Case Study: Los Angeles Water Services Restoration Following the 1994 Northridge Earthquake

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SUMMARY: (10 pt)
A case study is presented to show the impacts of the 1994 Northridge earthquake on the Los Angeles Water System's ability to provide the following services: water delivery, quality, quantity, fire protection, and functionality. These are the core water services customers depend and rely upon for personal and community survival and sustainability. Water system serviceability concepts have been applied in practice, but normally only one of the five services is addressed. This study defines the five service categories, their characteristics, and illustrates how all five services can be quantified using actual water system restorations from a damaging urban earthquake. This study also identifies the importance of understanding interactions among the services during restoration.

Keywords: Water System Services, Restoration, Recovery, 1994 Northridge Earthquake

1. INTRODUCTION

Past studies of water system serviceability and restoration have focused on the system's ability to provide some level of water flow, but have not addressed how the flow relates to customer services in relation to volume, pressure, quality, or reliability of the water service. Davis (2011) categorized water system services as delivery, quality, quantity, fire protection, and functionality and showed how neglecting the provision for volume, pressure, quality, and reliability leaves a significant gap in the understanding of water system performance and customer serviceability following an earthquake. The purpose of this paper is to show the multidimensional aspects of water system service restorations by using the well documented case of the Los Angeles Water System performance during and after the 1994 Northridge earthquake. The work presented herein summarizes an on-going effort and is the first attempt to show how actual post-earthquake water system restorations are multidimensional. Impacts to the Los Angeles Water System from the 1994 earthquake are described in terms of the raw water supply, treatment, transmission, and distribution subsystems identified in Davis and O'Rourke (2011) relative to five service categories described in Table 1. Viewing water systems in the context of the five services presented herein improves our understanding of water system resilience and strengthens our capabilities for reducing disaster risks.

2. POST-EARTHQUAKE WATER SYSTEM SERVICES

Davis (2011, 2012) described three primary water system seismic performance categories: water services, life safety, and property protection. The provision of water services and the protection of life and property are arguably the most important performances a water system can achieve. This paper focuses on the water services presented in Table 1. Water systems can assess their ability to provide services at any given time following an earthquake as a ratio of the number of customers with service after the earthquake divided by the number of customers having the service on a normal basis before the earthquake. The following case study for the Los Angeles Water System uses the methods described above for estimating restoration of the five service categories.

Table 1. Water system service categories.

Service Category	Description
Water Delivery	Able to distribute water to customers, but the water delivered may not meet water quality standards (requires water purification notice), pre-disaster volumes (requires water rationing), fire flow requirements (impacting fire fighting capabilities), or pre-disaster functionality (inhibiting system operations).
Quality	Water to customers meets health standards (water purification notices removed). This includes minimum pressure requirements.
Quantity	Water flow to customers meets pre-disaster volumes (water rationing removed).
Fire Protection	Able to provide pressure and flow of suitable magnitude and duration to fight fires. In many water distribution systems the minimum pressure required for fire protection is 20 psi (140 kPa), with flow quantities varying by neighborhood.
Functionality	System restored to meet or exceed pre-disaster functionality and reliability (operational constraints resulting from the disaster have been removed/ resolved) including pressures.

3. LOS ANGELES WATER SYSTEM AND 1994 NORTHRIDGE EARTHQUAKE

The Los Angeles Department of Water and Power (LADWP) owns and operates the Los Angeles Water System and is responsible for providing all water supplies within the City of Los Angeles. In 1994, the LADWP provided water and electric service to approximately 3.6 million Los Angeles City residents and businesses in a 1,204 km^2 area. The Los Angeles Water System was created over 100 years ago as essentially a gravity system with higher elevations being served by pump-tank facilities and provides water for domestic and fire suppression use. In the 1993-94 fiscal year, ending June 30 1994, the LADWP supplied a total of 737.5 million m^3 of water. The following discussion attempts to describe the LADWP water system as it existed in 1994 and the impacts from the January 17, 1994 Northridge earthquake.

3.1. Los Angeles Water System

Figure 1 shows the major water supply and transmission facilities for the LADWP water system. The principal sources of Los Angeles water supply are from the Los Angeles Aqueduct (LAA) system and wholesale treated or untreated water purchased from the Metropolitan Water District of Southern California (MWD). The MWD obtains supplies from the Colorado River Aqueduct (CRA) and the California Aqueduct (CA). The MWD owns and operates wholesale water treatment and transmission subsystems and provides raw and treated water to member agencies. Its transmission system is considered a supply source to the LADWP. The MWD has 29 bulk water connections (2 raw, 27 treated) to supply water into the LADWP water system, and the LADWP has 3 bulk water connections to supply water into the MWD transmission system (1 raw, 2 treated). Additionally, the LADWP has 16 inter-system connections with other systems, mostly to provide the water to other systems. Ground water supply is obtained from 84 local wells having a production capacity of 12.5 m^3 per sec. A small portion of water is provided from recycled sources for non-potable uses. The LADWP also maintains several large supply reservoirs within the city that can provide over 30 million m^3 of water; in 1994 these fed directly to the transmission network by gravity. In fiscal year 1993-94 the percentages of total supply were: 35.6% LAA, 5.0% ground water, 59.2% MWD, and 0.2 recycled.

