# Los Angeles water supply impacts from a M7.8 San Andreas Fault earthquake scenario

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## ABSTRACT

The City of Los Angeles, as well as the entire Southern California population of over 22 million people, is highly dependent on water imported through the Los Angeles, California and Colorado River Aqueducts. The San Andreas Fault poses one of the greatest risks to these critical water supply lines; all three aqueducts cross the San Andreas Fault. A preliminary review of potential damage to these three major aqueducts in response to a magnitude 7.8 earthquake scenario on the San Andreas Fault was performed. The results indicate repairs to restore flow into each aqueduct may take a year or more. Local storage is estimated to last approximately 6 months with significant rationing. As a result, there may be inadequate storage to supply the local population during the length of time it takes to repair the aqueducts. Inadequate water storage has significant health, safety and economic impacts on the Southern California region.

This investigation identifies the need for a more thorough evaluation of aqueduct restoration times. In addition, mitigation measures for additional local storage and more rapid aqueduct restoration must be implemented.

**Key words** | aqueducts, business interruption, earthquake restoration, emergency water supply, San Andreas Fault, shakeout scenario

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## INTRODUCTION

The Southern California population, exceeding 22 million people, is highly dependent on water imported through three major aqueduct systems, the California Aqueduct, Colorado River Aqueduct (CRA) and Los Angeles Aqueducts (LAA). Combined, these three aqueduct systems provide at least 70% of the average domestic water supply to Southern California, the remaining supplies coming primarily from local ground water. Agencies receiving these aqueduct supplies distribute water to more than 90% of the population. Thus, loss of these water supplies can have significant impacts on public health and safety, and the economy.

Droughts and earthquakes pose the greatest known risks to Southern California water supplies. Multi-year drought is the driver behind most water planning activities and is managed regionally, primarily through large storage projects, conservation and reclamation (MWD 2005). The greatest regional earthquake threat comes from the San Andreas Fault. The San Andreas Fault runs nearly the entire length of California (north to south) and is capable of producing some of the largest crustal earthquakes in the world. Water supply management in relation to the San Andreas Fault earthquake risk is not understood as well as that for drought. This is a critical issue considering: (1) a great San Andreas Fault earthquake recurs on average every 150 years and it has been over 150 years since the last earthquake, and over 300 years since the southernmost segments of the fault have slipped; and (2) all three major water supply aqueducts (California Aqueduct, CRA and LAA) cross the San Andreas Fault. Regional water supplies are managed assuming all three major water supply aqueducts are restored within 6 months after a major

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earthquake, provided adequate rationing is implemented for that period (MWD 2005), but the basis for this restoration time is not well developed.

A magnitude (M) 7.8 earthquake scenario on the southern San Andreas Fault was recently prepared (Jones *et al.* 2008) to gain a better understanding of how such an event may affect critical infrastructure, including water supply systems, and identify the physical, social and economic consequences of a major earthquake in Southern California. This scenario provides a realistic description of possible fault displacement and shaking throughout Southern California, and is useful for performing more detailed evaluations of water supply impacts from a San Andreas Fault event. The purpose of this paper is to present an initial evaluation, using the information presented for the M7.8 San Andreas Fault scenario, to understand expected impacts on the major water supply aqueducts and a timeframe within which they may realistically be expected to return to service. Results of this study identify areas where further investigation is needed regarding aqueduct damage and restoration, and provide a better understanding of the risks posed to Southern California by the San Andreas Fault. Additionally, this study is applicable to understanding how great events affect highly populated urban areas in other parts of the world.

## METHODS

### San Andreas Fault scenario

A M7.8 earthquake scenario on the southern San Andreas Fault was recently developed for use in the Great Southern California ShakeOut (Jones *et al.* 2008), the largest earthquake exercise ever undertaken in the United States (Cox & Pierce 2008). Hereafter, this scenario is referred to as the ShakeOut scenario. The scenario development is based on a plausible event and resulting impacts, not a worst case scenario, and accomplished through collaboration of many contributors coordinated by the United States Geological Survey (Jones *et al.* 2008). Figure 1 shows the Southern California region, ruptured portion of the San Andreas Fault, and shaking intensity for this scenario. The M7.8 earthquake has a hypothesized epicentre at the Salton Sea, near the southernmost end of the San Andreas Fault, and ruptures 300 km north to Lake Hughes. The scenario event and resulting impacts described

