9. Water and Wastewater Sector

9.1. Introduction

Water and wastewater systems play a critical role in our daily lives. They provide basic services for our homes, places of business, and industry. In the United States, most people take these services for granted because of the high level of service and reliability generally provided by water and wastewater utilities. It is not until a water main break or other disruption in service occurs, that we are reminded of the importance of water and wastewater systems.

This chapter addresses disaster resilience of utility-scale water and wastewater systems. While water and wastewater infrastructure that serve only a small number of households, such as groundwater wells and septic systems, are not specifically addressed, the basic resilience concepts are also generally applicable to these individual systems.

Utility-scale water and wastewater lifelines are often complex systems consisting of large distributed pipeline networks and localized facilities such as treatment plants and pump stations. The infrastructure for these systems was installed as communities developed and expanded over time. The American Society of Civil Engineers (ASCE) 2013 Report Card for America's Infrastructure gave the nation's water and wastewater systems a grade of D. A primary reason for this low grade is much of the water and wastewater infrastructure is reaching the end of its useful life; it is not uncommon for some system components to be over 100 years old.

While some utilities are already taking steps to improve the resilience of their system, capital improvement programs of many others often focus on emergency repairs, increasing system capacity to meet population growth, or making system improvements to satisfy public health and environmental regulations. Replacement of buried pipelines is often delayed until water main breaks become frequent or wastewater pipeline groundwater infiltration rates create excessive demand on the treatment system. Communities have a perfect opportunity to couple resilience improvements with retrofit or replacement of aging infrastructure over the coming years to improve the resilience of water and wastewater infrastructure.

9.1.1. Social Needs and Systems Performance Goals

The average person uses between 80–100 gallons of water per day. Personal uses include water for drinking and cooking, personal hygiene, flushing toilets, laundry, landscape irrigation, and many others. Many businesses and industries are also dependent on a continual supply of potable water and wastewater collection services. Without functioning water and wastewater systems the operation of restaurants, child care facilities, hotels, medical offices, food processing plants, paper mills, etc. is not possible. Additionally, water systems in urban and suburban areas provide emergency water supply for fire suppression. Chapter 2 discusses this societal dependence on water and wastewater systems and other lifelines in more detail.

In the United States, communities are generally willing to accommodate short-term (on the order of a few days) disruptions in water and wastewater services resulting from man-made or natural disasters. However, longer-term disruptions are less tolerable. The *Oregon Resilience Plan* (OSSPAC, 2013) indicated if business cannot reoccupy facilities (including functioning water and wastewater systems) within one month they will be forced to move or dissolve. This timeline likely varies depending on the needs of individual communities and the severity of the disaster. As detailed in Section 9.3, water and wastewater utility providers need to work with customers and regulatory agencies to establish realistic performance goals for post-disaster level of service, evaluate their systems' current status in relation to those goals, and then develop strategies to close the identified resilience gaps.

9.1.2. Interdependencies

As described in Chapter 4, the operation and repair of water and wastewater systems is highly dependent on other lifeline sectors. Other sectors are dependent on water and wastewater systems.

Water and Wastewater Systems depend on:

- ***Transportation –*** Water and wastewater utilities are dependent on roadway and bridge transportation systems for staff to access facilities for operation and repairs. Disaster damage to transportation infrastructure has the potential to complicate and lengthen repair times, or even prevent repairs in certain areas until roadways and bridges are accessible.
- ***Transportation –*** Water and wastewater buried pipelines are often co-located near other buried lifelines under or adjacent to roadways. Failure of pipelines may result in damage to the roadway (e.g., sinkhole from water main break or collapsed sewer pipeline) and impact to traffic when repairs are being made. Sometimes water and wastewater pipelines are co-located on bridges at river or other crossings. If not properly designed, relative movement between the bridge and surrounding soil could result in damage to the supported pipelines. Pipeline damage could result in damage to the bridge. For instance, if a supported water pipeline breaks due to relative movement between the bridge and surrounding soil, water flow from the broken pipe could cause scour of the soil supporting the bridge abutment and result in potential bridge collapse.
- ***Transportation –*** Water and wastewater utilities generally keep on hand a limited stock of pipe, fittings, and other repair materials. Depending on the size of the disaster, this stock may be quickly depleted. Utilities will rely on transportation networks to obtain additional repair materials from suppliers and other utilities. Also, utilities rely on a semi-regular delivery of water and wastewater treatment process chemicals. Supply chain disruption could lead to difficulty in meeting water quality and wastewater treatment regulations.
- ***Energy –*** Water and wastewater utilities rely on commercial electricity to run pumps, various components of processes equipment, and lab and office operations. Some of these functions have emergency backup generators, but overall power demands make it impractical to run a water or wastewater system entirely on backup generators.
- ***Energy –*** Water and wastewater utilities rely on a continual supply of fuel for trucks, equipment, and emergency generators. Disruption in fuel production, storage, or delivery could severely impact a utility's ability to continue limited operation on emergency generator power and perform repairs.
- ***Communications and Information –*** Water and wastewater utilities often rely on cellular networks for communication amongst operations staff and contractors. If the cellular network is down for an extended period of time, complications and delay in repairs can occur. This was observed in the 2010 Maule earthquake in Chile (Eidinger, 2012).
- ***Customers –*** Water and wastewater utilities rely on customers to pay bills as a continued source of operating capital. Utilities will potentially experience significant capital expenditures in the aftermath of a disaster and customers may not have the ability to pay bills, placing a large financial burden on the utilities.

Water and Wastewater Systems are required by:

- ***Wastewater –*** Wastewater collection systems are dependent on adequate water flow rates to keep sewage flowing. If the water system is down, sewer pipelines may quickly become plugged.
- ***Communications and Information –*** Air conditioning system cooling towers require water to keep sensitive electronic equipment in central offices at safe operating temperatures.
- ***Hospitals –*** Hospitals generally have a limited emergency water supply and ability to hold wastewater, but need water and wastewater services restored quickly to remain operational.
- ***Fire Departments –*** Fire Departments require a water supply with adequate fire flow and pressure for fire suppression.
- ***Commercial Buildings –*** Commercial buildings require a water supply with adequate fire flow and pressure for sprinkler systems; otherwise a fire watch may be necessary. Fire watch programs are expensive to maintain and may be cost prohibitive for any extended duration.

- ***Restaurants –*** Restaurants need water and wastewater service for cooking and cleaning.
- ***Hotels –*** Hotels need water and wastewater services for guest use and laundry.
- ***Agriculture –***Horticulture crops and livestock need water for irrigation in areas where precipitation is insufficient.
- ***Residential –*** Residential water and wastewater use includes drinking, food preparation, bathing, etc.

These items illustrate how highly interdependent water and wastewater systems are with other lifeline systems and how dependent communities are on water and wastewater services to maintain normalcy.

9.2. Water Infrastructure

This section describes basic components of water and wastewater systems. Performance observations from past disaster events characterize some key disaster vulnerabilities in water and wastewater systems, especially for the high-seismicity regions of the western US, and areas around Charleston, South Carolina and Memphis, Tennessee. While seismic hazards can broadly impact water and wastewater systems given that earthquakes regularly cause damage to buried lifelines (e.g., water distribution and wastewater collection systems), other hazards can have major impacts on aboveground and below grade (unburied) facilities like treatment plants and pump stations. In fact, water and wastewater treatment facilities are vulnerable to flood hazards because they are often located in or near flood hazard areas by design, given their functional dependency on natural water resources. It is important to appropriately consider all identified hazards when evaluating disaster resilience of water and wastewater systems. System interdependencies (e.g., loss of commercial electrical power in a wind event) can have a significant impact on operability of water and wastewater systems (Elliott, T. and Tang, A., 2009).

9.2.1. Water Systems

Water systems provide potable water for household, commercial, and industrial use. Water is obtained from groundwater or surface water sources, treated to satisfy public health standards, and distributed to consumers by a network of pipelines. Some water utilities have their own supply and treatment infrastructure, while others buy wholesale water from neighboring agencies.

Water systems are composed of five general infrastructure categories: 1) Supply (i.e., groundwater wells and surface water), 2) transmission, 3) treatment, 4) pumping, and 5) storage. The basic function of each of these categories is briefly described below.

9.2.1.1. Supply

Groundwater. Rainfall and snowmelt infiltrate into the ground to recharge groundwater aquifers. Groundwater wells tap into aquifers and supply water to individual households or municipal water providers. A well system consists of the groundwater aquifer, well casing and screen, pump and motor, power supply, electrical equipment and controls, connecting piping, and possibly a well-house structure. Typically wells are cased with a steel pipe to keep its sides from caving in. Screens in the well casing at the depth of the aquifer allow water to enter the casing. A submersible or surface-mounted pump conveys water to the transmission system.

Surface Water. Rainfall and snowmelt runoff that does not infiltrate into the ground collects in streams, rivers, and lakes, and is sometimes impounded by dams. Water intake systems vary depending on source type. Increased turbidity (suspended solids) of surface water supplies can decrease the amount of raw water a treatment plant is able to process and may cause surface water sources to become temporarily unusable.

Typical damage to water supplies includes:

- Flooding can cause contamination of surface and ground water sources. Floodwaters are rarely "clean" and generally include contaminants like petroleum, nutrient/organic matter, bacteria, protozoa, and mold spores that pose significant health risks.

