# A Way Forward to Increase Earthquake and Landslide Resilience of Water Supply Systems in Shimla, Aizawl, and Similar Hill Cities

World Bank Contract No. 7195356

GeoHazards International

GeoHazards Society INDIA

GFDRR
Global Facility for Disaster Reduction and Recovery

DRAFT September 25, 2020

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## Executive Summary

In 2020, the World Bank funded the program, Knowledge Exchange on Best Practices for Seismic Risk Management, to increase the earthquake and landslide resilience of water supply systems in two hill cities in India: Aizawl in Mizoram, and Shimla in Himachal Pradesh. On India's seismic hazard zone map, Aizawl is located in an area with very high earthquake hazard, and Shimla is in an area with high earthquake hazard, meaning that both can face damaging earthquakes in their future. The earthquake shaking is likely to trigger hundreds or thousands of landslides as well. Extreme monsoon seasons are already occurring in India, and a season of extreme rain may result in many landslides occurring over a short period of time. Residents and visitors will still need water, despite such events. In strong earthquakes around the world, water systems are damaged; most have older components that predate current knowledge and codes. Damage to systems elsewhere has provided lessons that can be applied in India to reduce such impacts. This document is a result of the knowledge exchange program, which brought together officials from both cities, the municipalities, the states, and others who play a role in ensuring water is available to citizens, both during normal times and in disasters. The officials were joined in a knowledge exchange with resilience professionals from the U.S. and India, to share what can be done to address the water system vulnerabilities.

This document is intended to serve as a resource for Shimla, Aizawl, and other hill cities at risk from earthquakes and landslides. The two cities are described in the document along with their water systems. The program focuses on Aizawl and Shimla, but the hazards they face, the vulnerabilities present in their water systems, and the ways they can be dealt with, are shared by numerous hill cities in the region. The document summarizes the eleven major challenges common to hill city water systems, and two more specific to Aizawl and Shimla, based on first-hand experience gained from global disasters. For each challenge, a solution, or a way forward, is suggested -- activities that can be taken over both the short- and long-terms.

There are four major activities of high priority for the near-term. 1) Develop and adopt an emergency response plan. 2) Practice the emergency response plan with regular emergency drills. 3) Create an earthquake disaster scenario to aid in planning/exercising for likely impacts; update the emergency response plan based on the scenario results. And, 4) create landslide hazard maps to identify areas of very high hazard and risk to the water system; update the emergency response plan based on the impacts indicated by the scenario.

This Way Forward document also outlines seven other key opportunities for increasing water system earthquake resilience: 1) Develop regulations on slope excavations to reduce instability that an earthquake would exploit. 2) Raise public awareness on avoiding activity that makes slopes more susceptible to landslides during the monsoon and an earthquake. 3) Develop Continuous Resilience Program for the water agency. 4) Appoint a Resilience Manager for the water agency to be responsible for emergency planning and response, as well as system mitigation. 5) Prepare a water system resilience plan. 6) Budget and implement resilient activities on annual basis. And, 7) mainstream resilient thinking, activities, and discussion.

Resilience cannot be achieved overnight. Incremental steps are needed and over time will mean that when an earthquake or extreme monsoon season arrives without warning, the water system can resume providing water in a short period of time (at least emergency quantities) will support the people dependent on the system to survive and to reconstruct their communities.

## Introduction

This document is a result of a World Bank-funded program to bring together technical experts and officials in India and the U.S. to share knowledge and best practices on landslide and seismic risk and resilience management for water utilities. Officials participated from the cities of Aizawl and Shimla, together with officials from the states of Mizoram and Himachal Pradesh. Those nominated to participate in the knowledge exchange represent the cities' water supply systems, municipalities, state disaster management, and state geology departments. They were joined by infrastructure resilience experts based in the U.S. along with resilience professionals from GeoHazards International (GHI) and GeoHazards Society (GHS), the non-profit organizations carrying out the program.

A major component of the knowledge exchange program involved five, two-hour-long video conference calls among the participants. These video meetings provided a forum for discussions. In the first meeting, the resilience experts shared their experience describing the common ways in which earthquakes and landslides have damaged water supply systems around the world, preventing them from delivering water to consumers. The second meeting included presentations by the managers of the Shimla and Aizawl water supply systems to provide an overview of their systems and plans for the future. During meeting three, the resilience experts described measures that can increase water system resilience, such as developing and exercising a disaster response plan. In the fourth meeting, the resilience experts described their observations of the challenges facing Aizawl and Shimla in making their water systems more resilient. Potential ways to address those challenges were also discussed. And in the fifth virtual meeting, the experts described how the various organizations represented could divide the responsibilities, and define organizational roles, in order to work cohesively and effectively to reduce vulnerabilities in their water supply system. The video exchanges included discussions on which system vulnerabilities most concerned the water supply managers, and the experts responded with ideas for possible solutions or specific activities that could increase resilience to earthquake and landslide hazards.

### Program Participants

We wish to thank each of the following nominated participants that joined in the knowledge exchange. Their contributions were invaluable and often requested with short notice.

- Gopal Krishan, Additional General Manager Distribution and Sewerage, Shimla Jal Prabandhan Nigam Limited (SJPNL)
- Rajesh Kashyap, Additional General Manager Bulk Water Supply, SJPNL
- Adarsh Chauhan, Asset Manager, SJPNL
- Gaurav Sharma, Geologist, Himachal Pradesh Department of Industries

- Vivek Sharma, Senior Consultant, Himachal Pradesh State Disaster Management Authority (HP SDMA)
- Rajesh Thakur, Executive Engineer Road and Building Department, Shimla Municipal Corporation
- Davinder Kumar Mista, Architect Planner, Shimla Municipal Corporation
- Dr. Harkanchan Singh, Shimla City Project Coordinator, United Nations Development Programme (UNDP)
- Anup Chhetry, Superintending Engineer, Mizoram Public Health Engineering Department (PHED)
- Z.D. Dengthuama, Executive Engineer, Mizoram PHED
- Lalrinzuala Ralte, Executive Engineer, Mizoram PHED
- P. Sanghnuna, Senior Geologist, Mizoram Department of Geology and Mineral Resources (DG&MR)
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- John L.T. Sanga, Director, Mizoram Department of Disaster Management & Rehabilitation (DM&R)
- D.C. Rana, IAS, Director-cum-Special Secretary, HP SDMA
- Anup Karanth, Task Team Leader, World Bank

The U.S. experts and team members from GHI and GHS are as follows:

- Dr. Craig Davis, Water systems resilience engineer, consultant to GHI
- Kevin Clahan, Landslide and earthquake hazards geologist, consultant to GHI
- Hari Kumar, Technical Lead, GHI
- Heidi Stenner, Project Co-Manager, GHI
- Dr. Janise Rodgers, Project Co-Manager, GHI
- Pranav Sethi, Northern India Coordinator, GHS
- Lalrinpuii Tlau, Mizoram Coordinator, GHI

This document was written by the U.S. experts, GHI, and GHS, and was reviewed by program participants from Aizawl and Shimla.