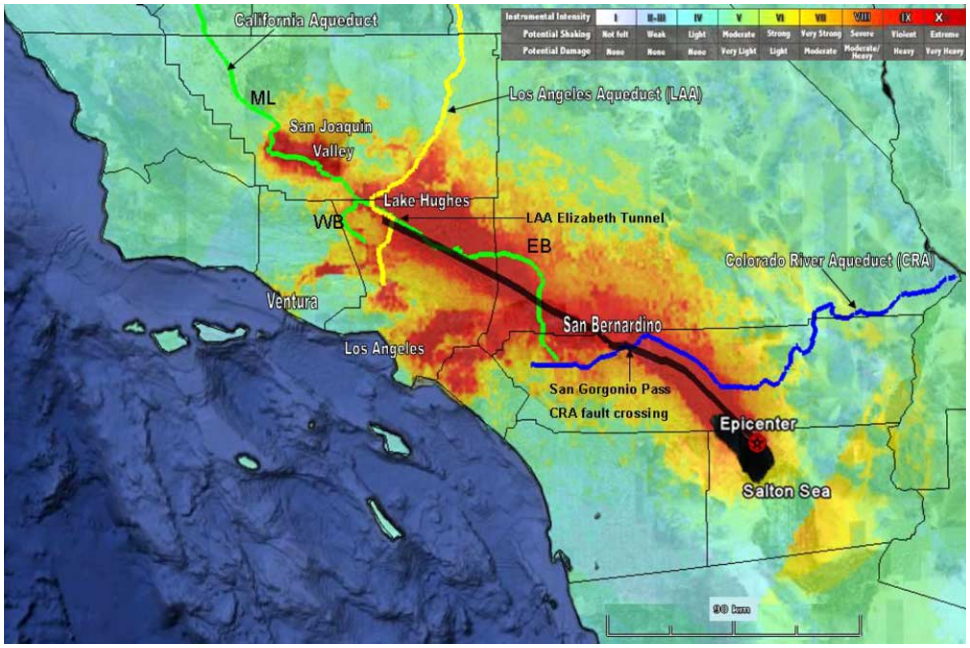

**Figure 1** | Southern California region showing the ShakeOut scenario epicentre (star), fault rupture (heavy line), shaking intensity (modified from USGS, 2010), Los Angeles Aqueduct (LAA), Colorado River Aqueduct (CRA), and California Aqueduct (ML, EB and WB are the California Aqueduct Main Line, East Branch and West Branch, respectively). The full colour version of all figures in this paper can be accessed by subscribers online at http://www.iwaponline.com/jws/toc.htm

in this section are summarized from more detailed reports presented in Jones *et al.* (2008).

The San Andreas is primarily a strike-slip fault moving with right-lateral motion; however, there are portions in the vicinity of San Bernardino that experience significant compression and uplift. Fault rupture displacements exceed 9 m and large ground motions result, especially near the northern end of the rupture where directivity effects cause large velocity pulses. Intense shaking is experienced over a large area of Southern California affecting over 22 million people. The Los Angeles and Ventura sedimentary basins trap and amplify seismic waves leading to several minutes of shaking. Ground failures from landslides, lurching, liquefaction and lateral spreading result in many locations in the severely shaken areas.

Earthquake-induced shaking from the main shock causes significant damage and disruption throughout Southern California. Millions of buildings are unusable as a result of structural and non-structural damage. Fault displacements disrupt many critical lifelines including major highways, railroads, power transmission, oil and natural gas, fibre optic communication and water supply crossing the fault, while shaking and other ground failures cause additional widespread damage to lifelines throughout Southern California. Transportation corridors and water supplies are severely disrupted for long periods of time. Hundreds of water systems, large and small, are damaged by the earthquake, disrupting the supply and distribution to customers and the ability to fight fires. An estimated 1.5 million people are without potable water immediately after the earthquake, and after 90 days over 180,000 are still without potable water because of distribution system damages. Approximately 1,600 ignitions are estimated, some resulting in large fires causing extensive damage after burning for a week in highly urbanized and populated areas.

The ShakeOut scenario estimates approximately 50,000 injuries, 750 requiring special treatment, and approximately 1,800 deaths. Over half of the fatalities and special treatment victims result from fire. This scenario earthquake causes over US$210 billion in economic losses, with slightly over half coming from property damage and the majority of the remainder from business interruption. Fire causes over $87 billion in total losses (over 40% of all economic losses). Over half of the business interruption losses (approximately a quarter of all economic losses) come from water supply and distribution-related problems, assuming the aqueducts are fully restored to service within 6 months. The combination of fire and water account for over $140 billion in economic loss, approximately two-thirds of the total loss. Considering the relation between fire damage and water system damage, the earthquake effects on water supply and distribution systems have possibly the greatest impact of all. Large aftershocks, in the range of M6.4 to M7.7, cause additional damage, further compounding the disaster and increasing water supply and distribution impacts. Restoration and recovery initially depends on the ability of local distribution systems to operate. Long-term regional recovery depends on the ability to restore imported water supplies. The remainder of this study primarily focuses on the aqueduct systems that import critical domestic water supplies. Davis (2009) and Romero *et al.* (2009, 2010) present evaluation results of the Los Angeles distribution system performance during the ShakeOut scenario. Davis & O'Rourke (2011) describe regional water system performances.