- Earthquake-induced permanent ground displacement can cause well casing and well discharge piping damage. The force of moving ground can bend well casings and brake well discharge piping.
- Increased turbidity of surface waters as a result of flooding can overwhelm water treatment systems. Water treatment processes include removal of particulates; however, their processes are based on a limited measure of turbidity existing prior to treatment. Floodwaters can have significantly increased turbidity that tax water systems and lead to treatment delays. Similarly, seismic events can trigger landslides which also impact turbidity. In the 2008 Wenchuan China earthquake, many landslides occurred in the mountainous region and led to increased turbidity in local waterways.
- In the 2011 Tohoku Japan earthquake, a tsunami inundated several freshwater intake facilities with seawater. These water intakes were unusable for a long period of time due to the high concentration of salts in the water (Miyajima, 2012). This type of salt water infiltration of water treatment systems is often experienced after storm surge events and as a result of coastal flooding in general.
- Reservoirs behind dams often serve as water supply features, but dam failure can present a secondary hazard in the wake of events including earthquakes, heavy rainfall, and flooding events.
  - Concentrated rainfall or precipitation and flooding can result in the most common means of dam failure: overtopping. While dams can control floods, many are specifically designed for other uses (e.g., water supply facilities), and therefore may not be equipped to contain large volumes of quickly accumulating surface water runoff. Additionally, older and poorly maintained dams are more vulnerable to overtopping or failure as the result of heavy precipitation and flooding.
  - In the 1971 San Fernando earthquake in Southern California, the Lower San Fernando Dam experienced a landslide and near failure. The event lowered the dam’s crest about 30 ft and put 80,000 people at significant risk while the impounded water level was being lowered. These types of dam failures are rare, but present a significant life-safety risk to anyone downstream of a dam. Dams are critical infrastructure components that need to be designed to withstand extreme events.

9.2.1.2. Transmission

Water system transmission and distribution pipelines are a significant asset class for water utilities. Large water utilities may have a network consisting of thousands of miles of pipelines. Typically these pipelines operate under pressure and are buried 2.5–6 feet or deeper underground, making them difficult to inspect and expensive and disruptive to repair. Pipeline material and joint type significantly influence the performance of a pipeline when it is located in an area subjected to permanent ground deformation occurring in an earthquake or landslide. Table 9-1 summarizes commonly in-place and currently used pipeline materials and joint types, along with their applicable American Water Works Association (AWWA) standard. Materials and joint types with no designated standard are no longer manufactured, but represent a significant portion of the installed pipelines in the US.

Table 9-1: Commonly Used Water Pipeline Materials, Standards, and Vulnerability To Ground Deformation (AWWA, 1994)

Material Type and Diameter	AWWA Standard	Joint Type
Low Vulnerability		
Ductile Iron	C100 series	Bell-and-spigot, rubber gasket, restrained
Polyethylene	C906	Fused
Steel	C200 series	Arc welded
Steel	No designation	Riveted
Steel	C200 series	Bell-and-spigot, rubber gasket, restrained
Low to Moderate Vulnerability		
Concrete cylinder	C300, C303	Bell-and-spigot, restrained
Ductile iron	C100 series	Bell-and-spigot, rubber gasket, unrestrained
Polyvinyl chloride	C900, C905	Bell-and-spigot, restrained
Moderate Vulnerability		
Asbestos cement (> 8-in. diameter)	C400 series	Coupled
Cast iron (> 8-in. diameter)	No designation	Bell-and-spigot, rubber gasket
Polyvinyl chloride	C900, C905	Bell-and-spigot, unrestrained
Steel	C200 series	Bell-and-spigot, rubber gasket, unrestrained
Moderate to High Vulnerability		
Asbestos cement (≤ 8-in. diameter)	C400 series	Coupled
Cast iron (≤ 8-in. diameter)	No designation	Bell-and-spigot, rubber gasket
Concrete cylinder	C300, C303	Bell-and-spigot, unrestrained
Steel	No designation	Gas welded
High Vulnerability		
Cast iron	No designation	Bell-and-spigot, leaded or mortared

Transmission Pipelines. Large diameter (> 12 in) transmission pipelines carry raw water from a source to the treatment plant, and treated water to storage facilities and community sectors before branching out into smaller diameter distribution pipelines. Transmission pipelines can be thought of as the backbone of the pipeline system.

Distribution Pipelines. Smaller diameter (≤ 12 in) distribution pipelines carry treated water from transmission pipelines to neighborhoods and industrial areas. For some smaller utilities, major transmission lines may also fall in this diameter range. Service connections branch off distribution pipelines to supply individual customers. The portion of the service connection before the water meter is typically maintained by the water utility and the portion after the water meter is the responsibility of the individual customer.

Buried pipelines are less vulnerable to some types of hazards (e.g., wind), but seismic events often result in widespread damage of buried infrastructure. Flood forces can also impact buried systems. Typical damage to water pipelines includes:

- Buried water pipelines can become exposed as a result of landslides (particularly in steeper terrain) or erosion associated with flood hazards. In these instances, pipe leaks, breaks and uncoupling of pipes are common. Breaks and leaks in buried water pipelines are one of the largest earthquake damage mechanisms in water systems.
  - "Leak" commonly refers to relatively minor damage to a pipe barrel or joint that results in minor to moderate water loss, but does not significantly impair the distribution system's function.
  - "Break" commonly refers to major damage to a pipe barrel or joint that results in major water loss that may cause loss of pressure in a zone or nearby tanks to completely drain.

- Pipeline leaks and breaks can cause collateral damage to adjacent infrastructure. Figure 9-1 shows the geyser from a water pipeline break in the 2011 Christchurch New Zealand earthquake and the damage it caused to the roadway. A major cause of pipeline breaks and leaks is liquefaction-induced permanent ground displacement. Large strains develop in pipelines at the movement boundaries between areas that did and did not experience permanent ground displacement. Another location of potential damage from permanent ground displacement is where pipelines cross active faults. Pipelines failed in past earthquakes at fault crossings that were not explicitly designed for the expected fault movement.
- Pipeline failures generally fall into one of several common types. Earthquake failure of pipe commonly initiates at locations of existing corrosion damage. For bell-and-spigot type joint pipe subjected to axial strains, pipe sections may pull apart (see Figure 9-2) or push together (“telescope”) resulting in damage to the pipe. Welded steel pipe may experience a similar axial compression failure where the walls of the pipe locally wrinkle to accommodate shortening of the pipe section (see Figure 9-3). Pipes may also fail in the middle of the pipe barrel, away from the joints (see Figure 9-4).

Figure 9-1: Water Pipeline Break, Christchurch Earthquake, Christchurch, New Zealand, 2011 (Source: Eidinger & Tang, 2014)

Figure 9-2: Pipeline Separated, Great Hyogoken-Nanbu Earthquake, Kobe, Japan, 1995 (Source: OSSPAC, 2013)

Figure 9-3: Welded Steel Pipe Compression Failure, San Fernando Earthquake, California, 1971 (Source: OSSPAC, 2013)

Figure 9-4: Water pipeline break, Christchurch earthquake, Christchurch, New Zealand, 2011 (Source: Eidinger & Tang, 2014)

- Pipeline damage is often concentrated at discontinuities such as pipe elbows, tees, in-line valves, reaction blocks, and service connections. Discontinuity creates a semi-support point that attempts to restrain movement of the pipe and causes locally high stresses in pipes and joints. If these stresses become too high the pipe or joint fails in a manner similar to one of the mechanisms described above.
- Major earthquakes continue to reveal new information about pipe material performance. For instance, in the City of Sendai in the 2011 Tohoku earthquake in Japan, polyvinyl chloride (PVC) pipe had twice the failure rate of steel or ductile iron pipe (Miyajima, 2012). Pipeline performance lessons

from past earthquakes have led to improvements in pipe materials and technology. Earthquake resistant ductile-iron pipe products have been developed in Japan. This pipe uses special restrained joints that accommodate axial and bending deformation in the joints. This type of pipe demonstrated good performance in the 1995 Kobe (NIST, 1996) and 2011 Tohoku (Tang & Edwards, 2014) earthquakes. High-Density Polyethylene (HDPE) pipe has been used by the natural gas industry for decades and is seeing increased use by water and wastewater utilities. HDPE water pipelines demonstrated good performance in the 2010 Chile (Eidinger, 2012) and 2011 Christchurch (Eidnger and Tang, 2014) earthquakes.

- Due to extensive damage to water distribution networks resulting in loss of service to individual customers, a system of emergency water distribution stations are often necessary after an earthquake. Figure 9-5 shows an example of a water distribution station employed after the 2010 Haiti earthquakes. Also, temporary small-scale water treatment plants were used after major earthquakes where the system treatment plant was not operational or operating at very limited capacity. Water systems typically rely on mutual aid and government resources to augment the limited trucked-in water distribution and treatment equipment that an individual utility may have available.
- In the Tohoku Japan earthquake, tsunami inundation resulted in erosion and several feet of scour that uncovered, undermined, and broke several large diameter (36 in and greater) pipelines (Tang & Edwards, 2014). It is expected that more tsunami damage to pipelines will be revealed as areas in the inundation zone are rebuilt.
- Water pipelines co-located on bridges often experience damage as a result of flood inundation and/or flood-borne debris impact. Hydrodynamic forces associated with coastal flooding or high velocity flows are more likely to damage structures and attached pipelines than inundation alone.
- Soil saturation combined with rising groundwater levels can result in uplift or buoyancy forces on buried pipelines and transmission structures leading to breaks within the system.

Figure 9-5: Water Distribution Location, Haiti Earthquake, Port Au Prince, 2010 (Source: Photo by Don Ballantyne)

9.2.1.3. Treatment

Water treatment plants process raw water from groundwater or surface water supplies to meet public health water quality standards and often to improve taste. Various processes are used, depending on the raw water source, to remove pathogens, organic or inorganic contaminants, chemicals, and turbidity. Water treatment plants typically consist of a number of process tanks, yard and plant piping, pumps, chemical storage and feed equipment, lab and office building space, and associated mechanical, electrical and control equipment.

Typical damage to water treatment plants includes:

- Water treatment plants are vulnerable to flooding because they are often located near flooding sources (i.e., lakes, rivers). Electrical control systems are often damaged as the result of flood inundation, leading to loss of functionality and service outages.
- Hydrodynamic forces generated from liquid movement within a process tank during an earthquake often cause damage to process tank covers, baffles, clarifiers, and other submerged equipment. This sloshing damage to process tank components has been observed in all recent major earthquakes (Ballantyne and Crouse, 1997; NIST, 1996; Schiff, 1997).

