-relation between resilience and sustainability following a significant natural hazard attack such as an earthquake, Figure 3 shows different possible trajectories of economic activity recovery [3,4].

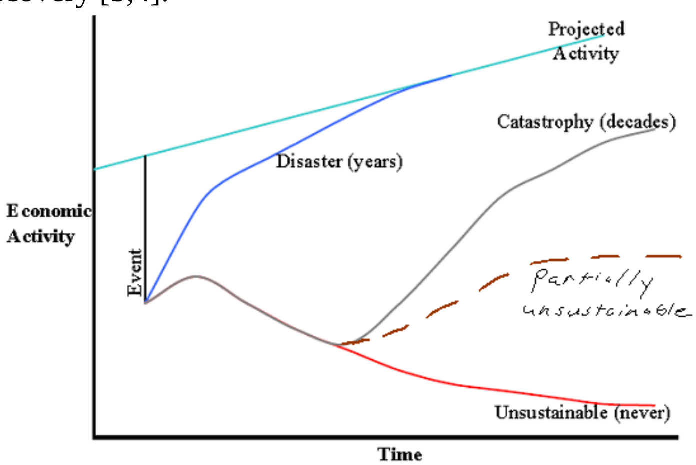


Figure 3. Economic resilience; trajectories of possible economic recovery [3,4].

When a damaging earthquake strikes there is an immediate drop in economic activity. Resilience is measured by the amount of economic loss and the time it takes to recover. There are several possible trajectories the economic activity may take over time. For a fixed initial loss, the shorter the recovery duration the more resilient is the economy. The event is considered a disaster when recovery takes several years (upper curve in Figure 3). A more rapid recovery is considered a disruption. In great earthquakes, economic activity may not recover for several decades resulting in a catastrophe [5]. In some cases the economy remains functional but has a permanent long-term reduction compared to the pre-event levels. This condition shows a limited resilience because there is not complete recovery to pre-event conditions and the economy is understood to be partially unsustainable to the earthquake hazard. In the greatest extreme the economic activity may never recover, continuing to decline and disabling a safe and equitable lifestyle for city residents (lower curve in Figure 3). In such a case, the economy is not resilient or sustainable (this trajectory is for descriptive purposes and not anticipated for Los Angeles).

The Water System's resilience is dependent upon the amount of service losses suffered as a consequence of the event and the time required to reestablish the services. In a disaster, water services may be disrupted and their recoveries are described by five basic categories [6,7,8]:

Water Delivery: This service is achieved when the system is able to distribute water to customers, but the water delivered may not meet quality standards (requires water purification notice), pre-event volumes (requires water rationing), fire flow requirements (impacting firefighting capabilities), or pre-event functionality (inhibiting system operations).

Water Quality: This service is achieved when water quality at customer connections meets pre-event standards. Potable water meets health standards (water purification notices removed), including minimum pressure requirements to ensure contaminants do not leach into the system.

Water Quantity: This service is achieved when water flow to customers meets pre-event volumes (water rationing removed).