## Scenario impacts on raw water supply systems

Figures 1 and 2 show the three aqueducts providing the greatest raw water supply for domestic and industrial use in Southern California: the LAA system, described in later

**Figure 2** | California map showing major Los Angeles area water supply sources and the San Andreas Fault. The full colour version of all figures in this paper can be accessed by subscribers online at http://www.iwaponline.com/jws/toc.htm

sections, owned and operated by the City of Los Angeles Department of Water and Power (LADWP); the CRA, owned and operated by the Metropolitan Water District of Southern California (MWD); and the California Aqueduct, owned and operated by the California Department of Water Resources, which was constructed as part of the California State Water Project (SWP). The MWD is a state-created regional wholesaler that receives water from the SWP. In addition to the CRA, MWD owns and operates a wholesale water transmission system and provides raw and treated water to distribution agencies, but does not distribute water to industrial or domestic customers. The LADWP obtains water through these three aqueducts and from local groundwater sources. Other aqueducts import water to Southern California cross the San Andreas Fault, but will not be addressed in this study. Additionally, many other major water supply conduits transport raw and treated water throughout Southern California, which may be classified as aqueducts, but are not discussed herein.

As shown in Figures 1 and 2, the three aqueducts cross the San Andreas Fault and are damaged by fault movements ranging from 0.04 m to 4.9 m. The largest movements occur on the San Andreas main trace and smaller movements are distributed over other parallel faults and splays within the San Andreas Fault zone. A review by the author estimates at least 18 fault displacements offset the aqueducts; this estimate differs slightly from that provided by Jones *et al.* (2008, App. D). The aqueducts are also affected by ground shaking and permanent ground deformations. The following subsections summarize the major aqueduct features and potential aqueduct damages: for the aqueduct locations identified refer to National Park Service (1998, 2001) and California Department of Water Resources (2010).

## Los Angeles Aqueducts

The Los Angeles Aqueduct system comprises the 375 km long First Los Angeles Aqueduct (FLAA) completed in 1913 and the 220 km long Second Los Angeles Aqueduct (SLAA) completed in 1970. Both aqueducts bring an annual average of 370 million $m^3$ (300,000 acre-feet) of water to Los Angeles from the eastern Sierra Nevada. Water flows by gravity; no pumping is used along the LAA. The FLAA approaches the San Andreas Fault from the northeast in a concrete lined box conduit, and parallels the fault in a southerly direction for approximately 20 km. Figure 3(a) shows a photograph of typical box conduit construction in the Mojave Desert. The SLAA approaches from the north in a welded steel pipeline. The FLAA and SLAA flows are combined at the Fairmont Reservoir, east of the fault, and pass through the San Andreas Fault in the 8.3 km long, 2.9 m wide concrete-lined Elizabeth Tunnel. Figure 3(b) shows a photograph of tunnel construction. Southwest of the fault both aqueducts connect with Bouquet Canyon Reservoir and remain combined for 14 km and flow through a series of above-ground pipes and tunnels, traversing steep mountainous terrain, and two power plants, after which they split. From the split the FLAA flows through tunnels and riveted steel and concrete pipes while the SLAA flows through welded steel pipe, delivering water to Los Angeles.

The ShakeOut scenario estimates 3.3 m of horizontal strike-slip fault movement through the Elizabeth Tunnel.

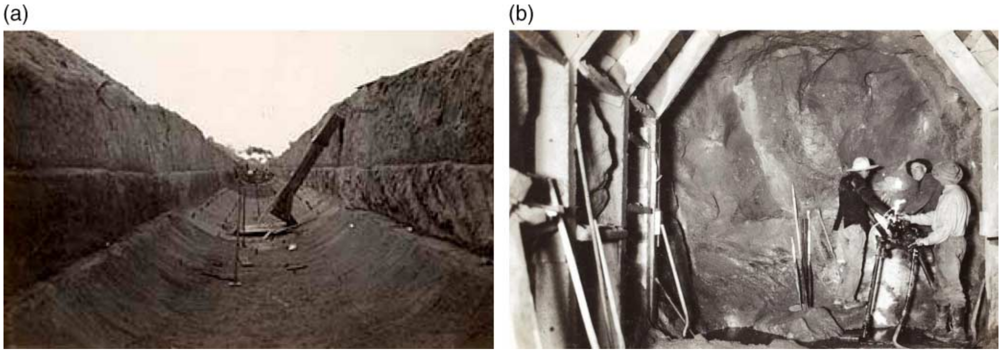

**Figure 3** | First Los Angeles Aqueduct: (a) construction of a box conduit north and east of San Andreas Fault; (b) construction of Elizabeth tunnel passing through the San Andreas Fault. The full colour version of all figures in this paper can be accessed by subscribers online at http://www.iwaponline.com/jws/toc.htm