The LAA system consists of the First and Second Los Angeles Aqueducts (FLAA and SLAA, respectively) extending as far as 544 km north of Los Angeles to import water by gravity from the Owens Valley and Mono Basin in the Eastern Sierra Nevada. The FLAA was completed in 1913 with 3,050-mm-diameter riveted and welded steel pipelines, concrete sag pipes (inverted siphons), and concrete lined tunnels in and near the epicentral area of the 1994 earthquake. Completed in 1970, the SLAA consists mainly of a 1,950-mm welded steel pipeline located above ground. The FLAA and SLAA both enter the city in concrete channels and deliver water to the LAA Filtration Plant (LAAFP).

Water quality is primarily maintained with treatment plants and chlorination stations. The LAA water and bulk raw water purchased from MWD (sourced from the CA West Branch) is treated at the LAAFP. The LAAFP was built in the mid-1980’s (commissioned Nov. 1986) with a capacity of 2.27

million m^3 per day. It purifies water by ozone pre-disinfection, rapid mixing, coagulation, anthracite coal filtration, and post-chlorination. The LAAFP effluent flows into the transmission subsystem. The treated water purchased from MWD enters the LADWP transmission subsystem at various connections throughout the city. MWD treats water supplied to the LADWP at the Joseph Jensen Treatment Plant (CA West Branch water) located at the north end of the city and at the F. E. Weymouth Treatment Plant (CRA and CA East Branch water) located east of the city. MWD uses chloramine for disinfection. The LADWP disinfection is maintained through chlorine injection into the transmission subsystem at 25 chlorination stations.

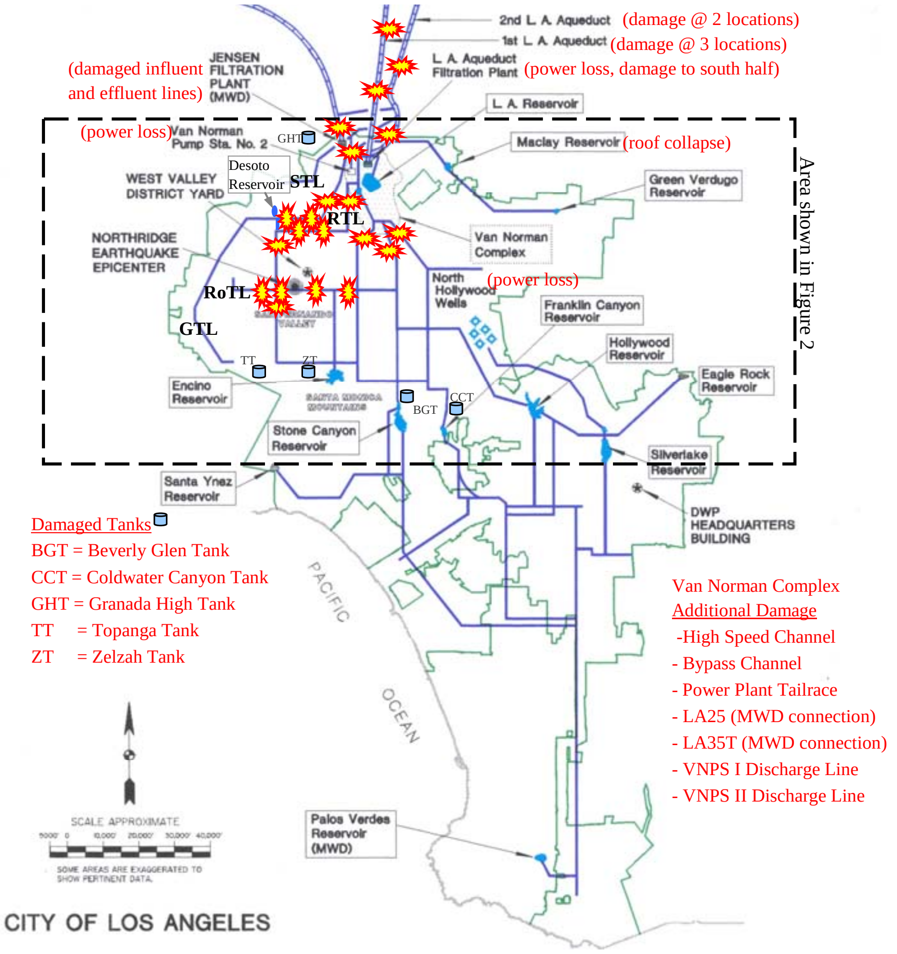

Figure 1. Los Angeles water supply and transmission subsystems showing major facilities and 1994 damages.