### Intent of this Document

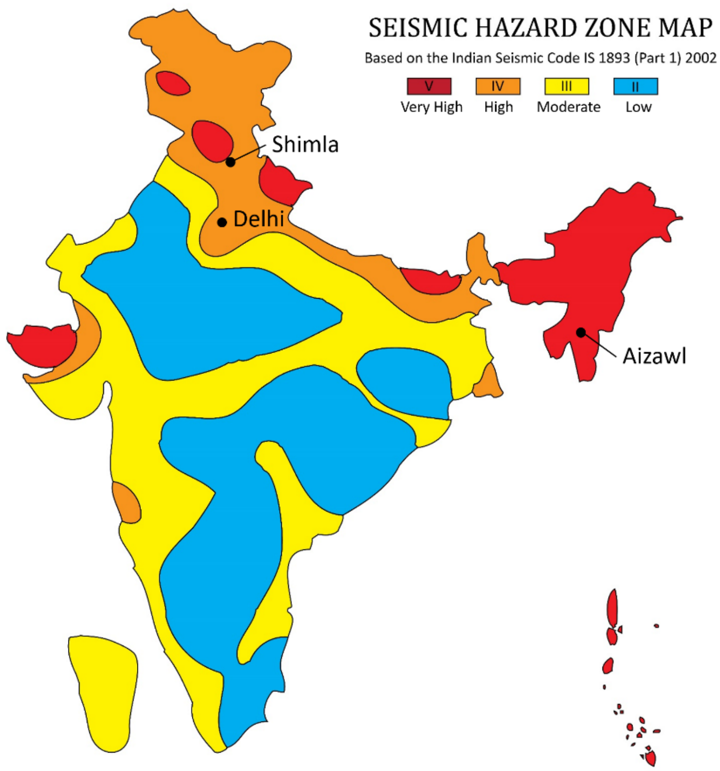
This document is intended to serve as a resource for Shimla, Aizawl, and other hill cities at risk from earthquakes and landslides. It is a summary of the major consequences or threats to Aizawl and Shimla's water systems from a damaging earthquake, multiple landslides, or an extreme monsoon season. Most importantly, the document describes a way forward – activities that can be taken over the short- and long-terms to reduce damage and recover more quickly, so that adequate water can be provided to those relying on it.

### Limitations

The knowledge exchange program was designed prior to the World Health Organization's declaration of the global COVID-19 pandemic in 2020. What had originally been a program with officials and resilience experts meeting in-person and examining water systems together was revised to accommodate the necessary restrictions against travel. This document presents our understanding of system vulnerabilities based on interactions during the five video conference calls described above along with first-hand experience with similar systems and their vulnerabilities elsewhere. No field visits were conducted, which limits the amount of site-specific vulnerabilities and recommendations for solutions that we are able to provide.

## Aizawl and Shimla, Hill Cities at Risk

The hill cities of Aizawl and Shimla are located in the actively deforming Indo Burmese and central Himalayan mountain ranges, respectively. These mountain ranges were formed as the result of the collision of the India plate and the Eurasia/Tibetan plate that has been taking place for about the past 50 million years. The geodynamics of the northward convergence of India beneath Eurasia generates high rates of seismicity that threaten millions of people in the mountainous regions of India. This is why the seismic hazard zone map shows northeastern and northern India as Zone IV or V (see map at right). The fault displacement associated with large (magnitude 7 or greater) earthquakes can rupture the ground surface but the strong ground shaking associated with these ruptures creates secondary effects that can damage infrastructure and trigger earthquake-induced landsliding across the entire region that often results in greater damage and loss of life.




**The seismic hazard zone map for India, based on the Indian Seismic Code IS 1893 (Part 1), 2002.**

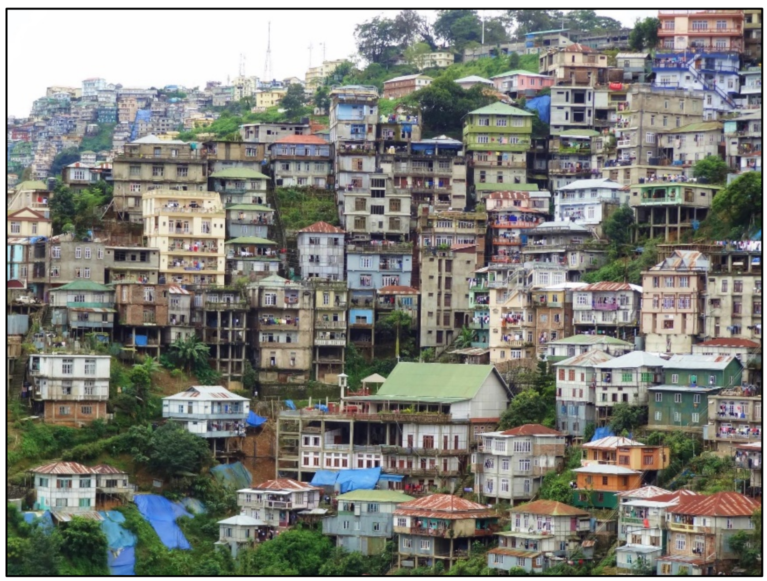
Landslides represent a major threat to human life, property and constructed facilities, infrastructure and the natural environment in most mountainous and hilly regions of the world. Aizawl and Shimla face an elevated threat of landslides due to specific geologic, seismic, climatic, and development conditions that exacerbate landslide hazard conditions. The unfavorable geologic conditions and steep slopes are subject to devastating failure in the form of pervasive landsliding, often triggered by heavy monsoon rains. As a result, destructive landslides dominate the historical geologic hazard record in the region, but conditions exist for less frequent, large magnitude seismic events which will contribute to the landslide hazard in the longer term.

The geologic conditions in both Aizawl and Shimla that contribute to elevated landslide hazard include: 1) steep slopes; 2) weak rock strengths; 3) pervasive discontinuities (i.e., joints, fractures, and faults); 4) very high seismic hazard; and in Aizawl, 5) slope parallel sub-surface bedding. These geologic conditions in conjunction with slope-destabilizing construction practices and the potential for strong seismic ground shaking, produce a high risk environment with potential for significant loss of life and property.