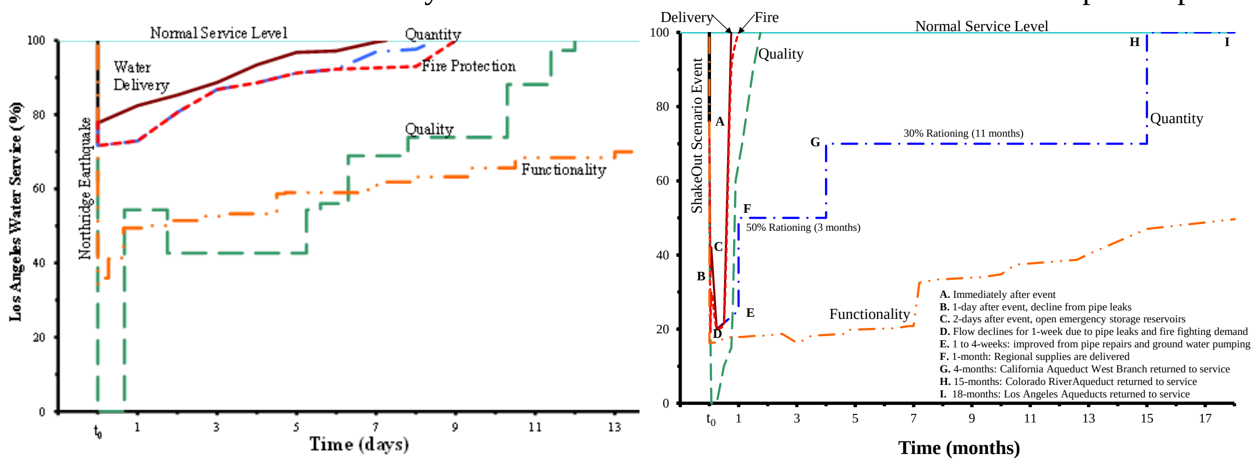
Fire Protection: This service is achieved when the system is able to provide pressure and flow of a suitable magnitude and duration to fight fires.

Functionality: This service is achieved when the system functions are performed at pre-event reliability, including pressure (operational constraints resulting from the earthquake are removed/resolved).

Each of these services can have an immediate loss and a recovery trajectory similar to that shown for the economy in Figure 3, including partial unsustainability. The goal of a resilient Water System is to limit the total number of service losses and restore the categories as rapidly as possible while protecting property, life safety, and the regional social and economic stability.

These services are best understood through example of Water System performance during and after the 1994 Northridge Earthquake. Figure 4a shows the 1994 earthquake service losses and restoration times. Total water system repair costs reached $41 million. The most significant water losses were in the highly residential San Fernando Valley impacting water services to an estimated 850,000 people, 670,000 of which lost water delivery for some period of time.

The water delivery service dropped to about 78%, with 22% of all Los Angeles customers receiving no water shortly after the earthquake due to water leaking from broken pipes. The quantity and fire protection services dropped to a low of about 72% on January 17, 1994. The quality service dropped immediately to zero because a water purification notice was issued across the entire city within 3 hours after the earthquake. As shown in Figure 4a, the water delivery service was restored to 100% at about 7 days, quantity and fire services at about 8.5 to 9 days, and quality service at 12 days after the earthquake. The functionality service initially dropped to about 34% and rapidly increased to about 60% once critical repairs were completed a few days after the earthquake and was 95% restored within 3 years. It took 6 years to return Functionality to 99% after completing a number of tank and reservoir repairs and replacements. Functionality was completely restored at about 9 years after relocating a major damaged trunk line and because of limited ability to remove the LAA channels from service to complete repairs.



(a) (b)

Figure 4. Los Angeles Water System service restorations: (a) following the 1994 Northridge Earthquake [7], (b) following the ShakeOut Scenario earthquake, based on analyses by [9].

Overall, the Los Angeles Water System is considered to have been highly resilient to the Northridge Earthquake because it was able to restore system operability within a relatively short period of time. Likewise, the Los Angeles economic system was also resilient to the Northridge Earthquake, resembling something like the upper curve in Figure 3. However, if the earthquake were larger or located elsewhere around the City the performance would have been different. The Water System will perform differently to different earthquakes based on shaking severity and locations of different vulnerabilities within the network. For example, Figure 4b shows results from simulated Water System performance subjected to a magnitude 7.8 earthquake on the southern San Andreas Fault. This earthquake scenario was developed for the 2008 ShakeOut event by a group of experts working with the USGS, and allows for independent assessment on how the Water System may perform in a great San Andreas Earthquake event.