- Liquefaction-induced permanent ground displacement causes separation of process tank construction joints, damage to pipelines, pipe racks, etc. Figure 9-6 shows pipeline damage due to differential settlement between the ground and an adjacent pile supported building.
- Seismic performance of buildings at water treatment plants is dependent upon the type and year of original construction and any seismic retrofits that may have been completed. Unreinforced masonry and older tilt-up concrete buildings are particularly vulnerable to damage in earthquakes.
- Building performance as a result of wind events is also dependent on building construction type and year. Building codes continue to incorporate strengthened wind-resistant design and construction requirements, but older building stock is at a higher risk. Buildings with continuous load paths for all loads (gravity, uplift and lateral), protection for openings (windows, doors), and adequate roof and wall coverings are better protected against the wind hazard.
- Temporary, small-scale water treatment plants (see Figure 9-7) are sometimes used after major earthquakes in areas where the system treatment plant is not operational or operating at very limited capacity. Water systems typically rely on mutual aid and government resources to augment the limited temporary treatment equipment that an individual utility may have available.

Figure 9-6: Pipeline Damage Due To Differential Settlement Between Ground and Pile Supported Building, Tohoku Earthquake, Japan, 2011 ***(Source: Tang & Edwards, 2014)***

Figure 9-7: Temporary Water Treatment Plant, Haiti Port Au Prince Earthquake, 2010 ***(Source: Photo by Don Ballantyne)***

9.2.1.4. Pumping

Pumping stations increase hydraulic head (i.e., raise water from one elevation to a higher elevation). A pump station typically consists of a simple building that houses pumps, motors that power the pumps, pipes, valves, and associated mechanical, electrical and control equipment. Pump stations often have standby emergency generators to enable continued operation when commercial power supply is interrupted.

Typical damage to water pump stations includes:

- Loss of commercial electrical power due to any type of hazard event prevents operation of pumps if there is no backup power supply.
- Floodwater inundation of pumps can disable and damage pumps and their motors.
- Floodwater inundation of electrical equipment and controls at pump stations located wholly or partially below grade and/or in flood-prone areas. Figure 9-8 shows a pump station adjacent to the Missouri River damaged by flood inundation.
- Seismic performance of pump station buildings is dependent upon the type and year of original construction and any seismic retrofits that may have been completed. Figure 9-9 shows significant cracking of the unreinforced masonry wall at a pump station after the 2011 Christchurch earthquake in New Zealand.

***Figure 9-8: Bismarck, ND Pump Station Damaged By Flood Inundation From Adjacent Missouri River** (Source: FEMA)*

***Figure 9-9: Pump Station Damage Due To Differential Settlement, Christchurch New Zealand Earthquake, 2011** (Source: Eidinger & Tang, 2014)*

- Building performance as a result of wind events is dependent on building construction type and year and the overall ability of the building envelope to stay intact during high winds as well as having a continuous load path.

9.2.1.5. Storage

Water utilities use storage tanks and reservoirs to balance water demand with water production capacity. Stored potable water is drawn down during times of peak usage and recharged during off-peak hours. Typically one to three days of average daily water demand is stored to satisfy increased usage demands from fire suppression or other emergency needs. Elevated storage tanks can be used to increase hydraulic head, as required by the characteristics of the distribution system.

Modern utility-scale storage tanks and reservoirs are constructed of steel or concrete. Typical construction types and their associated design standard are indicated in Table 9-2. Potable water in-ground reservoirs are often concrete-lined earthen structures. Security concerns require the reservoirs to be covered, typically with a concrete, metal, or wood roof supported by intermediate columns.

Table 9-2: Tank/Reservoir Types And Design Standard

Tank/Reservoir Type	Design Standard[1]
Ground-supported steel reservoir	AWWA D100
Steel standpipe	AWWA D100
Elevated steel tank	AWWA D100
Reinforced concrete tank	ACI 350
Wire- and strand- wound, circular, prestressed concrete tank	AWWA D110
Tendon-prestressed concrete tank	AWWA D115

Typical damage to water storage tanks and reservoirs includes:

- Elevated storage tanks are more susceptible to hazards from high winds than structures located at grade and can be damaged to the point of structural failure resulting in sudden release of their contents. High winds present a higher hazard in coastal areas.
- At grade or partially underground storage tanks are more susceptible to flood damage, particularly if located in or near flood-prone areas. Hydrostatic forces from standing or slow moving water or hydrodynamic forces imposed by higher velocity flows or wave action can damage or cause failure of the tanks. Buoyancy forces can cause uplift of subgrade tanks if the soil becomes saturated.
- Inlet and outlet piping connections on water storage tanks and reservoirs are prone to damage from a variety of hazards, particularly when the storage tank itself is damaged or fails. Figure 9-10 shows mechanical piping joints adjacent to a steel tank that were separated during the 1994 Northridge

[1] AWWA is American Water Works Association. ACI is American Concrete Institute.

earthquake. This type of damage typically occurs because a tank/reservoir is not adequately anchored to the ground or because of permanent ground deformation in the area surrounding the tank.

- Earthquake shaking induces hydrodynamic forces in the liquid retained within a tank that must be resisted by the tank's walls. If the tank wall thickness is not adequate to resist these loads, the tank wall may buckle. This type of buckling damage is commonly referred to as elephant's foot buckling because the buckled shape (see Figure 9-11) resembles the foot on an elephant.

Figure 9-10: Tank Piping Separated, Northridge Earthquake, California, 1994 (Source: Schiff, 1997)

Figure 9-11: Steel Tank "Elephant's Foot" Buckling, Northridge Earthquake, California, 1994 (Source: Photo by Don Ballantyne)

- Hydrodynamic forces generated from liquid movement within a tank during an earthquake often cause damage to tank roofs and submerged piping and equipment within a tank. Figure 9-12 shows damage to a concrete roof panel due to water sloshing around inside the tank during the earthquake.
- Water storage tanks are often located on high ground to help maintain adequate water pressure for customers. The ground around these water storage tanks often slopes away from the tank at a moderate to steep grade and may present a geotechnical landslide hazard.

(a) Overview ***(b) Close-up***

Figure 9-12: Segmented Concrete Reservoir Roof Damage, Christchurch Earthquake, Christchurch, New Zealand, 2010 (Source: Eidinger & Tang, 2014)

- Water storage tanks (especially partially empty tanks) in a tsunami inundation zone may be subjected to buoyancy (uplift) and wave impact forces that may be much larger than the seismic anchorage the tank was designed to resist. Figure 9-13 shows an example of this behavior: two liquid fuel tanks in the foreground were floated and toppled by tsunami wave inundation after the 2011 Tohoku Japan earthquake. The tank in the background was on higher ground and does not appear to be damaged.

Figure 9-13: Steel Tanks Displaced Due To Tsunami Inundation, Tohoku Earthquake, Japan, 2011 (Source: Tang & Edwards, 2014)

9.2.2. Wastewater Systems

Wastewater systems collect domestic and industrial liquid waste products and convey them to a treatment plant in a sewer (pipeline). After separation of solids, processing and disinfection, treated wastewater is discharged as effluent into a receiving body of water or may be reused for irrigation or other purposes. Some utilities have separate collection systems for wastewater and storm water. Other utilities have collection systems that are combined and collect both wastewater and storm water in the same pipelines.

Wastewater systems are composed of three general categories of infrastructure: 1) collection, 2) treatment, and 3) pumping. The basic function of each of these categories is briefly described below.

9.2.2.1. Collection

Table 9-3: Wastewater Collection Pipe Types and Design Standard

Wastewater Collection Pipe Type	Design Standard[2]
Clay pipe	ASTM C700
Prestressed concrete cylinder pipe	AWWA C301
Polyvinyl Chloride (PVC) pipe, gravity	ASTM D3034
Polyvinyl Chloride (PVC) pipe, force main	AWWA C900
Ductile iron pipe	ASTM A746 and AWWA C150
High-density polyethylene (HDPE) pipe	ASTM F714

The collection pipeline network for wastewater systems is similar to that for water systems, except instead of delivering water to individual customers the wastewater collection system conveys liquid and other waste products away from customers. Also, as opposed to water pipelines that operate under pressure, sewer lines are generally gravity feed systems that are not under pressure. The elevation and grade of the pipelines in the system need to be carefully controlled to maintain gravity flow in the system. Infiltration and inflow of groundwater into the collection system through cracks and breaks in the pipe can significantly increase the volume of wastewater that arrives at the treatment plant. In some instances pumps convey wastewater through pressurized force mains. A variety of pipe materials (see Table 9-3) are commonly used for constructing new collection pipelines and repair of existing pipes.

Buried pipelines are less vulnerable to some types of hazards, including wind, but seismic events can result in widespread damage of buried infrastructure. Flood forces can also impact buried systems. Typical damage to wastewater collection pipelines includes:

- Similar to water distribution systems, wastewater collection pipelines can be exposed and damaged as a result of landslides or erosion. This can lead to damage or breaks within the pipelines.

[2] ASTM is American Society for Testing and Materials. AWWA is American Water Works Association.

- Liquefaction-induced permanent ground displacement causes breaks and collapses of sewer pipelines. Observations from past earthquakes indicate approximately one sewer pipe collapse occurs for every 10 breaks and leaks in water pipelines (OSSPAC, 2013).
- Liquefaction often induces floating of manholes and sewer pipelines (see Figure 9-14). These changes in pipeline and structure invert elevations can cause disruption to the collection system gravity flow.
- Cracked and broken sections of pipe lead to significant increases in infiltration and inflow rates (see Figure 9-15). Increased flow rate creates excess demand on the already reduced capacity of wastewater treatment plants after earthquakes.

Figure 9-14: Manhole Floated due to Liquefaction, Christchurch Earthquake, Christchurch, New Zealand, 2011 (Source: Eidinger & Tang, 2014)

Figure 9-15: Sewer Pipeline Break, Christchurch Earthquake, Christchurch, New Zealand, 2011 (Source: Eidinger & Tang, 2014)

- Sometimes wastewater pipelines are co-located on bridges at river or other crossings. If not properly designed, relative movement between the bridge and surrounding soil could result in damage to the supported pipelines. Figure 9-16 shows a sewer pipeline attached to a bridge. The pipeline was damaged by differential settlement between adjacent bridge supports, resulting in discharge of raw wastewater directly to the river.
- Wastewater collection pipelines that are co-located on bridges experience damage as a result of flood inundation and flood-borne debris impact. Hydrodynamic forces associated with coastal flooding or high velocity flows are more likely to damage structures and attached pipelines than inundation alone.
- Soil saturation combined with rising groundwater levels can result in uplift or buoyancy forces on buried pipelines and collection system structures leading to ruptures and breaks within the system.