The LADWP transmission and distribution subsystems are made up of approximately 11,691 km of trunk and distribution pipelines ranging from 50 to 3,658 mm in diameter, having 200,000 gate valves, about 120 potable reservoirs, storage tanks, and fore bays having a total maximum capacity of 18.8 million m^3 (25 in the transmission subsystem), 260 pressure regulator stations, about 80 pumping stations (16 in the transmission subsystem), 58,300 fire hydrants, and over 712,000 service connections in 118 pressure zones. The transmission pipe consists of approximately 689 km of large diameter steel (610 to 3,658 mm) mostly riveted and welded (bell and spigot) joints, and some concrete cylinder pipe with bell and spigot joints. The distribution system consists mainly of cast iron (72%), steel (11%), ductile iron (8%), and asbestos (9%) pipelines.

3.2. Performance During 1994 Northridge Earthquake

On January 17, 1994 at 4:31 AM local time a M_W 6.7 earthquake struck below the San Fernando Valley in the northern area of Los Angeles, and caused significant damage to the Los Angeles water system. Recorded horizontal ground motion accelerations exceeded 1g and velocities reached 180 cm/s with Modified Mercalli Intensities reaching IX over large populated areas. Although there were areas of ground failure that caused pipeline damage in relatively flat or gently sloping ground containing weak clay and/or liquefied loose sands and some landslides in the steeper hillsides, ground failure was not widespread throughout the damaged region. Figure 1 identifies significant damage affecting the LADWP water supply and transmission subsystems. In summary, within the LADWP water system there were 14 repairs to the raw water supply conduits, 60 repairs to treated water transmission pipes, 1013 repairs to distribution pipe, over 200 service connection repairs, 7 damaged reservoirs, temporary suspension of half the treatment plant service, and other incidental damage. Total LADWP water system repair costs were $41 million. McReynolds and Simmons (1995) and Lund et al. (2005) summarized the damage and water outage areas in Los Angeles. Power was lost immediately throughout the city, and was returned within 27 hours. Most telecommunications were inoperable for several hours after the earthquake. Transportation was seriously disrupted due to loss of important transportation corridors.

The three aqueducts (FLAA, SLAA, and CA) supplying northern Los Angeles were cut off by ruptured pipelines. Although the main lines for the CA and CRA were not damaged, damage was sustained in the MWD supply conduits transporting CA water into Los Angeles. There was no damage to MWD lines supplying CRA water. All LADWP ground water pumping was lost due to power outage, and there were no backup generators for ground water pumps. Two MWD connections (treated LA25, raw LA35T) to the LADWP system were damaged. Additional damage reduced the MWD ability to transport water through their East Valley Feeder Line to aid in the LADWP system service restoration. There was no damage affecting operations of the large in-city storage reservoirs.

The LAAFP sustained minor damage from ground settlement around the plant, leaks at construction and expansion joints, and breaks in plastic chlorine solution lines. Ground settlement damaged power conduits inhibiting operation of the south half of the LAAFP. The LAAFP north half could not operate immediately after the earthquake due to power loss. Chlorination stations performed well, without damage, due to previously completed seismic retrofits.

The transmission subsystem damage was mainly limited to the transmission pipeline network and consisted of compression or tension deformation at the bell and spigot joints, damage at mechanical couplings, and damage at some riveted joints. The greatest disruption requiring the longest repair times occurred in ground failure zones. As seen in Fig. 1, all major transmission lines in northern Los Angeles were damaged. The Granada Trunk Line (GTL) was the most seriously damaged, with 28 breaks and locations of deformation. The next most seriously damaged pipeline was the Roscoe Trunk Line (RoTL) with about 15 breaks. The Rinaldi Trunk Line (RTL) was damaged at 6 locations, LA25 pipe connecting to MWD at 5 locations, Van Norman Pumping Station (VNPS) Discharge Lines at 4 locations, and 8 other trunk lines at one or two locations. Not all damage disrupted the transmission lines. Some pipe deformation did not result in leaks. Moreover, some leaks at damaged steel joints or mechanical couplings were small enough to allow the pipe to remain pressurized and flow water.

The largest transmission system pumping station, VNPS No. 2, is not equipped with backup power generation due to its excessive size, and as a result lost the ability to pump water to a significant population located at high elevations in the northeast and northwest areas of Los Angeles.

The distribution system sustained damage to pipelines and tanks. Pumping stations performed well due to prior seismic retrofits; there was only minor damage to enclosures housing the facilities. Seven distribution tanks were damaged, 5 severe enough to be removed from service for an extended time (Brown et al., 1995), one in the hills on the north end of Fig. 1 (Granada High Tank) and four in the Santa Monica Mountains in the middle of Fig. 1 (Zelzah, Beverly Glen, and Topanga, Coldwater Canyon Tanks). These tanks required extensive post-earthquake work. Most of the distribution tanks and reservoirs in the hills surrounding the San Fernando Valley drained soon after the earthquake either due to direct damages or from leaking through the damaged pipe network. At least seventeen service zones were inhibited from distributing water due to the damage.