Figure 5 maps the ShakeOut Scenario and shows the major water supply aqueducts crossing the San Andreas Fault. In the ShakeOut Scenario the San Andreas Fault damages the LAA, CRA, and California Aqueduct in a single rupture. As a result, in a matter of minutes all imported water is lost to Los Angeles and it may take over one year to return all of these aqueducts to operation [10]. In addition, the transmission and distribution systems suffer significant damage.

The Shakeout Scenario has greater impact on all services as compared to the 1994 Northridge Earthquake, mostly because the San Andreas Fault rupture has a regional impact while the Northridge Earthquake had a local impact to a portion of the Water System. Water delivery, quantity, and fire protection services drop to about 20% soon after the earthquake and water quality services are temporarily lost to all customers. Water delivery service is completely restored in about 3 weeks, fire protection service is restored in about 4 weeks, and water quality restored in about 7 weeks. Of great significance is the long quantity service restoration due to the need for long-term water rationing resulting from the water supply aqueduct damages. Water quantity services may not be restored for at least 15 months in this scenario. Functionality service initially drops to 16% and may take decades to restore, leaving the system more vulnerable during this timeframe.

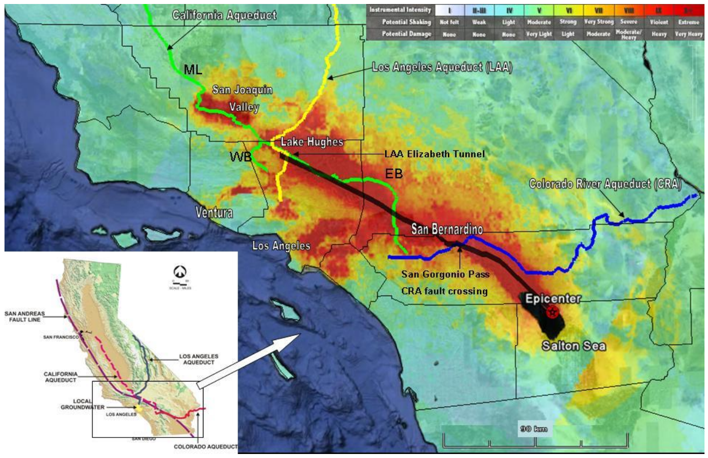


Figure 5. ShakeOut Scenario showing ground shaking intensity and fault rupture crossing the major water supply aqueducts.

The Water System is obviously less resilient to the San Andreas Earthquake scenario than it was to the 1994 Northridge Earthquake. Water service losses from a San Andreas event result in significant community impacts. Economic impacts include about $53 billion in direct and indirect economic losses throughout Southern California as a result of water loss alone, which is about 25% of the total $213.3 billion estimated losses to this event [5]. Business interruption from water loss is greater than 50% of the total business interruption losses for the entire event. This gross loss in output from water alone is sufficient to drive the region into a recession. Fire following earthquake results in significant social impacts having an estimated economic loss of about $87 billion, a large portion of this is within the City of Los Angeles. Considering the relation between fire and water service losses, the earthquake effects on the Water System has the greatest impact of all aspects considered in the ShakeOut Scenario. If unmitigated, the initial recession fostered by Water System losses could build toward a regional economic catastrophe [5] as defined in Figure 3. Further, it is unclear if some sectors in the City highly dependent upon water would be partially unsustainable. To achieve the Program goal, the water service losses and restoration times for the ShakeOut Scenario need to shift up and toward the left in Figure 4b. The target acceptable losses and restoration time, as well as strategies to shift these curves, needs to be determined as part of the Program.

A seismically resilient and sustainable Water System is achievable through:

- An organization capable of managing the planning and implementation of seismic resilience activities,
- Creating a seismically resilient pipe network,
- Increasing water supply reliability, and
- Ability to effectively respond after earthquakes followed by recovering and rebuilding to meet intended performance.

The Los Angeles Water System intends to put these resilience characteristics into action to secure a safe and reliable water supply against the threatening earthquake hazards and help protect the social and economic vitality of Los Angeles.