Figure 9-16: Sewer Pipeline Break Due To Bridge Support Settlement, Christchurch Earthquake, Christchurch, New Zealand, 2011 (Source: Eidinger & Tang, 2014)

9.2.2.2. Treatment

Wastewater treatment plants process raw sewage from household and industrial sources so the resulting effluent discharge meets public health standards. Various screens, sedimentation tanks, aeration tanks, and clarifiers remove organic and inorganic components of the raw wastewater influent. Sludge removed from primary sedimentation tanks is typically processed in anaerobic digesters. Wastewater treatment plants typically consist of a number of process tanks, yard and plant piping, pumps, chemical storage and feed equipment, lab and office building space, and associated mechanical, electrical and control equipment.

Typical damage to wastewater treatment plants includes:

- Wastewater treatment plants are often located in or near flood-prone areas because they return large volumes of treated water to naturally occurring bodies of water via gravity (see Figure 9-17). Therefore, they can be vulnerable to flood inundation from riverine or coastal sources resulting in damages to buildings, equipment, and electrical and mechanical systems and loss of functionality. The New York City Department of Environmental Protection (NYC DEP) noted in a recent study that all 14 of the WWTPs it owns and operates are at risk of flood damage (NYCDEP, 2013).

Figure 9-17: Wastewater Treatment Plants Are Often Located Adjacent To Or Along Waterways In Flood-Prone Areas. Hunts Point WWTP Along the East River In New York City Is Shown Here. (Source: NYC DEP, 2013)

- During Sandy over 560 million gallons of untreated and diluted sewage mixed with stormwater and seawater was released into waterways. This occurred as a result of infiltration of floodwaters into the sewer system, flood inundation of plant facilities, and power outages (NYC DEP, 2013).
- The Hurricane Sandy Mitigation Assessment Team (MAT) Report investigated damages at three WWTPs in the New Jersey and New York metropolitan area as a result of storm surge inundation including the Passaic Valley Sewerage Commission Wastewater Treatment Plant in Newark, NJ, the Bay Park Sewage Treatment Plant East Rockaway, NY and the Yonkers Wastewater Treatment Plant Yonkers, NY (FEMA, 2013). Some damage they experienced included:
  - A clarifying tank located in a basin with a height of 13 feet was overtopped at the Passaic Valley Sewerage Commission Wastewater Treatment Plant in Newark, NJ.
  - Electronic controls were inundated and damaged in many facilities, as shown in Figure 9-18, which delayed the facilities' recovery times significantly.
  - Floodwater inundation damaged other mechanical and electrical systems and components of the wastewater treatment process including settling tanks and biological treatment systems.

Figure 9-18: Subgrade Electric System Damaged By Floodwater at the Passaic Valley Sewerage Commission Wastewater Facility (FEMA, 2013)

- Many WWTPs are interconnected below grade via tunnels and utility conduits. During flood inundation, floodwaters can enter and travel via these pathways causing damage to utilities located within them and reaching some facilities and buildings that might otherwise be protected from floodwaters. Figure 9-19 shows floodwaters being pumped out of lower levels of WWTP.

Figure 9-19: Floodwaters Are Pumped Out of Lower Levels of a WWTP In the Atlanta Area After Severe Storms Resulted In Significant Damage

- Wastewater collection systems are generally gravity feed, meaning that the wastewater treatment plant is at a low point in the elevation of the system. Unfortunately these low points often coincide with areas of greater liquefaction potential during earthquakes. Liquefaction induced permanent ground displacement has often caused process tank joint separation (see Figure 9-20 and Figure 9-21), damage to pipelines, pipe racks, etc.

Figure 9-20: Process Tank Joint Offset Due To Permanent Ground Deformation, Maule Earthquake, Chile, 2010 (Source: Photo by Kent Yu)

Figure 9-21: Chlorine Contact Tank Joint Separation Due To Permanent Ground Deformation, Maule Earthquake, Chile, 2010 (Source: Photo by Kent Yu)

- The hydrodynamic forces generated from liquid movement within a tank during an earthquake often cause damage to process tank covers, baffles, and other submerged equipment. Figure 9-22 shows missing process tank roof panels due to damage from liquid sloshing around inside the tank during the earthquake. Figure 9-23 shows damage to clarifier equipment due to hydrodynamic forces of sloshing liquid within the tank.
- Damage to chain-driven solids collection systems (scrapers, etc.) has been observed in many past earthquakes. Damage consists of dislodged chains or sprockets and broken scraper blades caused by hydrodynamic forces from liquid movement within the tank (see Figure 9-24).
- Plant components are often connected by catwalks or other small access bridges. These bridges may support electrical conduit and process piping. Differential movement between components (i.e., two process tanks moving in different directions from seismic shaking) can damage these catwalks and supported utilities. Similarly, high wind events can damage these types of features. Figure 9-25 shows where one bridge experienced a permanent offset of about 12 inches and caused separation of electrical conduit and exposed wires during the 2010 Maule earthquake in Chile.

Figure 9-22: Process Tank Roof Damage Due To Sloshing, Maule Earthquake, Chile, 2010 (Source: Photo by Kent Yu)

Figure 9-23: Clarifier Equipment Damage Due To Sloshing, Maule Earthquake, Chile, 2010 (Source: Photo by Kent Yu)

Figure 9-24: Damage To Chain-Driven Scraper, Tohoku Earthquake, Japan, 2011 (Source: Matsuhashi, et al., 2012)

Figure 9-25: Damage To Electrical Conduit Due To Bridge Movement, Maule Earthquake, Chile, 2010 (Source: Photo by Kent Yu)

- Seismic performance of buildings at wastewater treatment plants is dependent upon the type and year of original construction and any seismic retrofits. Unreinforced masonry and older tilt-up concrete buildings are particularly vulnerable to damage in earthquakes. Similarly, building performance during high wind events is dependent on the age and type of original construction and any retrofits. WWTPs in coastal areas are generally more vulnerable to high winds than those inland.
- Nonstructural damage to lab and office spaces at wastewater treatment plants may impact continued operation of the facility (especially the lab). If paper drawing files are water damaged by broken sprinkler lines or lab equipment topples onto the floor because it is not adequately anchored, the ability of staff to perform their jobs after an earthquake will be hampered.
- Tsunami inundation may flood aboveground infrastructure causing damage to pumps, motors, and other equipment. High velocity water flows around wastewater treatment plants may cause scour damage to pipe rack foundations, buried tanks, pipelines, etc. (see Figure 9-26 and Figure 9-27). A major seismic structural upgrade was performed at the main wastewater treatment plant for the City of Sendai. The 2011 Tohoku earthquake's shaking caused no damage to the plant. However, the tsunami completely inundated the plant causing significant damage and a complete shutdown. Repair costs were estimated to be $1 billion US dollars (Tang & Edwards, 2014).

Figure 9-26: Collapse of Pipe Rack next to Digesters due to Tsunami Scour, Tohoku Earthquake, Japan, 2011 (Source: Tang & Edwards, 2014)

Figure 9-27: Eroded Pipe Support Foundation due to Tsunami Scour, Tohoku Earthquake, Japan, 2011 (Source: Tang & Edwards, 2014)

9.2.2.3. Pumping

Pump or lift stations may be required in a predominately gravity feed system to lift wastewater to a higher elevation. The pump may discharge at the higher elevation to another section of gravity feed pipeline or may remain a pressurized force main and discharge at a distant location, such as a treatment plant. A pump station typically consists of a simple building that houses pumps, motors that power the pumps, pipes, and associated mechanical, electrical and control equipment. Pump stations may have standby emergency generators to enable continued operation when the commercial power supply is interrupted.

Pump stations are often located in low-lying areas or below ground since they move water along below grade sewage collection pipelines. This makes them vulnerable to flooding and liquefaction during earthquakes.

Typical damage to wastewater pump stations includes:

- Floodwater inundation of pumps can disable and damage the pumps and their motors if they are not submersible type pumps. This was a common cause of pump station failure within New York City during flood inundation from Sandy (NYCDEP, 2013).
- Floodwater inundation of electrical equipment and controls.
- Liquefaction during seismic events can cause buried pump station wastewater collections wells to float and tilt (see Figure 9-28). This movement is also likely to damage connecting piping and possibly render the pump station inoperable.
- Loss of commercial electrical power prevents operation of pumps if there is no backup power supply.
- Tsunami inundation may flood aboveground infrastructure causing damage to pumps, motors, and other equipment. High velocity water flows around pump stations may cause scour damage to buried collection wells and pipelines.
- Tsunami inundation can cause significant damage to above-grade structures due to hydrodynamic wave forces and debris impact forces. Figure 9-29 and Figure 9-30 illustrate typical significant damage to pump stations from tsunami forces. Similar tsunami damage can be expected for other above-grade structures.

Figure 9-28: Pump Station Well Floated and Tilted Due To Liquefaction, Christchurch Earthquake, Christchurch, New Zealand, 2011 (Source: Eidinger & Tang, 2014)

Figure 9-29: Structural Damage From Tsunami Wave and Debris Impact, Tohoku Earthquake, Japan, 2011 (Source: Tang & Edwards, 2014)

Figure 9-30: Structural Damage From Tsunami Wave and Debris Impact, Tohoku Earthquake, Japan, 2011 (Source: Tang & Edwards, 2014)

9.2.3. Combined Storm and Sewer Lines

A combined sewer system is designed to collect storm water runoff, domestic sewage, and industrial wastewater in the same pipe. When heavy rainfalls produce a volume of water that exceeds the capacity of the wastewater treatment plant, untreated sewer contents may flow directly into the receiving body of water. Combined sewer overflow (CSO) may contain not only storm water but also untreated human and industrial waste, toxic materials, and debris. Over the last 25 plus years, wastewater utilities have made significant investments to minimize CSOs and meet requirements of the 1972 Clean Water Act. Various combinations of approaches have mitigated CSOs, including:

- ***Expanded treatment capacity –*** Adding treatment capacity to the wastewater system to handle the combined sewer flow associated with large storm events.
- ***Sewer separation –*** Adding a second separate piping system to decouple the sanitary and storm water collection systems.
- ***CSO storage –*** Adding storage capacity (typically one or more tunnels) to collect and store the combined sewer flow associated with large storm events. After the storm event the stored wastewater is then pumped to the wastewater treatment plant for processing as capacity is available.
- ***Screening and disinfection –*** Facilities are added to enable the flows to be treated with sodium hypochlorite for disinfection and solids greater than about 0.25 in. are removed with a series of screens. Solids are directed to the wastewater treatment plant for processing and the treated water effluent is directed to the receiving body of water.