Fig. 2 shows the region that lost all delivery service in the northern area of Los Angeles (refer to Fig. 1

to identify representative area of Fig. 2; covering about 557 km^2). The region in Fig. 2 lost water delivery services mainly due to damage in the transmission and distribution subsystems. Los Angeles did not lose delivery services as a direct result of supply subsystem damage; there were sufficient supply redundancies to maintain transmission, if the transmission systems were able to convey water. However, the area marked as "D-A" in Fig. 2 did lose delivery services as a direct result of power service loss to groundwater wells in the water supply subsystem and a critical pump station. One relatively small area south of the Fig. 2 map lost water services for up to 8 hours due to power loss to a pump station. System redundancy was a significant factor in allowing much of Los Angeles to maintain water delivery, as well as aiding in restoration. The majority of Los Angeles can receive water from several supply conduits. Even though the majority of water supply to Los Angeles was immediately cut off by the earthquake, water continued to flow to damaged areas and to those areas not damaged by the earthquake from the many large storage reservoirs located in the city, as shown in Fig. 1, and from MWD via the CRA. This allowed large areas throughout Los Angeles to maintain delivery services. Because this earthquake occurred in the winter, demands were lower, which helped to maintain quantity services in many of the undamaged areas.

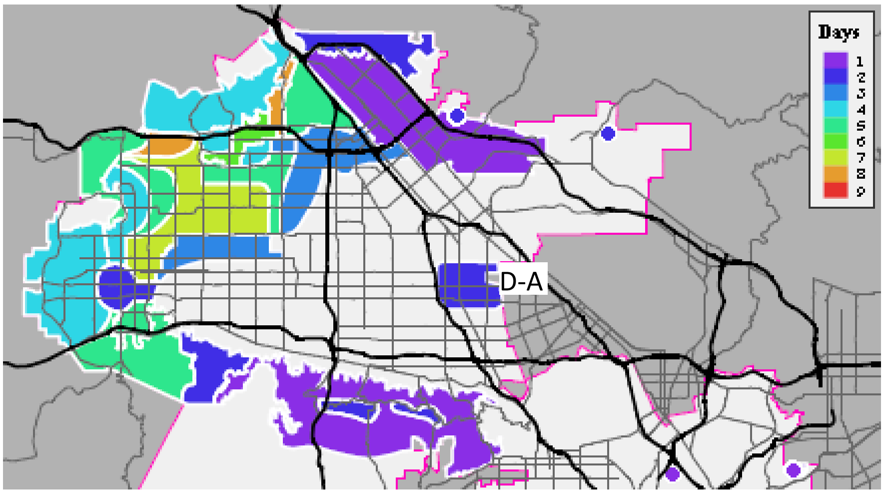

Figure 2. Areas without water delivery service in Los Angeles following the 1994 Northridge Earthquake.

4. WATER SYSTEM RESTORATION FOLLOWING NORTHRIDGE EARTHQUAKE

Figure 3 shows the water service restoration curves for the LADWP following the 1994 Northridge earthquake. As seen in Fig. 3 the delivery service dropped to about 78% shortly after the earthquake due to water leaking from broken pipes, draining several tanks, until the total losses resulted in the area shown in Fig. 2. Due to LADWP's ability to contain the impacted area and initiate restorations rapidly, the delivery services increased soon after the earthquake. The quantity and fire protection services dropped to a low of about 72% at some time on January 17, 1994. Figure 3 plots the accumulation of all service losses and restoration for each day. The quality service dropped immediately to zero because a boil-water notice was issued across the entire city within 3 hours after the earthquake, which was lifted within defined areas starting after one day as shown in Fig. 3. The functionality services initially dropped to about 30% and began to improve soon thereafter as restorations were undertaken. The water delivery, quantity, fire protection, and quality curves are calculated from recorded data. The functional service curve is estimated. As shown in Fig. 3, the water delivery service was restored to 100% at about 7 days, quantity and fire services at about 8 days, and quality service at 12 days after the earthquake. The remainder of this section describes the strategies and activities undertaken that directly affect the restoration curve shapes in Fig. 3.

The LADWP established restoration goals as follows: (1) restore water delivery service to the most people as quickly as possible, (2) lift the boil-water notice (currently known as a tap water purification notice) as soon as possible, (3) do not interrupt water service to an area once supply has been returned, and (4) do not degrade water quality in an area once the boil-water notice has been lifted (McReynolds and Simmons, 1995).