IMPLEMENTING PROGRAM RECOMMENDATIONS

The introduction to this paper outlines six initial recommendations for implementing the Program; additional background on these recommendations and associated tasks is provided in [1]. In addition, the Mayor's office made some specific recommendations to emphasize their priorities for improving the resilience to Los Angeles [2]. These include:

- Implement a Resilience by Design Program at the LADWP
- Improve the Water System's firefighting water supply
- Fortify the Imported Water Supplies and Water Storage
- Increase Local Water Sources
- Create a Seismic Resilient Pipe Network

The recommendations provided in [2] are consistent with those in [1], the primary difference is setting priority of focus from a city-wide perspective and the additional detail provided in by the Water System management group. Some of the plans and actions for implementing these recommendations are summarized in this section, with a primary focus of those given in [2]. The LADWP Water System has appointed a Resilience Program Manager to implement the Program.

Firefighting Water Supply

A preliminary plan to improve the Water System for managing the Fire Following Earthquake (FFE) Risks has been written. The goal is to develop a plan for addressing FFE risks by providing two end products:

I. A long-term plan for developing a resilient water system for firefighting
II. An emergency firefighting water supply plan

Both Plans I and II will address water supply for firefighting obtained through the distribution network and from alternate sources. Plan I primarily focuses on infrastructure development and improvement. Plan II primarily focuses on alternate water sources. As elements in Plan I are implemented to increase reliability, Plan II will be modified as necessary. The combination of both plans will work to build up and maintain capacity to fill, to the greatest extent possible, any potential gaps in firefighting water supply.

The LADWP and Los Angeles Fire Department (LAFD) are working collaboratively to undertake the steps needed to improve ability to reduce risks to FFE across Los Angeles. A key aspect for reducing FFE risks is to perform a risk assessment. This is recommended to be undertaken in three separate tasks: an assessment of FFE hazards, an FFE vulnerability study focusing on earthquake effects on Water System hydraulics and ability to meet fire protection services, and FFE consequence studies. Further, a program is being implemented to identify alternative water supplies throughout the city which can be used to fight fires. These include LADWP storage facilities, swimming pools, rivers, creeks, lakes, ponds, and temporary storage facilities (e.g., storm water detention basins).

Alternatives were identified as near-term, those which can be potentially implemented in a matter of years, and long term, those taking multiple years to decades to complete. Review of near-term alternatives identified the need to investigate: methods to improve access to existing storage and production facilities; methods to preserve water supply at storage facilities following a major earthquake specific to firefighting needs; feasibility of utilizing temporary storage facilities as alternate water sources for firefighting; feasibility of developing additional, new storage facilities for firefighting to provide an alternate water source in high risk regions; feasibility of developing drafting connections to rivers, creeks, lakes, and ponds; and procurement of additional water tankers in support of fire suppression. Long-term alternatives require the LADWP to: develop performance objectives for resilience improvements consistent with community resilience goals; develop a seismically resilient pipe network; incorporate seismic risk into pipe replacement evaluations when identifying and prioritizing pipe replacement projects; evaluate groundwater facilities to ensure operability following a major earthquake and to improve LAFD fire engine and helicopter access. The LADWP will also consider developing alternate water systems in support of firefighting such as using the recycled water system and developing a pressurized seawater system; both of these systems require feasibility studies. Additionally, the LAFD and LADWP will investigate feasibility of using large and ultralarge diameter hoses, and portable water supply systems [11].