All this shearing movement is likely to occur on the main fault trace, with little partitioning of movement along other nearby parallel faults within the San Andreas Fault zone. The tunnel crosses nearly perpendicular to the fault, thus these movements completely close off the tunnel. In addition, the tunnel is severely shaken by strong near-source ground motions. The combination of strong shaking and fault displacements causes severe damage to the tunnel liner on both sides of the fault. Some collapse may result, leaving concrete and spalling rock debris in the tunnel. Groundwater flows into the tunnel. The fault shearing motion is associated with vertical uplift and tilting, evidenced by the local topography, which dissipates with distance from the trace; this movement will reduce LAA flow capacity.

The box conduit and pipe of the FLAA and SLAA north of the Elizabeth tunnel is severely shaken by strong near-source ground motions. The strong shaking causes instabilities of the vertically excavated walls shown in Figure 3(a), especially in weak soils and rock and areas of land sliding. Both aqueducts are subjected to liquefaction and lateral ground spreading in areas of saturated, loose sandy soils and ground lurching in areas of weak clays. The pipes and tunnels southwest of the faults experience damage from landslides. At some locations, pipes experience some failures from inertial forces resulting from strong shaking. These described effects cause a wide variety of damages to the FLAA and SLAA at numerous locations extending long distances on each side of the fault.

## California Aqueduct

The California Aqueduct was completed in the early 1970s and transports an average of about 49 billion $m^3$ (40 million acre-feet) of SWP water per year to Southern California from the Sacramento-San Joaquin Delta in Northern California. Four pumping stations lift the water through 16 km of tunnels and shafts over the Tehachapi Mountains as it proceeds to Southern California. As shown in Figure 2, the 710 km long California Aqueduct parallels the San Andreas Fault for much of its length, with several crossings. North of Los Angeles, the California Aqueduct splits into the West Branch and the East Branch. The fault rupture in Figure 1 stops south of the West Branch; only the East Branch suffers damage from the main shock fault rupture. The West Branch is crossed by the San Andreas Fault at Quail Lake, a natural lake enlarged to safely move water across the fault. Near the split a pumping station lifts the West Branch water into Quail Lake. From Quail Lake water is transported through canal and pipe to Pyramid Lake then through a tunnel to Castaic Lake. Power is generated in plants at the entrance to Pyramid and Castaic Lakes.

From Castaic Lake the water is taken by SWP contractors, including MWD, who deliver it to Los Angeles and other cities through a series of pipes and tunnels. The East Branch flows mostly in an open channel southeasterly, paralleling and crossing the San Andreas Fault, to Silverwood Lake. Power is generated near the beginning of the East Branch. One pumping station is used about midway along the East Branch and power is generated prior to entering Silverwood Lake. Silverwood Lake is located east of the San Andreas Fault. From Silverwood Lake water is discharged into penstocks, which pass though the San Bernardino Mountains, and is delivered to Devil Canyon power plant and its two afterbays, near the City of San Bernardino. The San Andreas Fault passes through the Devil Canyon power plant and afterbay site. The Santa Ana Pipeline then takes water 45 km underground to Lake Perris, the southernmost SWP facility. The East Branch delivers water to SWP contractors on each side of the San Andreas Fault at various points along its length.

In total the California Aqueduct is estimated to be subjected to at least 13–17 ShakeOut scenario fault offsets, with movements ranging from 0.04 m up to 4.9 m; these estimates are made by the author using data provided in Jones *et al.* (2008). Additionally, tectonic movements uplift and rotate the channel along portions paralleling the rupture, reducing the hydraulic capacity. The northernmost East Branch crossings are near Palmdale where the aqueduct crosses the San Andreas Fault main trace at two locations, each having shear movement on the main trace and parallel fault splays, and the Nadeau Fault at five locations (Jones *et al.* 2008, App. E). The Nadeau Fault is an adjacent parallel fault strand within the San Andreas Fault zone that is expected to slip along with the main fault rupture. The impact of fault displacements depends on the angle of the fault crossing with respect to the aqueduct and how the aqueduct was constructed. In the Palmdale area,