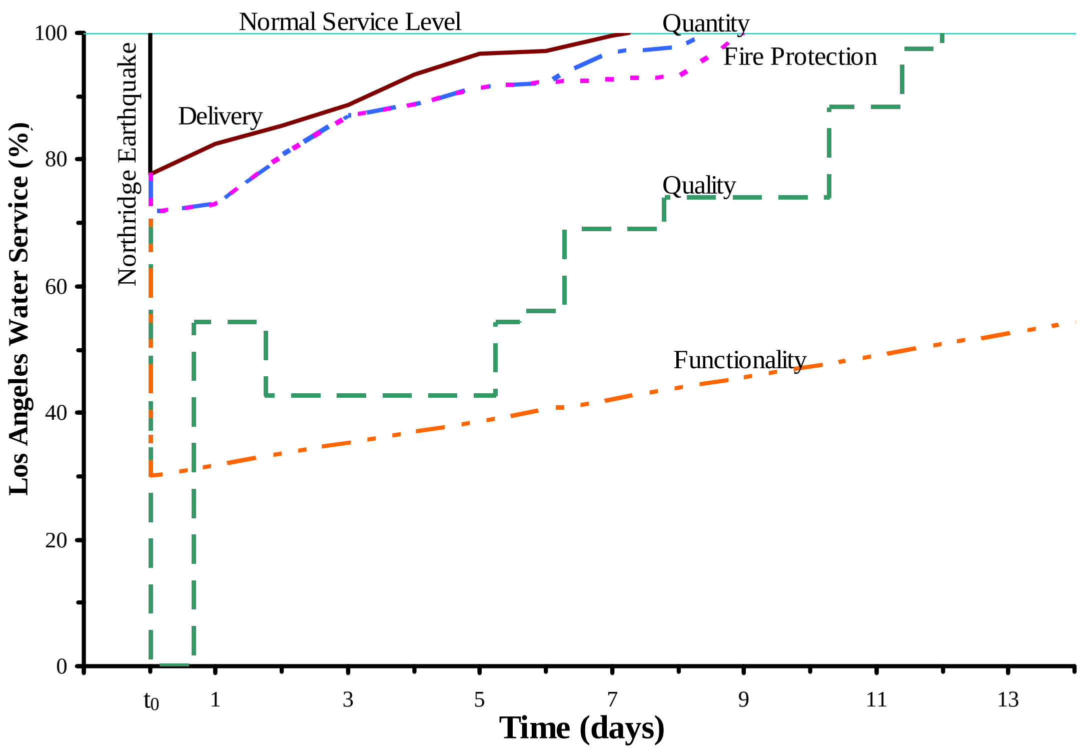

Figure 3. Los Angeles water system service restorations following the 1994 Northridge earthquake.

To initiate restoration, the LADWP enacted their emergency response plans. Within hours crews were able to assess and report on the LAAFP, chlorine treatment facilities, and major storage tanks. A field command center was established at the West Valley District yard, shown in Fig. 1. Crews from four other district yards and from the Mojave yard along the LAA were dispatched to aid in repairs. Over the days following the earthquake mutual aid also came from neighboring utilities and the East Bay Municipal Utility District in Oakland, California.

Booster pump stations and ground water pumps without backup generation could not function because of the power outage. As power was restored, these pumps came back on line and began restoring delivery services to customers. For the most part, this is how the delivery services shown in Fig. 1 were restored 1 day after the earthquake. The large area in the north east corner of Fig. 1 was restored with water delivery by starting emergency generators for the large VNPS No. 1 and partially isolating damage on the discharge line. Power loss was the only significant external lifeline interdependency that disrupted water delivery services. Loss of electricity also affected the remote monitoring and control system for the water distribution network.

In addition to the power service restoration, water delivery services were restored to the many different areas shown in Fig. 2 over the 8 different dates (Jan. 17 to Jan. 24) using a variety of strategies, including:

- Emergency power generation to run pumps,
- Utilizing alternate and redundant supply sources (LADWP and MWD),
- Isolating certain supply sources to feed damaged areas and others to feed undamaged areas,
- Isolating damaged transmission pipes and distribution mains to keep the system from draining,
- Isolating damaged tanks to keep system from draining locally,
- Utilizing redundant transmission lines and connections,
- Providing water supplies at lower than normal pressures (by gravity from lower pressure zones having water to higher pressure zones without water; flooding the network),
- Providing water supplies at higher than normal pressures (by gravity from higher pressure zones having water to lower pressure zones without water),
- Supplying water from higher to lower pressure zones at normal pressure using regulating

stations to break pressure head,
- Intra-system pumping using fire department pumper trucks to lift water from lower pressure zones having supply to higher pressure zones without supply; using fire hydrants designed for this purpose, and
- Repairing damage to trunk lines and mains.

Restoration for some areas may have only required one of the above listed strategies. Other areas required several strategies in combination. Of the numerous locations of trunk line damage, only about 8 required repairs to completely restore delivery, in addition to several key distribution main repairs. Reducing the number of repairs required for delivery was accomplished by utilizing the supply and transmission isolation capabilities and redundancies available within the Los Angeles Water System while allowing some lesser damaged trunk lines to remain in service as they continued to leak. The remaining pipe repairs were completed in the weeks and months following delivery restoration.