9.3. Performance Goals

The large and distributed nature of water and wastewater systems, combined with their interdependence on other lifelines, limits the practicality of maintaining 100 percent operational capacity in the aftermath of a major natural disaster. This section identifies a recommended level of service performance goals for water and wastewater systems.

We provide a recommended level of service performance goals as a starting point; they need to be discussed with individual utilities and communities before they are adopted. It is important to consider the uniqueness of the infrastructure of individual utilities and the specific needs of their customers when adopting system performance goals for a specific community. It is critical that all water and wastewater stakeholders be engaged in establishing community-specific level of service performance goals for each of the three different hazard levels (*routine*, *expected*, and *extreme*) discussed in Section 2.1.2. This group of stakeholders should include representation from:

- Residential customers
- Business customers
- Industrial customers (if applicable)
- Water wholesale customers (if applicable)
- Hospital customers (if applicable)
- Firefighters
- Local government officials
- Local emergency management officials
- Drinking water regulators (Health Authority, etc.)
- Wastewater regulators (Dept. of Environmental Quality, Environmental Protection Agency, etc.)
- Water and wastewater utility operators and engineers
- Consulting engineers
- Interdependent lifelines (power, liquid fuel, transportation, etc.)

The process of establishing performance goals involves a discussion amongst the stakeholders about their expectations for the availability of water and wastewater systems during post-disaster response and recover phases for different hazard levels (e.g., *routine*, *expected*, and *extreme*). The assumed expectation of the general public is that for *routine* disasters there would be little, if any, interruption of service for water and wastewater lifelines. A dialogue is required between utilities and customers to determine the appropriate level of service performance goals for *expected* and *extreme* events.

There may be elements in a system that are so critical to public safety that they need to be designed to remain operational after an *extreme* event. For example, failure of a water supply impoundment dam would present a significant life-safety hazard to downstream residents, and should be designed for an *extreme* event.

Interdependencies of water and wastewater systems with other lifelines also need to be considered when developing performance goals. For instance, availability of a reliable supply of liquid fuel impacts how long systems can run on backup emergency generators and impacts the vehicles and equipment needed by repair crews. Delivery of liquid fuels is in turn dependent on the status of the highway and bridge transportation network.

Table 9-4 and Table 9-5 provide recommended water and wastewater system performance goals for post-disaster response and recovery for an *expected* wind or seismic event. Performance goals are broken down into functional categories (i.e., water for fire suppression at key supply points, treatment plants operating to meet regulatory requirements, etc.) and further broken down into target timelines to restore the functional categories to 30 percent, 60 percent, and 90 percent operational status.

Table 9-4: Detailed Infrastructure System Resilience Matrix – Water

Disturbance		
(1)	Hazard	Any
	Hazard Level	Expected
	Affected Area	Community
	Disruption Level	Moderate

Restoration times		
(2)	30%	Restored
	60%	Restored
	90%	Restored
(3)	X	Current

Functional Category: Cluster	(4) Support Needed	(5) Target Goal	Overall Recovery Time for Hazard and Level Listed								
			Phase 1 -- Response			Phase 2 -- Workforce			Phase 3 -- Community		
			Days 0	Days 1	Days 1-3	Wks 1-4	Wks 4-8	Wks 8-12	Mos 4	Mos 4-36	Mos 36+
Source		1									
Potable water at supply (WTP, wells, impoundment)			30%		60%	90%			X		
Water for fire suppression at key supply points			90%			X					
Transmission (inculding Substations)		1									
Backbone transmission facilities (pipelines, pump stations, and reservoirs)			90%					X			
Distribution											
Critical Facilities		1									
Hospitals, EOC, Police Station, Fire Stations				60%	90%			X			
Emergency Housing		1									
Emergency Shelters				60%	90%			X			
Housing/Neighborhoods		2									
Drink water available at community distribution centers					60%	90%					
Water for fire suppression at fire hydrants						90%				X	
Community Recovery Infrastructure		3									
All other clusters					30%	90%				X	

Footnotes:

1 Specify hazard being considered
Specify level -- Routine, Expected, Extreme
Specify the size of the area affected - localized, community, regional
Specify severity of disruption - minor, moderate, severe

2 | 30% | 60% | 90% | Restoration times relate to number of elements of each cluster

3 | X | Estimated restoration time for current conditions based on design standards and current inventory
Relates to each cluster or category and represents the level of restoration of service to that cluster or category
Listing for each category should represent the full range for the related clusters
Category recovery times will be shown on the Summary Matrix
"X" represents the recovery time anticipated to achieve a 90% recovery level for the current conditions

4 Indicate levels of support anticipated by plan
R Regional
S State
MS Multi-state
C Civil Corporate Citizenship

5 Indicate minimum performance category for all new construction.
See Section 3.2.6

Table 9-5: Detailed Infrastructure System Resilience Matrix – Wastewater

Disturbance		
(1)	Hazard	Any
	Hazard Level	Expected
	Affected Area	Community
	Disruption Level	Moderate

Restoration times		
(2)	30%	Restored
	60%	Restored
	90%	Restored
(3)	X	Current

Functional Category: Cluster	(4) Support Needed	(5) Target Goal	Overall Recovery Time for Hazard and Level Listed								
			Phase 1 -- Response			Phase 2 -- Workforce			Phase 3 -- Community		
			Days 0	Days 1	Days 1-3	Wks 1-4	Wks 4-8	Wks 8-12	Mos 4	Mos 4-36	Mos 36+
Treatment Plants											
Treatment plants operating with primary treatment and disinfection					60%	90%					
Treatment plants operating to meet regulatory requirements						30%			60%	90%	X
Trunk Lines											
Backbone collection facilities (major trunklines and pump stations)						30%		60%	90%		X
Collection Lines											
Critical Facilities											
Hospitals, EOC, Police Station, Fire Stations					30%	90%				X	
Emergency Housing											
Emergency Shelters					30%	90%				X	
Housing/Neighborhoods											
Threats to public health and safety controlled by containing & routing raw sewage away from public				30%		60%	90%			X	
Community Recovery Infrastructure											
All other clusters						30%		60%		90%	X

Footnotes:

1 Specify hazard being considered
Specify level -- Routine, Expected, Extreme
Specify the size of the area affected - localized, community, regional
Specify severity of disruption - minor, moderate, severe

2 30% | 60% | 90% Restoration times relate to number of elements of each cluster

3 X Estimated restoration time for current conditions based on design standards and current inventory
Relates to each cluster or category and represents the level of restoration of service to that cluster or category
Listing for each category should represent the full range for the related clusters
Category recovery times will be shown on the Summary Matrix
"X" represents the recovery time anticipated to achieve a 90% recovery level for the current conditions

4 Indicate levels of support anticipated by plan
R Regional
S State
MS Multi-state
C Civil Corporate Citizenship

5 Indicate minimum performance category for all new construction.
See Section 3.2.6

It is assumed that the financial burden associated with upgrading all components of an entire system to be more disaster resilient would overwhelm the short-term capital improvement budgets of most utilities. Therefore, performance goals have been established around the concept of a hardened backbone system. This backbone network should be capable of supplying key health and safety related community needs shortly after a disaster, while more extensive repairs are being completed on the remainder of the system. Performance goals are based on a balance of societal needs and realistic expectations of system performance.

9.4. Regulatory Environment

Water and wastewater utilities are subject to rules and regulations that are generally intended to protect public health and safety and the environment. These regulatory requirements are administered by Federal, State, and Local governmental agencies.

9.4.1. Federal

United States Environmental Protection Agency (EPA)

- ***Safe Drinking Water Act***
  - ***Contaminant Level Limits –*** EPA sets limits on levels of certain chemical and microbial contaminants in drinking water.
  - ***Underground Injection Control (UIC) –*** EPA regulates construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal.
- ***Clean Water Act***
  - ***Analytical Methods –*** EPA publishes laboratory test procedures for use by industry and municipalities to analyze the chemical, physical, and biological components of wastewater.
  - ***Effluent Limitations Guidelines –*** EPA establishes regulations for industrial wastewater discharges to surface waters and publicly owned treatment works.
  - ***National Pollutant Discharge Elimination System (NPDES) –*** EPA controls water pollution by regulating point sources of pollutant discharge through the NPDES permit system.

9.4.2. State

- ***State Drinking Water Programs (e.g., Oregon Health Authority, Drinking Water Services).*** States ensure water systems meet Safe Drinking Water Act standards. They ensure water systems test for contaminants, review plans for water system improvements, conduct on-site inspections and sanitary surveys, provide training and technical assistance, and take action against water systems not meeting standards.
- ***State Water Quality Programs (e.g., Oregon Department of Environmental Quality, Water Quality Division).*** States ensure water systems meet water quality standards. They develop and implement water quality standards, regulate sewage treatment systems and industrial dischargers, collect and evaluate water quality data, provide training and technical assistance, and take action against wastewater systems not meeting standards.

9.4.3. Local

Individual municipalities or utility districts may elect to impose regulatory standards in excess of Federal and State standards. In practice this is seldom done due to the increased cost to customers associated with meeting higher than minimum regulatory standards.

9.5. Standards and Codes

The industry uses codes, standards, and guidelines to establish minimum acceptable criteria for design, assessment, and construction. Table 9-6 summarizes available codes, standards, and guidelines for design, assessment, and retrofit of water systems components. Table 9-7 provides a similar summary for wastewater systems.