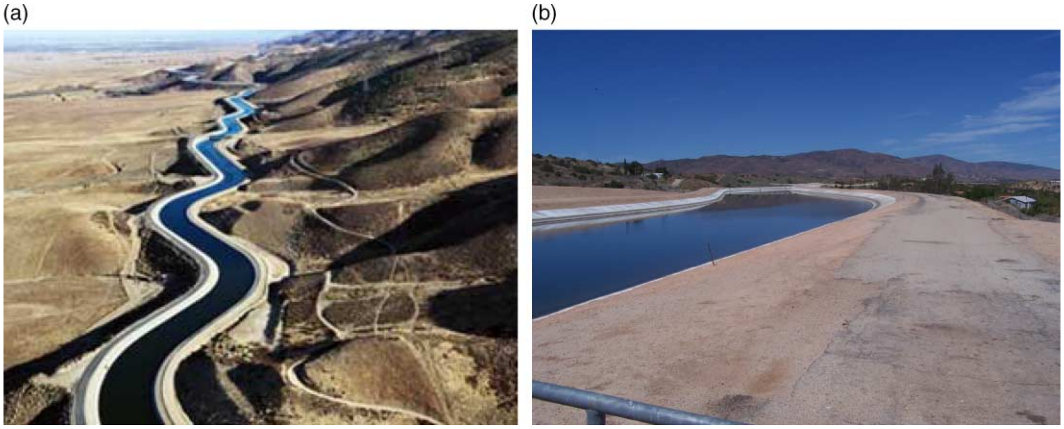

**Figure 4** | California Aqueduct Channel: (a) typical view of canal running parallel to San Andreas Fault (source: www.polizeros.com); (b) channel embankment at fault crossing near Palmdale. The full colour version of all figures in this paper can be accessed by subscribers online at http://www.iwaponline.com/jws/toc.htm

where 12 fault offsets occur, Figure 4 shows the California Aqueduct flowing in an open, concrete-lined channel retained by compacted earth embankment fills or graded natural ground on either side. Eight of the displacements impose a combination of lateral and extensional movement in the embankments causing the aqueduct to pull apart by as much as 1.7 m. This pull-apart movement opens gaps in the channel allowing soil to erode and large volumes of water to escape. Four of the displacements cause lateral plus up to 1.3 m of compressional movement, forcing the liner to buckle with extensive damage.

At Devil Canyon the main fault displacement of 4.9 m crosses in front of a power plant through a tailbay and channel where the oblique (combined horizontal and vertical) movement causes some facility damage. The upstream side of the aqueduct is uplifted. These movements may be accommodated without significant disruption to water flow if the combined horizontal and vertical deformations remain small enough with respect to the channel size to keep the water contained without significant erosion, the power plant can continue to pass water, and the dam can continue to safety retain water following this event. The main fault trace in Devil Canyon is accompanied by approximately four parallel fault splays of the Arrowhead Springs Fault, an adjacent parallel fault strand within the San Andreas Fault zone, two splays passing behind the power plant (MWD 2008). If the total movement is partitioned between these splays then the powerhouse and/or penstocks may potentially be damaged causing a greater disruption to operations.

In addition to fault offsets, the ShakeOut scenario shakes the California Aqueduct for approximately 300 km, including the West Branch, with strong to severe intensities. Further, portions of the aqueduct are located on potentially liquefiable soils (CGS 2009) and some areas are subject to landslide movements and debris falls. The strong shaking: (1) causes settlement of the embankment fills and foundation soils; (2) induces inertial forces from strong shaking causing embankment and natural slope deformations; (3) increases pore water pressures in saturated soils enhancing permanent ground movement potential; (4) induces lateral deformations from lurching in weak non-liquefiable foundation soils; (5) induces liquefaction in weak saturated sandy foundation soils leading to lateral spreading and greater embankment deformations. Soil settlements and inertial embankment deformations result for hundreds of kilometres, while the other impacts occur at vulnerable locations along the alignment. Embankment deformations cause transverse cracking; at some locations this provides seepage paths and allow for internal erosion and the potential for failure. Delayed failures may result hours or days following the event. Where large movements result, the channel may be breached. Owing to the very large number of embankments making up the aqueduct channel, some failures must be anticipated, but the total number of damaged embankments and their locations is difficult to determine. All of these effects cause liner damage in localized stretches over the length subjected to strong ground shaking. Based on experience and studies of channel performance in earthquakes (e.g. Davis *et al.* 2002, 2008), damage to the channel liner could be widespread when including the effects of voids resulting from ground separating from the concrete. The pumping stations and power plants may also experience some level of damage.

To the north where the San Joaquin Valley sediments and historic Buena Vista Lakebed amplify seismic waves (the northernmost area in Figure 1 with severe intensity shaking), portions of the California Aqueduct channel are expected to experience large deformations and possible channel breach. The 16 km of tunnels and shafts through the mountains have limited damage in only a few locations. The West Branch performs fairly well in the ShakeOut scenario, with shaking less intense than that experienced by the East Branch. The East Branch channel crosses many zones of weak soil deposits and will suffer damaging deformations, resulting in several channel breaches, some possibly in urbanized areas.