As previously noted, the loss of imported water supply lines was not a factor in the total delivery service losses. The restoration of imported water supply, however, became critical around January 20, 1994. Without one of the critical supply lines being restored on this date, additional delivery services could have been lost, involving at least a mandated reduction in quantity services to areas larger than those shown in Fig. 4. Fortunately, some additional CA West branch water supply from the MWD LA35 raw water connection was restored at 4 days.

The water delivery and quantity services maps in Figs. 2 and 4, respectively, represent close approximations where customers lost the services shortly after the earthquake, as defined in Table 1. The maps are not precise. Because of the many actions taken after the earthquake, system complexity, and number of people involved, it is not possible to identify exactly all areas and times for the respective service restorations. Nevertheless, the maps provide a reasonable demarcation of the total area of service losses, showing the locations and times of water service restorations on a regional scale. The maps do not incorporate detailed and localized service losses that may have impacted only a few service connections due to nearby distribution pipe damages; a few service losses (estimated to be less than 1%) may extend beyond the boundaries of Figs. 2 and 4 and for several days or weeks beyond that indicated in Fig. 3.

The regional quantity and fire protection service losses were primarily related to the losses in delivery services. Except for two areas in the east San Fernando Valley, identified in Fig. 4 as Q-A and Q-B, the total area of lost water quantity and fire services was contained throughout the city within about one day, and possibly up to 36 hours in some areas. As noted in Fig. 4, areas Q-A and Q-B were contained respectively within 48 and 72 hours; the dashed contours estimate the rate of continued quantity and fire protection services losses. The large areas throughout Los Angeles that did not loose quantity and fire protection services were maintained in the same manner as described for maintaining delivery services in the same areas.

All areas except for the area marked in Fig. 4 as F-A are expected to have had fire protection services restored at or about the same time as the quantity services. Therefore, Fig. 4 is also used herein to represent fire protection service restoration. The F-A area in Fig. 4 had quantity services restored on day 7, but the restoration of fire protection services were delayed until day 9. As a result, the descriptions herein for quantity services also apply to fire protection services, except for area F-A. The reason that area F-A fire protection services were not able to be restored at the same time as quantity services is because the delivery services were accomplished with a limited number of trunk line repairs. The critical GTL and RTL transmission lines were not providing additional water, requiring the Susana Trunk Line (STL), shown at the top of Fig. 1, to provide water to the majority of the San Fernando Valley in addition to an emergency connection to MWD that was providing only a very low flow compared to normal demands. The water volumes were restricted because they had to pass from the 1,372 mm diameter STL through 762 and 406 mm diameter pipes in order to supply the areas normally supplied by the GTL and RTL. As a result, quantity services could be restored in F-A once sufficient pressures were restored but due to limited volumes fire protection services were not restored until the south end of the GTL was returned to service on January 25, 1994. The area operated on a very small margin until January 29, 1994 when the GTL was able to resume water supplies to the area from its sources in the Van Norman Complex. The customers had a perception that water system functioning was back to normal in area F-A at day 7 because the earthquake occurred in the winter when there is normally low demand and no rationing or conservation was required. In reality, if a significant fire broke out in area F-A rationing would likely have been mandated to allow sufficient volume and flow for fire fighters to protect public safety. The rationing probably would have reduced quantity services.

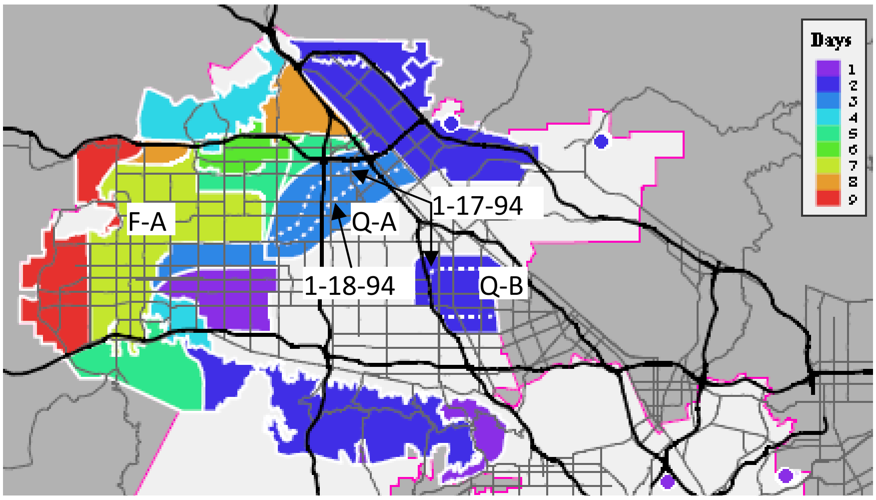

Figure 4. Areas without water quantity service in Los Angeles following the 1994 Northridge Earthquake.