A better understanding of landslide and seismic risk in both Aizawl and Shimla is important for future risk mitigation. Both cities have taken steps to understand their geologic hazards. Aizawl has implemented a 1:5,000 scale landslide hazard map to inform planning, design, and construction activities. Shimla has a more regional assessment of landslide hazard in the form of a 1:25,000 scale landslide hazard map and a 1:50,000 scale landslide vulnerability map.

## A Brief Introduction to Aizawl and its Water Supply System

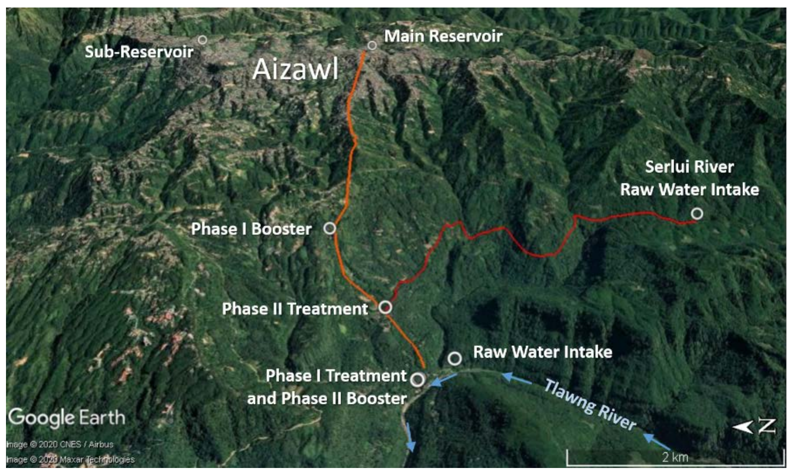
Aizawl is the capital city of Mizoram in North East India, with a 2011 census population of 293,416. The city sits at an elevation of 1,132 meters above sea level. Mizoram lies in one of the most earthquake prone zones of India, which is categorized as Zone V on the Indian seismic hazard map. A number of active faults in the State of Mizoram and surrounding areas are capable of causing large magnitude earthquakes that will result in damage to Aizawl city. Recently, on 22 June 2020, a magnitude 5.6 earthquake occurred 85 kilometers southeast of Aizawl, causing damage to buildings and landslides in the epicentral area.



**View of a section of Aizawl, Mizoram. Photo by GHI.**

Damaging landslides are commonplace in Aizawl where steep slopes are formed in young, weak geologic materials. Slopes in the city are heavily disturbed from construction of roads and buildings; in fact construction and quarrying are frequent causes for failure of the destabilized hillsides. Landslides cause huge economic losses, disruptions, and sometimes even loss of lives. In order to improve policies that address landslide risk the Aizawl Municipal Corporation (AMC) formed the working group 'The Landslide Policy Committee for Aizawl City' that consists of all stakeholder departments of the Government of Mizoram concerned with landslides. The committee identified concerns and developed a set of action plans called 'The Roadmap to Stability' that defines the roles for the stakeholder departments with a timeline for implementation. GHI provides technical support to the Landslide Policy Committee. The committee also developed 'The Aizawl Municipal Corporation Site Development and Slope Modification Regulations, 2017,' which serve to regulate construction or other activity that can destabilize slopes. The regulations were passed by the Government of Mizoram (Published in The Mizoram Gazette, 4th April, 2017)[1]. In support of the Landslide Policy Committee and the AMC Site Development and Slope Modification Regulations, Mr. Kevin Clahan and his team at Lettis Consultants International worked with GHI and GHS to create landslide hazard maps for Aizawl's municipal area at a 1:5,000 scale. These maps were first published in 2016 and were formally adopted by the AMC shortly thereafter. These landslide hazard maps are proving vital for risk management and are used regularly.

A portion of water used in Aizawl comes from local springs, wells, harvested rainwater, and a stream. The majority of water is supplied to Aizawl by the Public Health Engineering Department (PHED). Due to a supply shortage, municipal water is typically distributed on a rotating basis once a week to neighborhood distribution points and to homes and businesses. Homes and businesses maintain on-site tanks to store water from the periodic deliveries as well as from locally collected rainwater and private lorry tanker deliveries.



**Overview of Aizawl's water system. Base image from Google Earth.**

The Greater Aizawl Water Supply Scheme (GAWSS) Phases I and II, transport water through separate pipelines. A Phase III is scheduled to be completed by the end of 2020. Phase I was completed in 1988 and Phase II was added in 2007. Both Phases I and II intake raw water from the Tlawng River at Reiek Kai. Phase III will also intake raw water from the Tlawng River but at a different location. At the Phase I treatment station, the raw water is aerated, clarified, filtered, and disinfected. Treated water is pumped to the Phase I booster station. Phase II pumped raw water is sent to a Phase II booster station that pumps the raw water to a Phase II treatment station at Dihmunzawl. The treated water from Phases I and II combine to provide 24.8 MLD (million liters per day) and is pumped 1000 m in height to the main reservoir at Tuikhuahtlang. An additional source of seasonal water from the Serlui River was completed in 2015. During monsoon season from June to October, 30 MLD of raw water is fed by gravity to the Phase II treatment station mentioned above. The treated water is also pumped to the Tuikhuahtlang main reservoir. From the main reservoir in Tuikhuahtlang, it is distributed to the Laipuitlang sub-reservoir via a booster station and to 41 zonal tanks around the city. The zonal tanks distribute water to households, businesses, facilities, and to neighborhood distribution points. The nearly completed GAWSS Phase III is designed to supply water to the northern part of Aizawl. It will intake raw water from the Tlawng River at Sakawrtuichhun with an independent treatment and pumping system that will deliver the treated water directly to the Laipuitlang sub-reservoir. Separate from the GAWSS Phases I-III,

[1] Available for download at https://amcmizoram.com/uploads/files/Site%20Development_27062019101258.pdf

a local stream is the source of water for one zonal tank at Edenthar that receives water via a booster pump at Chhawnzinga Tuikhuah.