Table 9-6: Water System Codes, Standards, and Guidelines

Component	Organization*	Code, Standard, or Guideline
General	ALA	Seismic Fragility Formulations for Water Systems (2001)
		Guidelines for Implementing Performance Assessments of Water Systems (2005)
	AWWA	Minimizing Earthquake Damage, A Guide for Water Utilities (1994)
		G430-09 Security Practices for Operation and Management
		J100-10 Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Water and Wastewater Systems
		M19 Emergency Planning for Water Utilities
		M60 Drought Preparedness and Response
	ICC	2012 International Building Code or applicable jurisdictional building code (for buildings and other structures)
	MCEER	MCEER-08-0009 Fragility Analysis of Water Supply Systems (2008)
	TCLEE	Monograph 22 Seismic Screening Checklists for Water and Wastewater Facilities (2002)
Supply	AWWA	A100-06 Water Wells
		M21 Groundwater
Transmission	ACI	346-09 Specification for Cast-in-Place Concrete Pipe
	ALA	Guidelines for the Design of Buried Steel Pipe (2001)
		Seismic Guidelines for Water Pipelines (2005)
	ASCE	Guidelines for Seismic Design of Oil and Gas Pipeline Systems (1984)
	AWWA	C200-12 Steel Water Pipe 6 Inch (150 mm) and Larger
		C300-11 Reinforced Concrete Pressure Pipe, Steel-Cylinder Type
		C301-07 Prestressed Concrete Pressure Pipe, Steel-Cylinder Type
		C302-11 Reinforced Concrete Pressure Pipe, Noncylinder Type
		C303-08 Concrete Pressure Pipe, Bar-Wrapped, Steel Cylinder Type
		C304-07 Design of Prestressed Concrete Cylinder Pipe
		C600-10 Installation of Ductile-Iron Mains and Their Appurtenances
		C604-06 Installation of Steel Water Pipe – 4 In. (100 mm) and Large
		C905-10 Polyvinyl Chloride (PVC) Pressure Pipe & Fabricated Fittings, 14 in. Through 48 in. (350 mm Through 1,200 mm) for Water Transmission and Distribution
		C906-07 Polyethylene (PE) Pressure Pipe & Fittings 4 In (100 mm) Through 63 In (1,575 mm) for Water Distribution and Transmission
		C909-09 Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4” – 24” (100 mm Through 600 mm) for Water, Wastewater, and Reclaimed Water Service
		M9 Concrete Pressure Pipe
		M11 Steel Pipe: A Guide for Design and Installation
		M23 PVC Pipe – Design and Installation
		M31 Distribution System Requirements for Fire Protection
		M41 Ductile-Iron Pipe and Fittings
		M42 Steel Water Storage Tanks
		M55 PE Pipe – Design and Installation
	MCEER	Monograph Series No. 3 Response of Buried Pipelines Subject to Earthquakes (1999)
		Monograph Series No. 4 Seismic Design of Buried and Offshore Pipelines (2012)
	TCLEE	Monograph 15 Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities (1999)
Treatment	ACI, AWWA	Storage tank documents indicated below, as applicable
	ALA	Seismic Design and Retrofit of Piping Systems (2002)
	WEF	MOP 28 Upgrading and Retrofitting Water and Wastewater Treatment Plants
Pumping	ALA	Seismic Design and Retrofit of Piping Systems (2002)

Component	Organization*	Code, Standard, or Guideline
Storage	WEF	MOP 28 Upgrading and Retrofitting Water and Wastewater Treatment Plants
	ACI	350.3-06 Seismic Design of Liquid-Containing Concrete Structures and Commentary
		350.4R-04 Design Considerations for Environmental Engineering Concrete Structures
		371R-08 Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks
		372R-03 Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures
	AWWA	D100-11 Welded Carbon Steel Tanks for Water Storage
		D110-13 Wire- and Strand-Wound, Circular, Prestressed Concrete Tanks
		D115-06 Tendon-Prestressed Concrete Water Tanks

Table 9-7: Wastewater System Codes, Standards, and Guidelines

Component	Organization[3]	Code, Standard, or Guideline
General	ALA	Wastewater System Performance Assessment Guideline (2004)
	AWWA	J100-10 Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Water and Wastewater Systems
	WEF	Emergency Planning, Response, and Recovery
		Guide for Municipal Wet Weather Strategies
		MOP FD-17 Prevention and Control of Sewer System Overflows
	ICC	2012 International Building Code or applicable jurisdictional building code (for buildings and other structures)
	TCLEE	Monograph 22 Seismic Screening Checklists for Water and Wastewater Facilities (2002)
Collection	ACI	346-09 Specification for Cast-in-Place Concrete Pipe
	ALA	Guidelines for the Design of Buried Steel Pipe (2001)
	ASCE	Guidelines for Seismic Design of Oil and Gas Pipeline Systems (1984)
	MCEER	Monograph Series No. 3 Response of Buried Pipelines Subject to Earthquakes (1999)
		Monograph Series No. 4 Seismic Design of Buried and Offshore Pipelines (2012)
	WEF	MOP FD-5 Gravity Sanitary Sewer Design and Construction
		MOP FD-6 Existing Sewer Evaluation and Rehabilitation
Treatment	ACI	350-06 Code Requirements for Environmental Engineering Concrete Structures and Commentary
		350.3-06 Seismic Design of Liquid-Containing Concrete Structures and Commentary
		350.4R-04 Design Considerations for Environmental Engineering Concrete Structures
		372R-03 Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures
	ALA	Seismic Design and Retrofit of Piping Systems (2002)
	WEF	MOP 8 Design of Municipal Wastewater Treatment Plants
		MOP 28 Upgrading and Retrofitting Water and Wastewater Treatment Plants
Pumping	ALA	Seismic Design and Retrofit of Piping Systems (2002)

One shortcoming is that codes and standards do not take into account differences in expected lifespan of infrastructure when defining the design hazard level. Pipelines and other components of water and wastewater systems often have a service lifespan of 100 years, compared with the typical service lifespan of 50 years for buildings. Therefore, the implied level of reliability of a pipeline designed for a particular hazard level (i.e., 500-year return period earthquake) is less than that of a building designed for the same

[3] ACI is American Concrete Institute. ASCE is American Society of Civil Engineers. AWWA is American Water Works Association. ICC is International Code Council. MCEER is Multidisciplinary Center for Earthquake Engineering Research. TCLEE is Technical Council on Lifeline Earthquake Engineering. WEF is Water Environment Federation.

hazard level due to longer expected service life of the pipeline (i.e., a pipeline in the ground for 100 years is more likely to experience the design earthquake than one in the ground for 50 years).

9.5.1. New Construction

9.5.1.1. Implied or Stated Performance Levels for Expected Hazard Levels

Design of new aboveground structures (i.e., treatment plant office and lab buildings, pump stations, process tanks, water storage tanks and reservoirs, etc.) is typically governed by local building codes, or design standards that prescribe a similar wind and seismic hazard as the local building code. Design loads are prescribed by a consensus-based standard, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010). This standard uses the concept of Risk Category to increase the design force level for important structures. Typical buildings are assigned to Risk Category II. Water and wastewater treatment facilities are assigned to Risk Category III, because failure of these facilities can cause disruption to civilian life and potentially cause public health risks. Water storage facilities and pump stations required to maintain water pressure for fire suppression are assigned to the highest category, Risk Category IV.

The building code intends that structures designed as Risk Category III or IV should remain operational or require only minor repairs to be put back into operation following a design level (*expected*) wind or seismic event. By designing for this performance target for the *expected* level event it is assumed that water and wastewater systems would remain operational under a *routine* level event and may experience moderate to major damage during an *extreme* level event.

For the design of new underground pipelines there is a lack of a standard unifying code for water and wastewater systems. This is especially true for seismic design of buried water and wastewater pipelines or buried pipelines that may be impacted by landslides induced by flooding. Often the Chief Engineer of a particular utility is responsible for establishing design practices for their agency. While these agency-specific design practices are generally based on industry recommendations, variability in standards used by utilities results in variability between utilities in the intended system reliability for natural and man-made hazards.

Some utilities develop their own standards to specifically address significant local hazards. For example, the San Francisco Public Utilities Commission (SFPUC) developed its own internal standard that outlines level of service performance goals following a major Bay Area earthquake and specific requirements for design and retrofit of aboveground and underground infrastructure. The SFPUC Engineering Standard *General Seismic Requirements for Design of New Facilities and Upgrade of Existing Facilities* (SFPUC, 2006) establishes design criteria that in many cases are more stringent than building codes and/ or industry standards, but are intended to ensure the SFPUC is able to achieve its basic level of service performance goal of delivering winter day demand to their wholesale customers within 24 hours after a major earthquake.

9.5.1.2. Recovery Levels

The performance level implied by codes and standards for new construction provides an indication of the recovery level (timeframe) expected for individual system components. The timeframe required for a water or wastewater system to return to normal operating status following a major disaster is highly dependent on the recovery time for individual system components and the system's specific characteristics (e.g., type and number of components, age of construction, system redundancy, etc.). For instance, if a pump is damaged by an earthquake and will take six months to repair, but a redundant pump is undamaged, the system recovery time is not impacted by the six month repair time. Estimating system recovery times for a specific hazard requires in-depth engineering and operational knowledge of the system.

Table 9-8 summarizes water and wastewater system component performance and recovery levels for earthquake hazard levels as implied by current codes and standards for new construction. Predicted recovery times are based on individual system components.