Power service loss and restoration had a significant influence on quantity service loss and restoration, similar to that described for the delivery services. In many locations where electrical power service restoration was a factor, the quantity and fire protection services were restored at about the same time as the delivery services. Exceptions apply to areas where emergency pump generator units were used to restore delivery, but unable to provide sufficient flow to restore quantity and fire protection services. In addition to the power service restoration, water quantity and fire protection services were restored to the many different areas shown in Fig. 4 over the 9 different dates (Jan. 17 to Jan. 25) using the same strategies described for water delivery restorations. The spatial and temporal differences are mostly a function of the difference in ability to provide water for delivery as well as the ability to provide sufficient volumes and pressures to meet normal service expectations, which do not always coincide at the same time or location.

Figure 5 shows the sequential restoration of quality services. As shown in Fig. 3, the quality service remained at zero for nearly one day while the boil-water notice remained in place across the entire city. The California Department of Public Health (CDPH) provided criteria for lifting boil water notices as: (1) earthquake leaks and breaks repaired, (2) chlorine residuals of 2 mg/l, and (3) two consecutive negative coliform bacteria tests. Testing for an area took at least one day. Approval by CDPH was obtained before boil-water notices were lifted. Communicating boundaries of the boil-water areas to the public was a major challenge.

The city-wide boil-water notice was issued as a precautionary measure until the public health risks could be assessed in various parts of Los Angeles. After evaluating chlorine residuals and consulting with CDPH the boil-water notice was lifted on the evening of January 17 for approximately half of the city, leaving only the area (approximately 557 km^2) shown in Fig. 5a with the boil water order. On the following night, as shown in Fig. 5b, the boil-water notification was reinstated in a portion of west Los Angeles after learning there was greater damage to the water and sewer pipeline networks, and thus public health risks, than initially understood. The drop in quality service shown in Fig. 3 lasting for about 3 days corresponds with the increased highlighted area shown in Fig. 5b. The remainder of quality restoration was primarily due to disinfecting the broken pipe network. The quality restoration was completely restored on January 28 but due to communication delays with the public it was not fully advertised until the morning of January 29, 1994, 12 days after the earthquake. During those 12 days, the notices were lifted nearly sequentially in the seven areas shown in Fig. 5 (Figs. 5a and 5c cover the same area) as water pressure was restored and sampling indicated that water was safe.

The LAAFP was immediately affected by power failure, and it took about 4 hours to put the standby generator into service (McReynolds and Simmons, 1995). Although there was no inflow due to the aqueducts damage, the LAAFP could have treated 1.14 million m^3 per day (half capacity). The LAAFP was not operated until January 20, 1994, about 4 days after the earthquake. There was no water quality service impact as a result of damages to any treatment facility.