## Colorado River Aqueduct

The CRA was completed in 1941 and currently transports an average of about 900 million $m^3$ (730,000 acre-feet) of water per year from the Colorado River to Southern California. The 392 km long CRA approaches the San Andreas Fault from the east in concrete conduits, lined canals and tunnels, and parallels the fault in the Coachella tunnels in a northerly direction for approximately 70 km. East of the San Andreas Fault, five pumping stations lift water to higher elevations. The San Andreas Fault zone is crossed in conduits and tunnels mainly constructed of 4.9 m diameter reinforced concrete. The CRA continues east of the fault in a series of conduits and tunnels where it terminates at Lake Mathews. The CRA water is delivered to Los Angeles and other cities through a transmission network covering much of Southern California.

The CRA crosses four fault strands making up the San Andreas Fault zone in the San Gorgonio Pass. The ShakeOut scenario fault movements estimated to affect the CRA concrete conduit and tunnel sections range from 0.4 m to 1.3 m (Jones *et al.* 2008, App. E). The fault slip in this region is complex and includes significant vertical components with the CRA upstream side lifted upward. Total uplift in the San Gorgonio Pass, which includes faulting and folding, may exceed 4 m. This will reduce the CRA hydraulic capacity, which primarily flows unpressurized. The horizontal fault movement component pulls the CRA apart by several tenths of metres. The combined horizontal and vertical fault movements cause damage to tunnel liners and concrete conduits, resulting in spalling and opening of gaps, exposing water to the surrounding ground. In locations of large openings the water can erode the surrounding ground, which may result in further damage to the aqueduct and leave sinkholes and eroded slopes.

Over 140 km of the CRA is subjected to strong to severe shaking. Tunnel sections are damaged by strong shaking and the conduit is damaged at locations where it passes through liquefiable soils or weak clays. Channel sections are subjected to strong intensity shaking and may experience some deformations and concrete liner cracking similar to that described for the California Aqueduct. The pumping stations may also experience some level of damage.

## Afterslip and aftershocks

Afterslip describes the continued creep along the fault for weeks or months after it ruptured. The fault displacements described above include afterslip. The majority of movement occurs during the main event but, depending on geological conditions, afterslip may amount to up to 40% of the total slip in regions of deep sediments overlying the main fault. Afterslip at the LAA is expected to be relatively small. The amounts effecting the California Aqueduct and CRA are not well understood, but the majority of afterslip should dissipate within several weeks following the earthquake. Nonetheless, afterslip presents a problem of continued damage, complicating repair efforts.

All of the damaging effects described for each aqueduct are enhanced during large aftershocks. Aftershocks subject the aqueducts to further strong shaking in localized areas and possibly additional fault offsets. Aftershocks cause significant increases in damage and potential failures at locations previously damaged by the main shock, and require rework to previously completed repairs, leading to further delays in returning the aqueducts to service.

## RESULTS AND DISCUSSION

### Aqueduct restorations

The damages described above have a severe impact on aqueduct operations and provide a complete disruption to imported water supplies. The length of time for which Southern California must operate without additional imported water is a function of damage level and repair time. Figure 5 shows the time estimates for returning the aqueducts back to service. The time estimates are conceptual and depend on the actual extent of damage and available resources to make repairs, but are considered reasonable based on the anticipated damage. Figure 5 represents time to return to initial service, additional shut down periods may be needed at later times to perform more repairs. It is possible that restoration could be achieved in a somewhat shorter timeframe than that shown in Figure 5, and summarized in the following subsections, but it is also possible that restoration times could take significantly longer than that estimated because of resource conflicts (labour, equipment, materials, supplies), transportation difficulties following the earthquake, additional damage from aftershocks and afterslip, and other issues. Further, each aqueduct has interactions with other lifelines, causing delays in initiating repairs and extending repair durations; these are difficult to account for and are not included in the estimated repair times.

### Los Angeles Aqueduct

Figure 5 shows the LAA is not expected to be returned to service for 18 months. Elizabeth Tunnel takes the longest time to repair as it is completely closed off. Mining a new portion of the tunnel is difficult. The blockage requires many kilometres of tunnel to be pumped free of dammed up water. Damage assessment and repair workers are exposed to a hazardous environment of collapsed tunnel with potential spalling rock and concrete liner, and groundwater infiltration. Survey measurements are difficult to obtain, but show extensive tunnel mining necessary to match the hydraulic grade due to tectonic uplift. Engineering design is needed before construction starts. Construction contract procurement may be difficult because of the risks involved with the hazardous work environment and potential large aftershocks, and constructing the repairs is time consuming. In addition to the Elizabeth Tunnel, the FLAA and SLAA require repairs to pipe, tunnel and channel damages at numerous locations extending many kilometres on each side of the fault; Figure 5 shows that the timing of these repairs is not as critical as for the Elizabeth Tunnel.