Table 9-8: Water and Wastewater System Component Performance and Recovery Levels for Various Earthquake Hazard Levels as Implied by Current Codes and Standards for New Construction

System Component	Hazard Level	Performance Level	Recovery Level
Structures (pump stations, treatment plants, office/lab buildings, tanks, reservoirs, etc.)	Routine (50 year return period earthquake)	Safe and operational	Resume 100% service within days
	Expected (500 year return period earthquake)	Risk Category III (I=1.25) – Safe and usable during repair	Resume 100% service within months
		Risk Category IV (I=1.5) – Safe and operational	Resume 100% service within days
	Extreme (2500 year return period earthquake)	Risk Category III (I=1.25) – Safe and not usable	Resume 100% service within years
		Risk Category IV (I=1.5) – Safe and usable during repair or not usable	Resume 100% service within months to years
Nonstructural components (process, lab, mechanical, electrical, and plumbing equipment, etc.)	Routine (50 year return period earthquake)	Safe and operational	Resume 100% service within days
	Expected (500 year return period earthquake)	Risk Category III (I=1.25) – Safe and usable during repair	Resume 100% service within months
		Risk Category IV (I=1.5) – Safe and operational	Resume 100% service within days
	Extreme (2500 year return period earthquake)	Risk Category III (I=1.25) – Safe and not usable	Resume 100% service within years
		Risk Category IV (I=1.5) – Safe and usable during repair or not usable	Resume 100% service within months to years
Pipelines	Routine (50 year return period earthquake)	Operational	Resume 100% service within days
	Expected (500 year return period earthquake)	Operational to not usable	Resume 100% service within months
	Extreme (2500 year return period earthquake)	Not usable	Resume 100% service within years

9.5.2. Existing Construction

9.5.2.1. Implied or Stated Performance Levels for Expected Hazard Levels

The design seismic hazard level has been refined over time as the engineering and seismology communities understanding of the seismicity of the United States has improved. A significant portion of water and wastewater system components in the high seismicity regions of the western and central United States were designed and constructed considering a significantly lower seismic hazard than used by current codes and standards.

Expected seismic performance of water and wastewater system components is dependent on the hazard level and codes and standards used in original design. System components built prior to the mid-1970s are generally expected to perform poorly in earthquakes, because design codes and standards used at that time lacked the detailed requirements that reflect our current understanding of earthquake behavior of structures. System components built after the early 2000s are generally expected to perform similar to new construction as described above. Performance of system components built between the mid-1970s and early 2000s is dependent on the code edition and seismic hazard used in design. Structures that satisfy the benchmark building criteria of ASCE 41-13 (ASCE, 2013), and where there has not been a significant increase in seismicity, are generally expected to perform similar to new construction as described above.

Expected performance of nonstructural components should be evaluated on a case-by-case basis, as engineers have only recently started to pay close attention to seismic design and construction of nonstructural components. Expected performance of pipelines should be evaluated on a system-by-system basis because performance of pipelines is dependent on pipe type, joint type, and earthquake ground movement parameters.

9.5.2.2. Recovery Levels

In general, the recovery timeframe for system components will decrease for newer construction or retrofit. The *Oregon Resilience Plan* (OSSPAC, 2013) estimated the restoration time for pre-1975 structures to be 18 months to three years, 1975–1993 structures to be three to six months, and 1994 to present structures to be one to three months.

9.6. Resilience Assessment Methodology

9.6.1. Assessment Methodology

Section 9.2 describes the basic components of water and wastewater systems and observations of where these systems failed in past disasters. System performance is also highly dependent on the current condition of the system and standards used in its design. This information about past disaster performance of similar systems, combined with knowledge of current condition and original design standards of the system, helps a utility estimate the expected level of service they would be able to provide after a major disaster. There is likely to be a gap in the level of service a system would provide if a major disaster occurred today versus community-established performance goals. It is likely the capital expenditure required to close this performance gap far exceeds the short-term capital improvement project budgets of the utility. However, the resilience of any system can be improved incrementally over time by appropriately considering design criteria to reduce the impact of natural and man-made hazards in design of new and upgrade of existing infrastructure.

To estimate the level of service a water or wastewater system would provide after a given scenario disaster, an assessment of expected damage to the system and restoration times is required. For instance, the *Oregon Resilience Plan* indicates the current estimated time to restore water and wastewater services after an *expected* level earthquake in the Willamette Valley (including Portland, Salem, and Eugene) is from one month to one year, and along the Oregon Coast the estimated time is from one to three years. Comparing these restoration estimates with a community's post-disaster level of service goals provides an indication of the resilience gap (OSSPAC, 2013).

The level of detail of this assessment can take one of three basic forms:

- ***Tier 1 –*** A high level assessment of performance by persons knowledgeable about the system and anticipated hazard (chief engineer, operations manager, etc.)
- ***Tier 2 –*** A more refined assessment based on typical system inventory (i.e., pipe type, length and soil type) using generalized component fragilities
- ***Tier 3 –*** A detailed assessment of all components in a system, specific component fragilities, and the intra-dependencies of system components.

To appropriately characterize the current disaster resilience of water and wastewater systems, each service provider should undergo a Tier 1 assessment. If potential resilience vulnerabilities are identified they should undergo a more refined Tier 2 or 3 assessment. Several methodologies and tools are available to conduct these resilience assessments, a few of which are described below.

HAZUS-MH is a multi-hazard (flood, earthquake, and hurricane) loss estimation tool developed by the Federal Emergency Management Agency (FEMA) for use in pre-disaster mitigation, emergency preparedness, and response and recovery planning (FEMA, 2012). Communities can use this tool to characterize their hazard exposure, estimate losses to the water and wastewater systems, and estimate repair costs and duration.

AWWA J100-10 *Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Water and Wastewater Systems* (AWWA, 2010) provides another methodology for conducting multi-hazard system resilience assessments. The RAMCAP Plus process was originally developed by the American Society of Mechanical Engineers – Innovative Technologies Institute (ASME-ITI) and is intended to be a consistent and comparable methodology for evaluating risk/resilience across various critical infrastructure sectors. It consists of a seven-step process for analyzing and managing risks associated with malevolent attacks and naturally occurring hazards (earthquake, hurricane, tornado, and flood).

1. Asset Characterization
2. Threat Characterization
3. Consequence Analysis
4. Vulnerability Analysis
5. Threat Analysis
6. Risk/Resilience Analysis
7. Risk/Resilience Management

AWWA J100-10 includes an optional Utility Resilience Index (URI). The URI includes two indices:

- An ***operational resilience index*** is based on a series of indicators that reflect a utility's organizational preparedness and capabilities to respond and restore critical functions/services following an incident.
- A ***financial resilience index*** is based on a series of indicators that reflect a utility's financial preparedness and capabilities to respond and restore critical functions/services following an incident.

URI can be used as a benchmark to evaluate potential resilience improvement projects and as a measure to track a utility's progress over time towards achieving resilience performance goals.

The EPA developed the Water Health and Economic Analysis Tool (WHEAT) to assist water and wastewater utilities in quantifying an adverse event's: 1) public health consequences, 2) utility-level financial consequences, and 3) direct and indirect regional economic consequences (EPA, 2014). This tool was developed to assist utilities in performing step 3 (consequence analysis) of the RAMCAP Plus process. WHEAT version 3.0 supports consequence analyses for three scenarios: 1) loss of one or more assets, 2) release of a stored hazardous gas, and 3) intentional contamination of a drinking water distribution system.

The EPA also developed the Vulnerability Self-Assessment Tool (VSAT) to assist water and wastewater utilities perform security threat and natural hazard risk assessments (EPA, 2010). The tool was developed to assist utilities in updating their Emergency Response Plans (ERPs). VSAT software uses an eight-step process to guide users through a risk assessment consistent with the 2007 RAMCAP framework.

1. Analysis setup and utility information
2. Asset identification
3. Countermeasure evaluation
4. Threat identification
5. Baseline assessment
6. Improvement assessment (propose new countermeasures)
7. Cost/Risk evaluations
8. Summaries and reports

An example Tier 1 plus (more detailed than Tier 1 but not as detailed as Tier 2) resilience assessment procedure for water systems, used in developing the *Oregon Resilience Plan*, is outlined below.

9.6.1.1. Tier 1 Plus Resilience Assessment:

1. Identify the appropriate earthquake hazard level

For buried pipelines:

2. Compile an inventory of system pipelines including pipe material, joint type, and length.
3. Superimpose the pipeline distribution system onto maps of the scenario hazard (peak ground acceleration, liquefaction potential, and landslide potential).
4. Use empirical relationships developed by the American Lifelines Alliance (ALA) to predict the number of breaks and leaks in the distribution system.
5. Estimate the time required to repair the predicted number of breaks and leaks based on historical crew productivity data. Modify this repair time, as appropriate, based on discussions of the expected damage states of interdependent lifelines (transportation, liquid fuel, etc.).

For aboveground infrastructure:

6. Compile an inventory of system components (tanks, pump stations, treatment plants, etc.) including type of construction, date of original construction and any subsequent retrofits.
7. Estimate the level of damage predicted for the aboveground water system components based on observations from past earthquakes, the seismic hazard prescribed by the building code at the time of original construction or retrofit, and the professional judgment of engineers knowledgeable in the seismic performance of water systems.
8. Estimate the time required to repair the predicted damage to aboveground infrastructure. Modify this repair time, as appropriate, based on discussions of the expected damage states of interdependent lifelines (transportation, liquid fuel, etc.)

For the system:

9. Determine the expected repair time for the system based on the repair times for buried pipelines and aboveground infrastructure estimated in steps 5 and 8.
10. Compare this estimate of repair time for the system to the performance goals established by the community to determine the resilience gap.

These different resilience assessment approaches should be evaluated and refined into one consistent methodology prior to implementation of nationwide water and wastewater system resilience assessments.

Note that recovery time for utilities that purchase water from wholesale suppliers is highly dependent on the recovery time of the supplying utility. Wholesale water suppliers should work with their customers to assess the expected damage and restorations times from the source to the final individual customers. In this case, water and wastewater system resilience assessments may require a regional approach to appropriately characterize the expected performance of the system of systems in a major disaster.

9.6.2. Strategies for New Construction

Water and wastewater providers should consider resilience performance goals in all new construction projects. Projects should be designed to satisfy current code requirements or exceed code requirements where code minimum standards are not anticipated to provide a final product that would be expected to meet the utility's resilience performance goals. The incremental cost of designing and constructing for improved disaster resilience is generally a relatively small percentage of total project costs.