Fortify the Imported Water Supplies and Water Storage

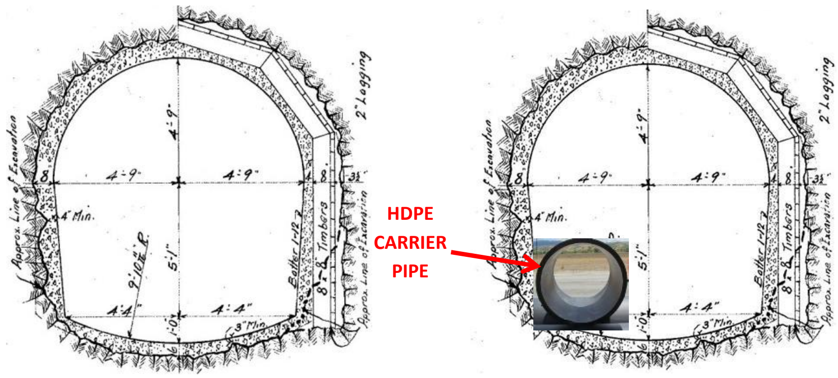
As shown in Figures 1 and 5, all imported water to Los Angeles crosses the San Andreas Fault, and as previously described some scenarios identify how this fault can damage all the aqueducts at the same time. This requires significant action to ensure adequate water supplies are available following a regional event. The primary items being undertaken to improve Water System resilience and sustainability are to: (1) investigate and implement cost effective measures where the LAA crosses the San Andreas Fault, (2) perform a systematic seismic assessment of the LAA, (3) establish a seismic resilient water supply task force consisting of LADWP, MWD, and DWR, and (4) Enhance the Dam Safety Program using risk-based methods. These four items are being implemented; only items (1) and (3) will be summarized in this subsection.

As seen in Figures 1, 2 and 5, the LAA crosses the San Andreas Fault nearly perpendicularly in an 8 km long approximate 3 m wide tunnel. Figure 6 shows a cross-section of the tunnel completed in 1913. The Elizabeth Tunnel is vulnerable to seismic shaking and may be subject to fault movements ranging from relatively small offset, to as much as approximately 12 m in any given earthquake. This range of fault rupture is capable of damaging the Elizabeth Tunnel to the point of failure, which would eliminate the LAA’s ability to deliver water to Los Angeles.

Currently more than 15 alternatives are being investigated to identify the most cost-effective strategy to mitigate the San Andreas Fault rupture hazard. Due to the complexity of the San Andreas Fault rupture hazard, the problem is being approached using project-oriented risk-based methods, categorized within one of the two project types:

1. Risk reduction/retrofit project type to enhance seismic performance by evaluating measures that would increase the opportunities for continued water flow in the event of damage to the Elizabeth Tunnel in the near term.

2. Replacement/modification project type to provide an engineered solution to crossing the San Andreas Fault for the expected largest offset (approximately 12 m), which will minimize service disruption in the long term.



(a) (b)

Figure 6. Los Angeles Aqueduct Elizabeth Tunnel crossing the San Andreas Fault: (a) Typical cross section of Elizabeth Tunnel; (b) Example proposed retrofit with HDPE carrier pipe.

Figure 6b shows the proposed risk-reduction method by placing a highly ductile HDPE pipe within the tunnel to protect water flow in the event of relatively small fault movement or liner collapse. This solution does not prevent loss of water flow for large fault movements so in parallel more extensive alternatives are being pursued, but these take much more funding and longer to implement. In addition to the San Andreas Fault crossing, the LAA is being investigated for other vulnerabilities with an initial focus along the stretch from the San Andreas Fault to Los Angeles.

A seismic resilient water supply task force consisting of LADWP, MWD, and DWR is being created to address the seismic risks for each of the aqueducts individually and combined as a regional water supply system. Some key aspects these agencies will address are strategies for how to respond as a team once a major earthquake strikes, emergency preparedness and response, mutual aid and assistance agreements, pre-earthquake assessments of each aqueduct system, and potential mitigations which may be undertaken.