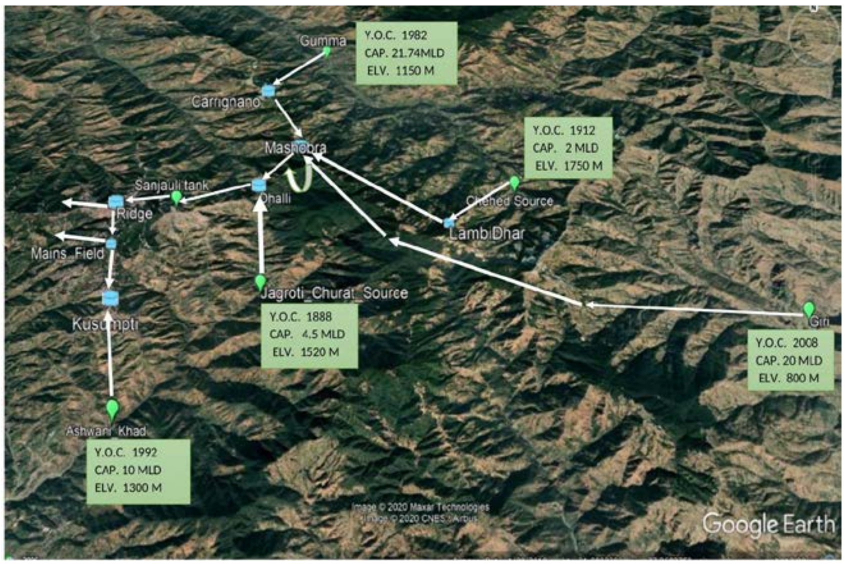
## A Brief Introduction to Shimla and its Water Supply System

The historic city of Shimla is one of the most visited hill cities in North India, with a population of 169,578 people as of the 2011 census. Located in the state of Himachal Pradesh, the city was established before independence and is an important part of India's rich history. The hill city attracts tourists primarily in summer, as the cooler climate attracts visitors escaping the scorching heat over the Gangetic plains, including the Indian capital of Delhi. The city has been growing rapidly over the years with an economy dependent mostly on tourism. As the demand for water grew, the city started to face water shortages, and water is provided to zones in the city each day during specific hours. The system has been evolving since 1875, but in 2016, the city experienced a jaundice outbreak, resulting from people consuming contaminated water.

**View of buildings constructed on steep slopes in Shimla. Photo by Ryan, CC license via Flickr.**

To tackle the challenge of providing potable water to the people, Shimla Jal Prabandhan Nigam Limited (SJPNL) was established which stared exploring new sources of water and expanding the capacity with time. Today the SJPNL is not only able to provide clean drinking water to the people of the city but also to areas outside the city limits. A part of this water is pumped from the rivers and spring sources in and around the city and a part is received from springs situated at higher altitude and transported via gravity methods. The major water sources come from pumping water from the Giri and Gumma rivers in single or multiple stages, up to 1500 meters in height, using separate water lines to multiple treatment plants. Combined, these river sources provide 41.74 MLD to the city. An additional 16.5 MLD is obtained by pumping from Ashwani Khad, Jagroti – Churat and Chehed sources. The water is collected, treated and released to various tanks across the city from where it is supplied to the community. Over the years, modifications and upgrades to the water delivery infrastructure has resulted in the water system becoming more efficient and overall water loss has been reduced to less than 3%. The SJPNL is also in the process of providing 24 hour water supply in the next few years by linking the water system to the Satluj river which is a perennial river flowing close to the city.

The city of Shimla is situated at an elevation of nearly 2276 meters above sea level in the Himalayas, and lies in Zone IV, the high seismic zone, on the Indian seismic hazard map. A large historic earthquake occurred in 1905. The magnitude 7.9 Kangra earthquake shook Himachal Pradesh and the surrounding areas; killing an estimated 20,000 people. The epicenter was approximately 170 kilometers north of Shimla. These types of large magnitude earthquakes are expected to occur in the future as a result of ongoing tectonic deformation.




**Water supply sources for Shimla. Image courtesy SJPNL.**

As Shimla is located in the actively growing Himalaya Mountains, landslides are common, particularly during the heavy rains of monsoon season. Landslides in and around the city have been caused by inherent slope weaknesses such as bedrock discontinuities and thick deposits of colluvium. These hazardous slope conditions are exacerbated by road or infrastructure construction, sometimes causing loss of life and significant economic impacts; landslides can also increase the turbidity of the water sources from which the city gets its supply, requiring additional cleaning of silt-laden equipment. Existing landslide hazard maps have been prepared at the state level. More detailed landslide hazard maps for the city are needed to assist in planning at a local level.

## The Interconnection of Risks

When an earthquake or extreme monsoon season causes damage to a water system, the disaster will also have affected the environment on which the system relies and the surrounding region. For instance, the network of roads used to reach water system components for repairs will likely have also suffered damage. Roads blocked or collapsed by landslides, or buried under collapsed structures, may mean equipment cannot reach damaged facilities, and people may have to walk long distances to reach sites that normally are readily accessible. In 2014, GHI developed a scientific scenario, constructing what may happen in Aizawl from a magnitude 7 earthquake (Rodgers et al., 2014). This scenario, along with others in the region,[2] concluded that hundreds to thousands of landslides are likely to occur during a moderate to large earthquake. Such extensive landslides will mean that reopening roads will take considerable time. One cleared landslide allows passage only to the next damaged road location. Goods like food, equipment, and repair supplies will not be able to reach the city until the roads are passable again.

[2] For example, see earthquake scenarios for districts in far western Nepal. Download at XXX

Flying in such materials via helicopter is expensive and is usually limited to only the most critical needs. External aid will be needed for emergency response and recovery, but the help will not only focus on Shimla or Aizawl, but also the other numerous cities and towns severely impacted by the same event.

Fuel that is normally purchased in the city to operate the repair equipment may quickly run out as supply tankers from out of town may be blocked from reaching the city due to the impassable roads. The electric power grid may not function as the long transmission lines rest on individual towers, any number of which could be toppled during earthquake shaking or by landslides. The electric grid has many points of weakness that a disaster will find, all of which take time, supplies, and manpower to repair. The same is true for communication systems such as mobile phones and the internet. If earthquake shaking or landsliding does not directly damage communication towers, then the lack of electric power will cause networks to fail. Most infrastructure has older components that predate current knowledge and codes, and are vulnerable to damage.

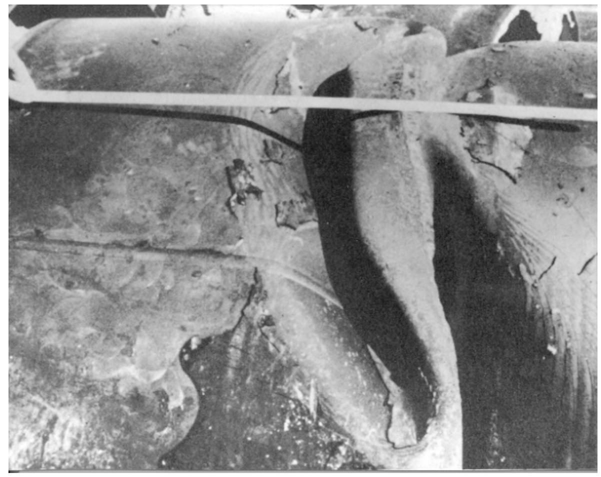
Most importantly, the people on which the water system depends are likely to be personally impacted by the disaster, too. Managers, field staff, and record-keepers -- everyone plays a critical role in keeping the system operating. If employees' homes suffer damage and family members or themselves are injured, they may not be able to contribute to repairing the water system.