### California Aqueduct

The California Aqueduct is exposed to strong ground shaking for long distances, and is expected to require lengthy repairs at many locations. Owing to deep sediments

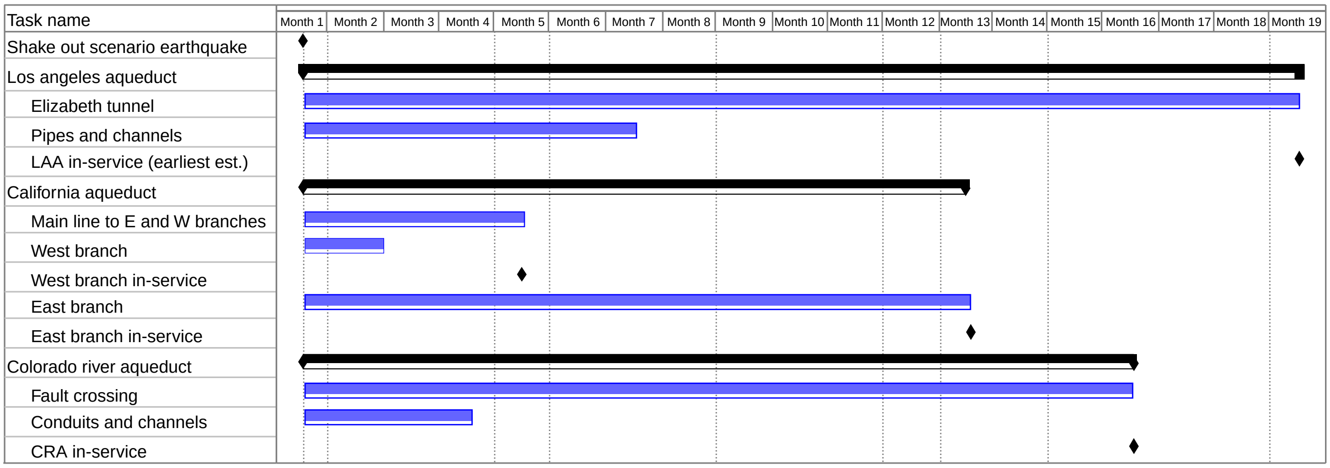

**Figure 5** | Aqueduct restoration time estimates. The full colour version of all figures in this paper can be accessed by subscribers online at http://www.iwaponline.com/jws/toc.htm

and weak lakebed deposits, the main channel line requires extensive repairs in the San Joaquin Valley north of the fault rupture. However, the West Branch is not expected to require as much repair because of the more favourable geological conditions, even though it is much closer to the seismic source. Figure 5 shows the main line to be more critical to restoring flows to the West Branch, taking approximately four months. The East Branch requires extensive repairs taking at least 1 year to complete. This time estimate is developed assuming large breaches result from fault slip and ground deformations, some of the repairs are slowed by the added damage to structures and transportation corridors, and that repairs proceed simultaneously in different regions along the aqueduct but there are inadequate resources to proceed with all repairs at once.

### Colorado River Aqueduct

The greatest damage to the CRA, requiring the most extensive repairs, is experienced at the San Andreas Fault zone crossing. Damage assessment and initial surveys may be difficult, and show total uplift in the fault zone and surrounding region result in nearly total disruption of aqueduct flow, requiring: (1) excavation to lower the CRA and re-establish the necessary hydraulic gradients; and/or (2) construction of new pumping facilities to boost the hydraulic gradient to accommodate increased elevations. Aftershocks and afterslip disrupt progress and, in some periods, require redesign of aqueduct repairs because of continued damage and movement. Thus, determining the extent of repairs and developing designs is difficult initially, and evolves continually during and after initial restoration is completed. Restoration progress is further hampered by repairs simultaneously performed to many nearby lifelines (Jones *et al.* 2008). Figure 5 shows an estimated repair time of at least 15 months, and that the fault zone crossing is the most critical repair area.

### Storage

Recent reports indicate there is an estimated 6 months of storage (surface and groundwater) in Southern California available for use following a great San Andreas Fault earthquake, if 25% rationing is implemented (MWD 2005). Some populated areas have limited or no access to this stored water, while others have more than 6 months of storage available to them. Groundwater pumping is significantly increased. However, even for those who can use them, not all supplies are immediately accessible as a result of damage sustained to the local water transmission and distribution systems.