Increase Local Water Sources

To address the vulnerability and uncertainty of imported water supplies, LADWP is focusing on a combination of two important initiatives: the Local Water Supply Program and the San Fernando Groundwater Basin (SFB) clean up and remediation program. In the 2010 Urban Water Management Plan (UWMP) LADWP set goals for developing local water supplies through storm-water capture, water conservation, and water recycling. The 2010 UWMP also addresses the need to clean up and remediate SFB contamination and ensure extracted water meets safe drinking water regulations. A healthy SFB also sets a foundation for implementing conjunctive use, recycled water and storm water capture projects. Local supply development will enable LADWP to reduce reliance on imported water and cut purchases from MWD in half by 2035 or sooner. This enhances resiliency by improving the water quantity services (see Figure 4). Additionally, local supply development will enhance water availability in emergencies and help shift the post-earthquake service restoration curves in Figure 4b up and to the left. Water System resilience will be improved with continued implementation of the local water supply program and SFB clean up and remediation program. Additionally, Water System resilience can be improved by incorporating important resilience design aspects into these two programs during development, which may include, but not be limited to: emergency power, emergency production capacity, treatment plant bypass capabilities, and well placement.

Create a Seismic Resilient Pipe Network

A seismic resilient pipe network is designed and constructed to accommodate damage with ability to continue providing water or limit water outage times tolerable to community recovery efforts. The resilient network will include the use of earthquake resistant pipes placed at key locations to help increase the probability of continuous water delivery and reduce the time to restore areas suffering a total loss of water after an earthquake. Earthquake resistant pipes are designed to accommodate seismic forces meeting defined performance criteria, and may include Japanese manufactured Earthquake Resistant Ductile Iron Pipe (ERDIP), High Density PolyEthylene (HDPE), specially designed welded steel pipe, PolyVinylChloride (PVC) and others providing sufficient robustness against design level ground deformations. The proposed resilient network, as it relates to the fire protection service, will be developed by placing earthquake-resistant pipe in a grid to form an arterial sub-network at intervals consistent with capabilities of firefighting equipment to relay water and targeted system performance criteria. From the arterial sub-network earthquake resistant pipes can be placed to critical facilities such as hospitals, schools, and emergency evacuation centers to improve reliability of the water delivery, quality, quantity, fire protection, and functionality services. This network will also reduce restoration times for other less critical customers who may lose some water services. This minimizes economic disruptions and supports overall community recovery following an earthquake.

The Los Angeles Water System piping network is mostly built-out. As a result, improvements to create the seismic resilient pipe network will primarily consist of replacing existing pipe with earthquake resistant pipe in a manner consistent with on-going asset management and pipe replacement programs. Existing pipe must be replaced strategically to address regions with the greatest risk while simultaneously replacing deteriorating infrastructure to improve overall water system resilience. As an outcome, developing a seismic resilient pipe network will take decades and require significant continued investments. However, its development will make incremental and continuous improvements in prioritized areas throughout the entirety of its implementation. In the meantime, other tasks for improving service reliability need to be undertaken in parallel.

In 2011, LADWP initiated concepts on how to implement a seismic resilient pipe network and began developing a pilot project to investigate the use of ERDIP. The pilot project is on-going and initial results are described in [12]. Initial studies show the pilot projects are making incremental progress for increasing network seismic resilience. Evaluation of an ERDIP pilot project located at the Northridge Medical Center, located at the epicenter of the 1994 Northridge earthquake, indicates this critical facility may not loose water delivery, quantity, or fire protection if a repeat of this earthquake were to occur; whereas in 1994 it lost water delivery services for approximately three days, water quantity and fire protection services for approximately 3.5 days, and water quality services for approximately ten days.

CONCLUSIONS

The Los Angeles Department of Water and Power (LADWP) is highly exposed to numerous seismic hazards. The water supply is essential to the economic vitality of the city, much of the USA and the Pacific rim. As a result the LADWP is implementing a water system seismic resilience and sustainability program with a purpose to cost-effectively improve system resilience in a manner supporting the community resilience. Some key initial steps in this program improve the Water System's firefighting water supply, fortify the imported water supplies, increase local water sources, and create a seismic resilient pipe network.

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