These interdependencies need to be critically assessed in developing plans for making a water system resilient. Careful planning is needed, including developing an emergency action plan that identifies ways to work around issues and analyzes each assumption. In addition, repeated practice in carrying out the emergency plans through exercises simulating disasters of various sizes will prove to be invaluable. Further, advance planning and mitigation can reduce or prevent some damage which may allow portions of the system to continue operating during and following the event and thus reduce the need for repair during an emergency.

## Recognizing Common Vulnerabilities that Result in Damage and Impacts in Water Supply Systems

Water systems are made up of pump stations, treatment plants, tanks, reservoirs, and pipelines. All have potential vulnerabilities to earthquakes and landslides. Earthquakes can affect all components of a water system from broken above-ground pipes due to high frequency, short period ground motions to tank collapse from low frequency shaking from more distal sources. This is in addition to permanent ground displacement caused by earthquake induced landsliding which severely damage underground pipes and the foundations of critical water facilities. The following describes some common vulnerabilities to earthquake and landslide hazards. This is not intended to be a comprehensive list or exhaustive description, but instead provides an overall understanding of the potential water system impacts from earthquakes and landslides.

**Pipelines**: When originally installed, water pipelines were generally not designed to resist earthquake effects. This is common in most all water systems around the world. Pipes are vulnerable to ground shaking and permanent ground deformations. Generally, more leaks result from shaking movement but the permanent ground deformations from landslides, lateral spreading, differential settlement, and surface fault rupture cause greater damage and disruption to system hydraulics. Buried pipelines also deteriorate over time. Deteriorated pipelines are more fragile to earthquake effects. Some pipelines have greater inherent resistance to earthquakes, but if not specifically designed and constructed to resist the earthquake hazards they are exposed to, pipelines are may be damaged from earthquake shaking or ground movements. To date most buried pipeline networks have never been improved to ensure post-earthquake water supplies can be provided to customers. Some above-ground pipelines have been designed and constructed to resist shaking or permanent ground movements.



**Welded steel transmission pipeline damaged from landslide in 1971 San Fernando earthquake. Image courtesy Los Angeles Department of Water and Power.**

**Building Structures**: Building structures are used in water systems for headquarters and other office buildings, maintenance yards, for pumping stations to house pumps and equipment, treatment plants and chemical storage, among other things. Buildings not designed or modified to meet expected seismic shaking are likely to be damaged in an earthquake. Buildings meeting current international seismic code requirements have a lower likelihood of collapse from shaking but may not be safely accessible after the earthquake nor usable to aid in supplying water for customers. Current codes are intended to prevent collapse and protect life but not necessarily be usable following a design level shaking. Buildings exposed to permanent ground movements can be severely damaged starting at the foundation level and propagating up into the main structure; large ground movements can pull structures apart and potentially lead to collapse. Common issues with building structures include roof connections, floor anchorage, structural components, soft stories, masonry infill, and non-ductile concrete.

**Tanks and Reservoirs**: Tanks and reservoirs may be above or below ground and are vulnerable to damage from shaking and water sloshing. These structures may be constructed of many different types of materials including masonry, reinforced concrete (normal or pre- or post-tensioned) or steel (bolted or welded). Older tanks and reservoirs not meeting current standards or code design (e.g. American Water Works Association standards or IBC) are subject to damage. Tanks and reservoir structural walls need to be properly anchored to the foundation to prevent sliding. Reinforcing is needed to handle the design base shear and overturning, including sloshing forces from the water and lateral forces from the roof structure. Adequate freeboard is needed to ensure sloshing does not damage the roof. The roof structure needs to be properly anchored to the tank or reservoir walls to ensure stability. Tanks and reservoirs not meeting these design requirements may leak, collapse or be sufficiently damaged not allowing them to be usable following an earthquake. These structures can be severely damaged from permanent ground movements. Small movements on the order of centimeters may be sufficient for some tanks or reservoirs to crack or separate at joints and leak sufficiently for them to become unusable or significant safety hazards. Large movements can render these structures completely unusable.

Some reservoirs are retained by dams. Dams may be made of masonry, concrete, earthen materials (rock, soil, etc.) and of any height. Concrete dams may be gravity or arch-type. Dams need to be designed to withstand earthquake effects and potential for weakening the foundation by degrading the soil modulus or from liquefaction. Dams not properly engineered or upgraded to current engineering standards may potentially result in severe earthquake damage and create concerns for a catastrophic release of water, which can result in severe loss of property and life. Older dams are of particular concern because they commonly do not meet current engineering standards unless they have been upgraded. Sufficient freeboard is needed for dams to prevent overtopping from seismically-induce seiche.

**Treatment Systems**: Treatment systems include the plants and greater chemical injection stations needed to ensure proper water quality. Treatment plants can be damaged from shaking, sloshing or permanent ground movements. Landslides and liquefaction are common causes of damage for treatment plants due to their natural locations near water sources. Structures and piping making up portions of the treatment systems have vulnerabilities as described for pipelines, building structures, tanks and reservoirs above. In addition, treatment plants and stations contain specialized equipment. Equipment in general is subject to damage as described in the paragraph below. Some specialized equipment for treatment systems are subjected to sloshing, which can result in severe damage and halt a portion or the entire treatment process until repaired or replaced. Examples include scrapers, baffles, aerators, clarifiers, and other equipment. Additional equipment and associated materials require proper supports and anchoring to keep them from sliding, falling, or tipping over. These include chlorinators, chlorine tanks, chemical storage, and other specialty items used within treatment systems and those described as part of the equipment description below. Hazardous material releases are of great concern following an earthquake because they potentially lead additional casualties and property damage. Except in regions where water system seismic design is commonplace, the seismic securing of specialized treatment system equipment may be overlooked.