Figure 5 shows that restoration of the LAA, California Aqueduct East Branch, and CRA as a result of damage sustained from a ShakeOut scenario event takes much longer than 6 months. As a result, there does not seem to be enough storage to sustain Southern California during the total aqueduct restoration duration for this plausible earthquake scenario. Restoration of the California Aqueduct West Branch within 6 months helps some cities such as Los Angeles, but does not help all of the Southern California population because of the limited ability to transmit West Branch water throughout the urban areas. Even those receiving West Branch water must continue rationing for many months to stretch this limited supply as far as possible. The net result of not having a local storage capacity to supply the population through the aqueduct restoration period is increased rationing for a longer duration and overdraft of local groundwater basins, leading to potential environmental problems. The lack of storage and supplies has a significant impact on the regional economy; the US$53 billion in business interruption losses due to reduced water supply (Jones *et al.* 2008) may have been greatly underestimated for this event.

## CONCLUSION

A preliminary review of potential damage to three major aqueducts (Los Angeles, California and Colorado River) in response to a M7.8 earthquake on the San Andreas Fault was performed. The results indicate there may be inadequate storage to supply the local population during the length of time it takes to repair the aqueducts. Inadequate water storage has significant health, safety and economic impacts. As a result of this investigation, a more thorough evaluation of aqueduct restoration times is needed. In addition, mitigation measures for additional local storage and more rapid aqueduct restoration must be implemented.

## REFERENCES

California Department of Water Resources 2010 *California State Water Project Overview*, http://www.water.ca.gov/swp/ (accessed 7 May 2010).

CGS (California Geological Survey) 2009 *Seismic Hazards Zonation Program*, http://www.consrv.ca.gov/cgs/shzp/Pages/Index.aspx (accessed 7 May 2010).

Cox, D. & Pierce, I. 2008 Results Are In: Great Southern California ShakeOut Successful, Sets U.S. Record! *USGS Newsroom*, 19 December 2008, http://www.usgs.gov/newsroom/article.asp?ID=2098 (accessed 7 May 2010).

Davis, C. A. 2009 Scenario response and restoration of Los Angeles water system to a magnitude 7.8 San Andreas Fault earthquake. *Proc. 7th US Conference on Lifeline Earthquake Engineering*, ASCE, Oakland, 28 June–1 July 2009, paper 232.

Davis, C. A. & O'Rourke, T. D. 2011 ShakeOut scenario: Water system impacts from a M7.8 San Andreas earthquake. *Earthquake Spectra* (accepted).

Davis, C. A., Bardet, J. P. & Hu, J. 2002 Effects of ground movements on concrete channels. In: O'Rourke, T. D., Bardet, J. P. & Hamada, M. (eds) *Proc. 8th US-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction*, Tokyo, Japan, pp. 111–122, (Tech. Rep. MCEER-03-0003).

Davis, C. A., Hu, J. & Bardet, J. P. 2008 Case studies of earthquake induced ground movement effects on concrete channels. *Proceedings ASCE GeoCongress 08, paper No. 07120703715*, New Orleans, LA, 9–12 March 2008.

Jones, L. M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M., Seligson, H., Shoaf, K., Treiman, J. & Wein, A. 2008 *The Shakeout Scenario*, US Geological Survey OFR 2008-1150 and California Geological Survey Preliminary Report 25.

MWD (Metropolitan Water District of Southern California) 2005 *The Regional Urban Water Management Plan*, http://www.mwdh2o.com (accessed 7 May 2010).

MWD (Metropolitan Water District of Southern California) 2008 *Inland Feeder Arrowhead East Tunnel Breakthrough, Brochure*, http://www.mwdh2o.com (accessed 7 May 2010).

National Park Service 1998 *Colorado River Aqueduct Recording Project, Historic American Engineering Record CA-226, available at US Library of Congress* http://www.loc.gov/pictures/collection/hh/item/CA2472/?sid=f0293511f38c7610439d485549157861 (accessed 7 May 2010).

National Park Service 2001 *Los Angeles Aqueduct Recording Project, Historic American Engineering Record CA-298*, available at US Library of Congress http://www.loc.gov/pictures/collection/hh/item/CA3170/ (accessed 7 May 2010).

Romero, N., O'Rourke, T. D., Nozick, L. K. & Davis, C. A. 2009 Los Angeles water supply response to 7.8 $M_w$ earthquake, *Proc. 7th US Conference on Lifeline Earthquake Engineering*, ASCE, Oakland, 28 June–1 July 2009, paper 220.

Romero, N., O'Rourke, T. D., Nozick, L. K. & Davis, C. A. 2010 Seismic hazards and water supply performance. *J. Earthquake Eng.*, in press.

USGS (United States Geological Survey) 2010 *Earthquake Hazards* Program, http://earthquake.usgs.gov/earthquakes/shakemap/sc/shake/ShakeOut2_full_se (accessed 7 May 2010).

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