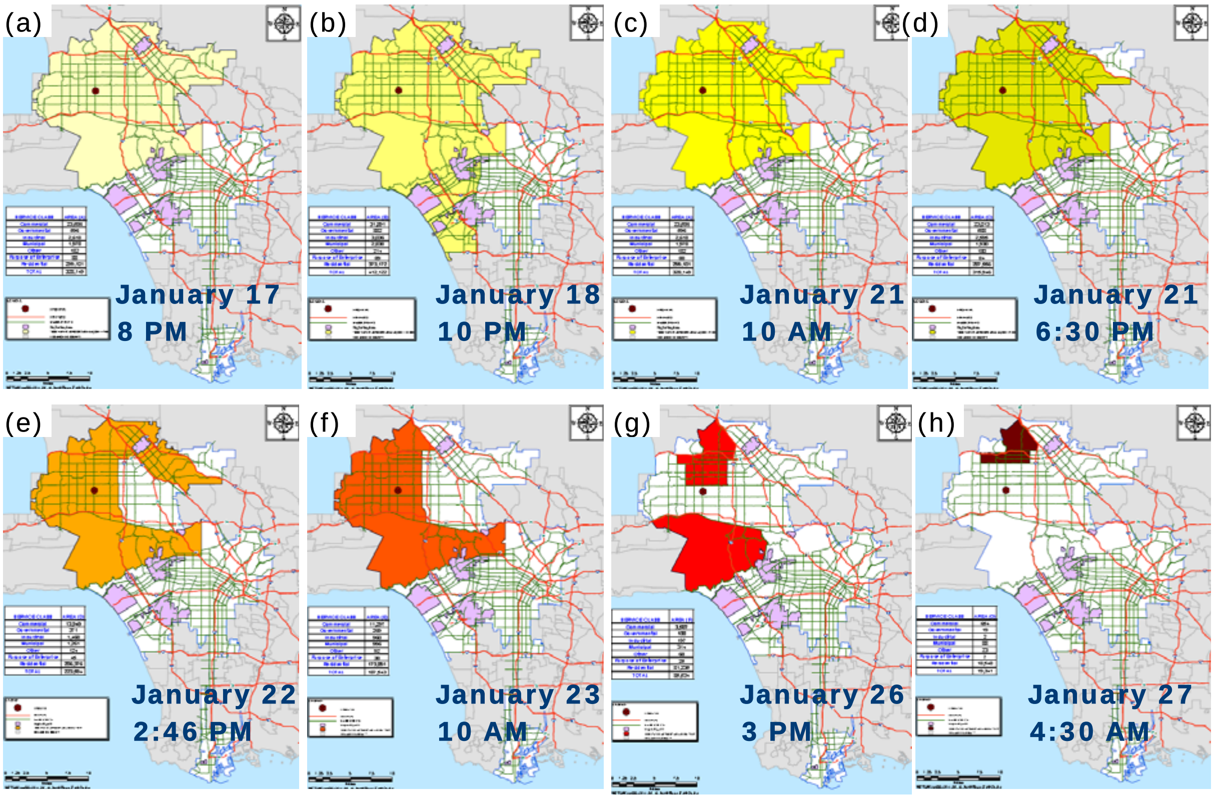

Figure 5. Areas without water quality services in Los Angeles following the 1994 Northridge Earthquake.

Issuing the boil-water notice enabled LADWP to return many trunk lines and storage tanks to service as soon as they were repaired, thereby rapidly restoring water delivery, quantity, and fire protection services to many areas affected by the earthquake. Chlorine doses were increased to 3 mg/l following the earthquake. Agreements were made with MWD within 8 hours to switch from chloramine disinfection to free chlorine also using 3 mg/l doses at the 2 treatment plants that delivered water to the LADWP earthquake affected service areas, thus allowing LADWP to take MWD water without disinfectant compatibility problems (McReynolds and Simmons, 1995). After water quality restorations were completed, the damage repair process took longer than anticipated due to the need to disinfect the pipes and tanks thoroughly before putting them back into service. The boil water notification identifies the customer as temporarily responsible for disinfecting water. When the notice was lifted, the LADWP resumed responsibility for complete disinfection. For this earthquake, the water quality restoration did not have a significant impact on regional water delivery, quantity, or fire protection service restorations, but it did have a short-term impact on functionality service restoration.

Figure 3 shows the functionality service dropped to about 30% but was restored over time as the supply and transmission pipelines were repaired. The functionality service is shown in Fig. 3 to have a relatively linear increase over the 13-day period following the earthquake. The percent restoration values for the functionality services presented here are approximations. Many temporary repairs and rerouting around damage were made within the first week to restore and maintain delivery, quality, quantity, and fire protection services, but this did not significantly increase the functionality service because of the many system vulnerabilities that remained until permanent repairs were completed.

In addition, repairs to the LAAFP transmission and distribution pipeline networks and damaged tanks continued for months even though system-wide water delivery, quality, quantity, and fire protection services were restored within days after the earthquake, as shown in Figs. 2 through 5. Some damage, which reduced overall system reliability without impeding the other services, were repaired over a period of years. As an example, the severely damaged concrete channels that bring LAA water to the LAAFP were initially repaired as a temporary measure to return MWD raw water supply to the city at day 4. The repairs were of such temporary nature there were concerns if they would hold, fortunately they did, but in the meantime the water system network operated with much less reliability. The channels were removed from service for additional repairs at least 4 times over the next several years, each increasing reliability. There were long periods of incremental restoration improvements to different components until the system functionality returned to normal at about 4.5 to 5 years. Several improvements were made to the system as a direct result of knowledge gained and repairs made following the 1994 earthquake, increasing reliability above the pre-earthquake levels after 6 years.

7. CONCLUSIONS

The Los Angeles Water System restoration case study from the 1994 Northridge earthquake identifies the multidimensional aspects of water service restorations. Although Figs. 2 and 4 show similarities in the overall service outage areas, there are some significant differences in the temporal and spatial restoration components. As previously noted for area F-A in Fig. 4, the fire protection service restoration does not completely correlate with the quantity service restoration. Comparisons of Fig. 5 with Figs. 2 and 4 shows that quality service restoration was not completed spatially or temporally in accordance with restoration trends for the water delivery and quantity services. Thus, the actual performance of a major water system during and following a significant earthquake shows that water service restoration is multidimensional and that restoration of one water service does not generally coincide with the restoration of other services. Davis (2011, 2012) shows how the Los Angeles Water System has completely different service restorations following a great M7.8 earthquake scenario on the San Andreas Fault, thus showing that water systems may perform very differently in response to different earthquakes. The analysis presented herein indicates a strong interaction among infrastructure repairs and water system operations, quality, and control. The resumption of water flow to certain portions of a water system does not mean that the restored water is useful for public health, safety, businesses or industrial use, etc. To improve community resilience, a greater understanding of the multidimensional aspects of water system, and other lifeline system, post-disaster restorations is required. To quantify the parameters that influence restoration, additional case studies are needed of lifeline systems affected by earthquakes.

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