**Atsuma Water Purification Plant destroyed by an earthquake-induced landslide in the 2018 Hokkaido Eastern Iburi Japan Earthquake. Images courtesy GEER, 2019.**

**Equipment**: Water systems use a variety of specialized equipment from computers to electrical cabinets and mechanical devices. These can also include pumps, valves, emergency generators, transformers, and other aspects built directly within the water system or linked to support the system as key components needed to support the water system operations (e.g., connections and stations from electric power, natural gas, fueling, and waste discharge systems). The variety of equipment is too long to list but includes all apparatus needed to operate and monitor the supply, treatment, transmission, and distribution subsystems. It is important to ensure all equipment are designed to secure critical systems against horizontal and vertical shaking. This is commonly accomplished using anchorage systems. In some cases, chains and strapping are sufficient to secure them. Further, the buildings and structures housing equipment must be structurally stable to ensure protection and allow post-event operations. Except in regions where water system seismic design is commonplace, the seismic securing of specialized treatment system equipment may be overlooked.

**Damaged tank inlet/outlet lines in the 1994 Northridge earthquake. Image courtesy Los Angeles Department of Water and Power.**

**Pipe-Structure interfaces**: Movement from earthquake shaking, landslides, or other earthquake-induced permanent ground movement results in differential displacements between buildings and connecting pipelines. This is true regardless of the pipelines or structures being buried or above ground. Pipelines at interfaces are commonly damaged when the connections do not have adequate flexibility to handle the differential displacements.

## Challenges and Potential Solutions for Water System Resilience

The hill cities face many challenges related to earthquake and landslide hazards. The most critical are those related to earthquakes, but the most common are those related to individual landslides. The following outlines the challenges, mostly focusing on those resulting from potential earthquakes. Each item identifies a challenge, which is followed by describing actions which can be taken to improve water system resilience. Actions are rated as [H] High, [M] Medium, or [L] Low relative to each other. These ratings are intended to give an indication of relative importance and benefit for improving resilience based on existing India Hill City conditions.

1) **Numerous pipe breaks all at once in distribution network (i.e., from shaking, settlement, landslides).**

   Challenge: 100s to 1000s of pipe breaks are anticipated based on the experience of the GHI/GHS team, given the water systems' piping and the terrain exposed to a magnitude 7-8 earthquake. This number of pipe repairs were observed in the 1994 Northridge, 2008 Wenchuan, and 2015 Nepal earthquakes where similar pipeline materials were used, just as examples.

Resilient Actions:

a) Stockpile materials (pipes, clamps, etc.) which can be used for rapid repairs (it is best if the type and number of materials are based on an analysis of expected damages). This allows water systems to have materials on hand after a damaging earthquake to potentially initiate repair work right away. Additional materials needed for repairing the systems may not be immediately accessible due to road closures and the extent of damage in the greater region from the earthquake (many other water systems will be damaged resulting in competition for the same materials). [H]
b) Develop plans, and include in an emergency response plan, for wetting the network, identifying leaks, making repairs, and disinfecting pipelines. Water flow is needed in the pipelines to find most pipe damages. If there is no water in the pipes, it is difficult to locate pipeline damage. It is the leaking of water to the surface that easily allows most damage detection. [M]
c) Perform landslide hazard assessment to know where landslides are located and most likely to occur. Use results to preliminarily mitigate or plan for how to repair the water system in these places (sufficient mitigation designs). These plans should be included in the emergency response plan. [H]
d) Add automatic isolation valves that sense rapid flow and lowering of pressure (this may have the most impact on transmission lines, see following section, and limited use in distribution areas not providing continuous water supply). [M-L]
e) Add flexible connections at interfaces to tanks, reservoirs, and pump stations. Rigid connections can break during earthquake shaking. [H]
f) Add instrumentation and monitoring to help identify damage. [M-L]
g) Utilize seismic resilient pipelines. There are emerging technologies which are proving very effective to withstand earthquake effects. Examples include butt-welded steel, high- and medium-density polyethylene with electrofused joints, and earthquake-resistant ductile iron. [H]

**Earthquake resistant ductile iron pipe. Image courtesy Kubota Corporation.**

2) **Transmission pipe exposure to landslide movements**

Challenge: Of the numerous earthquake-induced pipe breaks, several are expected on transmission pipelines which will remove essential water supplies from the city. Transmission pipelines are also highly exposed to individual landslide events, even without an earthquake or extreme monsoon event.

Resilient Actions:

a) Check pipeline structural capacity to resist forces resulting from permanent ground movement. There are methods for addressing needed structural capacity for anticipated permanent ground movements. More information is available in Wham and Davis (2019) and ALA (2005). [H]

b) Identify how to increase pipeline capacity to withstand ground movement based on results of the above action by either increasing strength and ability for joints to not separate, and/or adding flexibility into the pipeline. [H]
c) Identify areas prone to landsliding and engineer solutions for crossing these areas (i.e. avoidance or bridging)
d) Utilize actions listed for 1c to 1g above.

3) **Pumping stations, tanks and reservoirs, and other structures vulnerable to earthquake shaking**

Challenge: Pumping station, tank, and reservoir structures are vulnerable to damage from earthquake shaking. The damages commonly occur in roof connections, floor anchorage, undersized structural components, and buildings lacking an adequate lateral force resisting system. Load bearing (unreinforced) masonry and non-ductile concrete frame structures commonly have poor seismic performance. Certain features, such as very tall walls and gables in masonry buildings, and soft storeys in concrete buildings, make these structures more vulnerable to damage.

Resilient Actions:
a) Add flexible connections for pipelines at interfaces. Rigid connections can fail during earthquake shaking. [H]
b) Analyze structures to determine if strong earthquake shaking will result in collapse or damage such that they cannot be entered or used (design to the building code is inadequate to ensure structures are usable following a design-level event). Use a prioritization scheme as outlined in item 8a below. [H]
c) Anchor equipment, cabinets, and material storage units so that they do not injure workers, result in damage, damage any stored contents, or release any dangerous materials. [H]

4) **Treatment systems and equipment vulnerable to earthquake shaking, landslides, and sloshing**

Challenge: Treatment systems are vulnerable to earthquake and landslide damages as described in the prior section. Damages can occur from shaking, permanent ground movements and water sloshing.

Resilient Actions:
a) Address items 3a to 3c above.
b) Evaluate if specialized equipment is vulnerable to sloshing damage. [H]
c) Prepare repair plans and include in the emergency response plan. [H]
d) Identify methods for bypassing treatment plants to provide some water supply, even if poor quality. [H]

**Clarifiers are vulnerable to sloshing and ground movement. Image courtesy SJPNL.**

5) **Limited gravity water supply, high reliance on energy for pumping**

Challenge: The strong dependency on energy for pumping requires reliance on other systems for water system resiliency.

Resilient Actions:

a) Add a fuel-based (e.g. diesel) pumping system as emergency backup if they do not already exist, and maintain fuel supplies. [H]
b) Maintain emergency fuel contracts so that emergency supplies can be guaranteed. [H]
c) Strengthen electric power substations (anchor transformers and other equipment, design bushings for flexibility, etc.). [H]
d) Work with electric power company to ensure a seismically reliable system. [H]

**Diesel fuel emergency storage tank. Image courtesy AMC.**

6) **Limited emergency response preparation**

Challenge: The lack of emergency response preparation, including developing written plans and exercising them, leaves the water system vulnerable to lengthy restoration times following an earthquake.

Resilient Actions:

a) Create/update emergency response plans and practice carrying out the plans in regularly scheduled exercises simulating different emergencies. [H]
b) Prepare to deploy emergency water supplies, include this in the emergency response plan. [H]
c) Maintain emergency construction contracts to ensure equipment and operators are available for repairs. [M-H]
d) Create an emergency management system within the water system organization. [H]
e) Train and equip personnel for earthquake emergencies. This includes formal schooling on emergency preparedness and response fundamentals (for example, see FEMA, 2020 regarding Incident Command System training) and ensuring responders have proper materials and supplies easily accessible after an event such as personal protective equipment, maps and documents on critical system components, food, water, etc., beyond the normal equipment used to continually maintain water services. [H]
f) Improve documentation of existing facilities, especially the location of the buried pipeline network. [M-H]
g) Develop hazard scenarios (earthquake, landslide, extreme monsoon, etc.) to aid in preparing for disasters. [M-H]

7) **Limited knowledge on seismic and landslide hazards**

Challenge: The lack of knowledge about the seismic and landslide hazards a water system is exposed to limits the ability to manage a system resiliently. Knowledge of these hazards (i.e., expected shaking intensity, locations and extent of permanent ground deformation) allows for proper assessment of component-level damage.

Resilient Activities:

a) Identify plausible extreme earthquake and monsoon events. [H]
b) Perform landslide hazard assessment to know where landslides are located and most likely to occur. [H]
c) Develop and utilize earthquake and other hazard scenarios to enhance the understanding of each hazard and the locations likely to be affected by the hazards. [M-H]
d) Evaluate the potential for seismic and extreme monsoon-induced landslides:
    i) Damaging the system; and [H]
    ii) Blocking and/or silting the river sources. [H]

8) **Limited knowledge on system vulnerabilities to seismic and landslide hazards**

Challenge: The lack of knowledge about system vulnerabilities to seismic and landslide hazards limits the ability to manage a system resiliently. Knowledge on these vulnerabilities as described in the prior section allows for proper assessment of component-level damage and how the damages affect system-level performance and ability to provide services to customers. It also inhibits ability to plan for response, post-event repairs, and recovery.

Resilient Activities:

a) Perform system seismic assessments (e.g. assess each component, including pipelines, as well as how damage to a component can impact the overall ability for the system to operate), including: [H]
    i) Structural assessments of buildings and equipment housing structures; [H]
    ii) Prioritize carrying out assessments based on the component's risk related to: [H]
        (1) Life safety;
        (2) Importance of the structures and components for providing critical water services. Include contents for which building structures are housing (equipment, materials, etc.);
        (3) Vulnerability types (e.g., unreinforced masonry, non-ductile concrete, soft stories, anchorage concerns, etc.); and
        (4) Exposure (e.g., located on known landslide, expected large shaking intensity, in liquefaction hazard zone, etc.).
b) Identify vulnerabilities and prioritize improvements. Link with other needed system improvements where possible. [H]

9) **No fuel stockpile for vehicles and large equipment that will be needed to make repairs**

Challenge: Lack of fueling supplies strongly inhibits ability to rapidly respond to earthquake impacts. Fueling resources are expected to be limited and in high demand following an earthquake. Ability to replenish will be difficult due to expected damages to the regional and local transportation system.

Resilient Activities:

a) Create a fuel stockpile and ensure it remains in usable quality. [H]
b) Develop a Memorandum of Understanding (MOU) with several petrol stations that in a disaster will provide fuel only to the water agency or municipality, not consumers. [H]

10) **Lack of transparency to customers on hazards and system vulnerabilities**

Challenge: Customers have a need to know how the water system is expected to perform in an earthquake, the potential for loss of water services, and a realistic timeframe for restoring services based on science and engineering. The transparency is essential for customers to prepare for an earthquake event and is a major step for ensuring community resilience.

Resilient Activities:

a) Inform customers of landslide and earthquake vulnerabilities so they can be prepared. [M]
b) Inform customers of expected loss in services and realistic service restoration times based on the system seismic assessments identified in item 8 above. [M-H]

11) **Hundreds of earthquake-induced landslides occurring all at one time**

Challenge: An earthquake can generate hundreds to thousands of landslides (Rodgers et al., 2014), many of which will result in damage to the water, electric power, fueling, and transportation systems.

Resilient Activities:

a) Perform landslide hazard assessments/mapping to know where landslides are located and are most likely to occur. Use the assessments/map to plan for how to repair the water system in these places. [H]
b) Take preventative measures to divert surficial runoff away from slopes and control drainage. [H]
c) Acquire equipment or ensure access to equipment (e.g., dozers, excavators, laborers, and tools) to respond to multiple ground failure incidents at once. [M-H]
d) Stockpile materials that can be used to temporarily shore up hillsides (e.g., gabions, slope coverings, H-beam anchored wooden retaining systems, etc.). [H]

## Challenges and Potential Solutions Specific to Shimla's Water System Resilience

In addition to the challenges and potential solutions common to most hill cities as described in the prior section, here we identify specific challenges for Shimla's water system.

1) **Backup pumping power relies on electrical grid**

Challenge: Redundancy is an important trait of a resilient network. Understanding the dependencies and interdependencies is also a resilient trait. Electric power systems are vulnerable to loosing service provision from earthquake damage. Even though Shimla has back-up generators, they are as dependent on electricity as the primary pumps. As a result, Shimla's ability to provide water following an earthquake has no redundancy to the electric power system.

Resilient Actions:

a) Increase the resilience of the electric power network. [H]
b) Develop sources of emergency power generation using liquid fuel-based energy sources (e.g. diesel) and ensure adequate fuels are available for use following an earthquake. [H]

2) **Without electrical power, cannot pump from major water sources (Giri and Gumma); resulting in a supply volume much less than demand**

Challenge: The majority of the water supply is dependent upon electric power. In absence of electric power, inadequate water supplies can be provided resulting in public health and safety concerns.

Resilient Activities:

a) Explore diesel pumps with the ability to lift the full elevation gain needed, or install booster stations that use diesel power. [H]
b) Prepare to provide for emergency water supplies (domestic and fire-fighting use). [H]

## Challenges and Potential Solutions Specific to Aizawl's Water System Resilience

In addition to the challenges and potential solutions common to most hill cities, as described in the prior section, here we identify specific challenges for Aizawl's water system.

**1) Buried pipelines are corroding**

Challenge: Corroding pipes loose strength and are more vulnerable to leakage on a daily basis and to damage in an earthquake. A deteriorated pipeline network will have an increased number of post-earthquake repairs.

Resilient Activities:

a) Replace pipelines with non-corrosive or corrosion protected materials. [M-H]
b) Line interior of pipelines. [M-H]

**2) Silt in water requiring extensive cleaning**

Challenge: Aizawl currently has a problem with excessive silt in the source water and needs to clean and dispose of the particles removed from the water during treatment. The expected large number of landslides from an earthquake will significantly increase the amount of silt in the source water for long periods of time.

Resilient Activities:

a) Prepare a plan that includes labor, equipment, and disposal for cleaning extensive silt build-up after earthquakes. Include this as part of the emergency response plan. [H]
b) Identify potential methods to reduce silt build-up, such as adding pre-settling capabilities (pending space availability). [M-H]

## Recommended Near-Term Actions for Increasing Earthquake Resilience for Shimla's Water System

The following items are recommended actions to be taken based on observations of the GHI/GHS team through the on-line discussions with Shimla. Shimla identified need for and interest in creating emergency response plans. Based on the understanding obtained on Shimla's current preparation status, the GHI/GHS team believes this is one of the most important activities Shimla can undertake at this time to improve its resilience.

1) Create an earthquake disaster scenario to aid in planning and exercising for likely impacts.
2) Develop and adopt an emergency response plan. This should take place in advance of completing the scenario and should be updated based on the scenario findings.
3) Practice the emergency response plan with regular emergency drills.

## Recommended Near-Term Actions for Increasing Earthquake Resilience for Aizawl's Water System

The following items are recommended actions to be taken based on observations of the GHI/GHS team through the on-line discussions with Aizawl. Aizawl identified need for and interest in utilizing the existing earthquake scenario to improve emergency planning. Based on the understanding obtained on Aizawl's current preparation status, the GHI/GHS team believes this is one of the most important activities Aizawl can undertake at this time to improve its resilience.

1) Use the existing earthquake scenario (Rodgers et al., 2014) to aid in planning/exercising for likely impacts.
2) Use the existing landslide hazard maps to identify areas of very high hazard and risks to the water system.
3) Review and further develop the emergency response plan.
4) Practice the emergency response plan with regular emergency drills.

## Overarching Opportunities for Increasing Water System Earthquake Resilience

In addition to the above identified resilient activities that hill cities may undertake to improve resilience, and the specific solutions and recommendations for Shimla and Aizawl, the following lists some overarching opportunities all hill cities may undertake to improve resilience for water systems and the greater community exposure to landslides.

1) Develop regulations on slope excavations to reduce instability that an earthquake would exploit.
2) Raise public awareness on avoiding activity that makes slopes more susceptible to landslides during the monsoon and an earthquake.
3) Develop a Continuous Resilience Program for the water agency (see Davis et al., 2018).
4) Appoint a Resilience Manager for the water agency to be responsible for:
    a) Emergency planning & response; and
    b) System mitigation.
5) Prepare a water system infrastructure resilience plan (i.e., a written plan consistent with Davis et al., 2018, that assigs responsibilities and is updated on a periodic basis to implement the resilience program).
6) Budget and implement resilient activities on an annual basis.
7) Mainstream resilient thinking, activities, and discussions (i.e., discuss earthquakes in every water system meeting).

## Conclusions and Encouragement for Taking Action on the Way Forward

This document identifies vulnerabilities of hill cities and how their water supply systems can be damaged from landslides and earthquakes. It further discusses opportunities for improving the resilience to water systems. Although this document is a result of a program focusing on the exposure of water systems in Aizawl, Mizoram, and Shimla, Himachal Pradesh, the challenges are not unique to these cities or even India's hill cities. Most concerns are common to water systems around the world. The solutions offered above are being implemented in various forms by many different water systems. With each action, the water system becomes more resilient. Creating a resilient water system requires a long-term program that becomes mainstream within the agencies and communities they serve. The authors offer this way forward as a way to leverage what others' have already learned, so that when a major earthquake occurs, your water system is already ahead. If you wait to implementing resilient actions once an earthquake has damaged your system, your way will be harder and more expensive.

One useful example of learning from others' experience comes from the Los Angeles Department of Water and Power (LADWP) which has experienced multiple earthquake events since it was developed. The most notable earthquakes were the 1971 San Fernando and 1994 Northridge earthquakes. Both events were Magnitude 6.7 and shook similar areas of the Los Angeles. Prior to 1971, the LADWP was proud of the important actions taken to ensure the system would perform as best it could in an earthquake (Lund and Davis, 2005). Even though efforts were made using the technologies of the time, they were not enough to prevent great devastation to the water system from the 1971 earthquake. That earthquake damaged nearly every type of facility within the water system. The LADWP system is extremely large in area, so much was spared from damage, but the components experiencing large shaking were severely damaged. It took nearly 20 years of concerted effort and great expense to get the system working as it did prior to the earthquake. This was followed by several more decades of significant effort to upgrade and improve other facilities across the system to be less vulnerable to earthquakes.

Twenty-three years later a similar sized event, the Northridge earthquake, struck the LADWP water system in 1994. The earthquake again caused significant damages even though there were many prior seismic upgrades; the greatest damages occurred to those facilities which were not seismically improved. However, the overall performance was significantly better than in 1971. Water was lost to about 670,000 people from the 1994 event, but all customers had water services restored within 12 days (Davis et al., 2012). The LADWP water system is considered to have been highly resilient to this earthquake.

Some important lessons were learned from the 1994 event, coupled with the prior 1971 earthquake. First, it is difficult to prevent earthquake damage in such large complicated systems, but systems can still be designed, constructed, and managed to be resilient. Second, resilience requires a continued and focused effort. Different earthquakes can cause different types of problems, requiring numerous re-evaluations as knowledge is improved. As a result, the LADWP continues to implement seismic mitigation measures and improve emergency response capabilities through a continuous resilience program (Davis, 2018). The continuous resilience program is integrated with an asset management program to improve facilities when they require an upgrade or replacement; this program is combined with specific seismic improvement projects as found necessary. Resilience is best achieved through considering a systems approach and focus on restoring service to customers as quickly as possible. This is most effectively achieved through a comprehensive program. The lessons here are applicable to all lifeline systems, not just water supply. Organizations need to work together to address resilience, as each system is required for a healthy community.

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