9.6.3. Strategies for Existing Construction

Water and wastewater providers should consider resilience improvements to existing infrastructure as part of the capital improvement planning process. The process of conducting system resilience assessments will likely identify key pipelines and facilities that significantly impact the overall resilience of a system. These components should be evaluated in greater detail. Providers should evaluate a number of potential strategies, including retrofit or replacement of existing components, or building redundant components, in anticipation of failure of existing components. Retrofit of existing infrastructure or new redundant components should be designed such that the final product would be expected to meet the utility's resilience performance goals.

9.6.4. Addressing Resilience Performance Gaps

Once water and wastewater providers have worked with the community to establish resilience performance goals and completed baseline resilience assessments, there may be a number of goals not currently met due to the expected performance of system components, financial resources of the utility, interdependencies with other lifelines, etc. These performance gaps are likely to be addressed by a phased program (perhaps over as long as a 50-year time horizon) of new construction, retrofit of existing system components to better withstand disasters, modifications to emergency response plans, coordination with interdependent lifeline providers, and other strategies. It is expected that these resilience enhancements will be coupled with other system improvements to maximize the benefit of limited financial resources.

For instance, it can be difficult to justify replacing hundreds of miles of water pipelines based on earthquake resilience considerations alone, but coupled with replacement of aging and failing pipelines, the incremental cost of using more earthquake resistant pipe materials and joints is relatively minor. For major resilience improvements to take place on a shorter timeline a more extensive campaign of public outreach and education would be required.

9.7. Tools Needed for Resilience

9.7.1. Standards and Codes

Good design references are available for seismic design of water pipelines. However, there is no nationally adopted design standard that requires utilities to consider seismic design for their pipeline installations. The US water and wastewater industries need to develop and adopt design standards for new pipelines and retrofit standards for existing pipelines.

9.7.2. Practice and Research Needs

9.7.2.1. Current Research

- The Los Angeles Department of Water and Power (LADWP) and the Portland Water Bureau (PWB) are conducting demonstration projects with Kubota earthquake-resistant ductile iron pipe (ERDIP). This type of pipe has been used successfully in Japan for 40 years and recent earthquakes have demonstrated its superb performance with no documented breaks or leaks. LADWP and PWB have installed this pipe in two locations to become familiar with design and installation of ERDIP, evaluate field installation procedures, and enable a first-hand evaluation on the use of ERDIP to improve the resilience of the LADWP and PWB water distribution systems.
- Researchers are conducting large-scale experiments to fill gaps in the knowledge database on seismic performance of newer pipeline materials like restrained joint polyvinyl chloride.
- Academic researchers (O'Rourke, 2014) are beginning to investigate the next generation of disaster resilient pipelines. Hybrid pipelines like FlexSteel®, a steel reinforced and polyethylene lined pipe, are being evaluated for resistance to earthquakes and other disasters.

9.7.2.2. Future Development Needs

- Benefit cost analysis is a useful method to provide economic justification for resilience improvement projects. However, most current tools do not adequately consider indirect economic losses. It is recommended that a tool be developed that explicitly considers indirect economic losses. This will allow communities to make informed decisions regarding the economic benefit of various resilience improvement project options and provide utilities with another means to justify the benefits of capital improvement expenditures.
- Seismic design of buried infrastructure is highly dependent on geotechnical engineering predictions of peak ground displacement. Refinements to these peak ground displacement prediction models based on data gathered in recent earthquakes would be helpful in prioritizing areas for retrofit of existing pipelines or installation of new pipelines that are more tolerant of ground movement.

- Gravity sewer systems are intolerant of shifts in vertical alignment due to permanent ground deformation and liquefaction. It is recommended that research be conducted on how to design sewer pipelines to be more resistant to the effects of permanent ground deformation and liquefaction.

9.8. Summary and Recommendations

Water and wastewater systems play a critical role in our daily lives. They provide basic services for our homes, places of business, and industry. Utility-scale water and wastewater lifelines are often complex systems consisting of large distributed pipeline networks and localized facilities such as treatment plants and pump stations. The large and distributed nature of water and wastewater systems, combined with their interdependence on other lifelines, limits the practicality of maintaining 100 percent operational capacity in the aftermath of a major natural disaster.

This chapter describes the basic components of water and wastewater systems, common weak links of these systems in major disasters, current design codes and standards, and a process by which communities can establish performance goals for their water and wastewater systems as well as evaluate their current level of disaster resilience. The following are recommendations to help communities, regions, states, and the nation improve the disaster resilience of water and wastewater systems.

Hardened Backbone: Performance goals can be established around the concept of a hardened backbone system. A backbone network should be capable of supplying key health and safety community needs shortly after a disaster, while more extensive repairs are being completed on the remainder of the system.

Implementing Innovative Technologies: The US water and wastewater industry should be encouraged to adopt promising new technologies into practice. Newer developments, such as earthquake resistant ductile iron pipe joints (see Figure 9-31) have demonstrated successful seismic performance in Japan and should be considered for implementation in US practice.

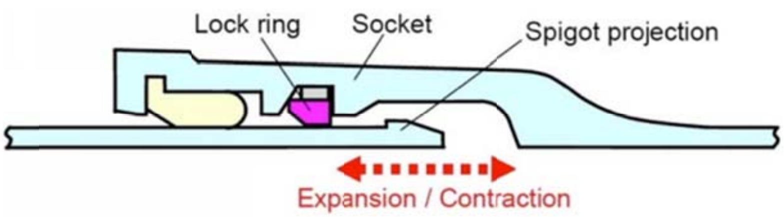

Figure 9-31: Earthquake Resistant Ductile Iron Pipe Joint (Source: Kubota)

Interdependencies: Communities should critically review co-located lifelines for impacts on resilience. For example, failure of a bridge supporting a water pipeline could result in failure of the pipe. Failure of pipe supported by a bridge may result in major leaks causing scour of the soil around the bridge abutment and potential failure of the bridge.

Interdependencies: Water and wastewater utilities should review plans for supplying critical facilities with emergency power for extended periods of time, potentially including on-site renewable options to enhance power supply redundancy.

Interdependencies: There is a current general lack of coordination of interdependencies amongst various lifeline providers. Communities should initiate discussion amongst lifeline providers and critically review interdependencies between various lifelines for impacts on disaster resilience.

Standards Development: Professional organizations (ASCE, AWWA, etc.) should be encouraged to take the leading role in development of missing standards. This standards development process should follow the typical path of prestandard or manual of practice to gain industry support and acceptance before balloting as a standard. In particular, it is critical that a standard should be developed for the seismic design of both water and wastewater pipelines.

Water Quality Impacts: Communities should consider potential adverse water source quality impacts of a disaster. Runoff following wildfire has the potential to increase surface water source turbidity and render the water source unusable for drinking water. Man-made hazards, flooding, and earthquake events have potential to generate fuel spills from storage tanks, releases of untreated wastewater, and other adverse impacts for source water quality.

Resiliency Assessment: Utilities should be required to complete a resiliency assessment as part of periodic master planning updates and develop plans to mitigate identified resiliency deficiencies. It is recommended that current resilience assessment methods be evaluated and refined into one consistent methodology prior to implementation of nationwide resilience assessments. A strategy must also be developed to minimize potential liability concerns a utility may have if a disaster was to strike after a potential deficiency had been identified but before a utility had adequate time to address the deficiency.

Capital Improvement Planning and Asset Management: Utilities should be encouraged to consider disaster resilience in establishing priorities for capital improvement projects and asset management. It may not be economical to complete a project from a disaster resilience perspective alone, but the incremental cost of considering disaster resilience in planned retrofit and replacement projects is minor compared to the added resilience benefit. Using this phased approach to resilience improvement projects will greatly improve the resilience of a community's water and wastewater infrastructure over a period of years, while minimizing the financial burden of these improvements.

Facility Site Planning: Utilities should be encouraged to consider disaster resilience in site planning for new facilities and prior to significant capital improvement projects at existing facilities. New facilities should not be located in disaster prone locations, such as floodplain or tsunami inundation zones. Additionally, it may not be a wise economic investment to complete multi-hazard resilience upgrades to facilities in these disaster prone locations unless the locational hazard is also addressed.

Redundancy: The City of Sendai, Japan installed 21 buried water tanks after the 1995 Kobe earthquake. To prevent the tank from draining due to damage elsewhere in the system, these tanks include earthquake shutoff valves that close automatically when strong ground shaking is detected. The water saved in these tanks is then used as a source of potable water immediately after the earthquake. The majority of these tanks and earthquake valves performed well in the 2011 Tohoku earthquake and were able to serve as a water source for the local community after the earthquake. However, two tanks were in the tsunami inundation zone and therefore, not usable as a potable source after the earthquake and tsunami (Tang & Edwards, 2014). US utilities should consider various options, such as these added storage tanks, to improve system redundancy.

Redundancy: Redundant systems are inherently more resilient. In Japan, many water utilities are implementing loop transmission main systems to increase system redundancy. Water and wastewater utilities should evaluate this loop system approach, addition of isolation valves, and other methods to improve system redundancy. This is especially important for backbone system pipelines that serve critical locations (hospitals, large industrial customers, etc.) and need to be robust and redundant.

Consequence-based planning: When conducting *precovery* planning (pre-disaster and recovery) it is recommended that a consequence-based approach be adopted. By thoroughly considering the downstream physical, societal, and economic impacts of a given action from a disaster resilience perspective the optimum decision can be reached.

Scenario Development: When developing design and assessment standards for disaster resilience it is important to consider the appropriate hazard level. A system could be designed to remain operational after an extremely rare event, but the economic cost of system upgrades and required new infrastructure would be prohibitively costly. However, the system should be designed to have enough resilience to remain operational after a minor, semi-frequently occurring disaster (i.e., 50 year return period earthquake). Scenario development and consequence-based planning should be closely linked. The components of a system where the consequence of failure is much higher should be designed for a less frequently occurring (more extreme) disaster. It is recommended that water and wastewater backbone components be designed or retrofit to be operational after an *extreme* level event.

Rating System: The water and wastewater industry should be encouraged to develop a disaster resiliency rating system to track how utilities are performing with respect to improvements in system resilience.

Disaster Response Plan: Utilities should be encouraged to create or update their disaster response plans based on community-established response and recovery goals. Community-wide training events should be conducted to exercise these plans and work out issues prior to implementing them in an actual disaster.

The Water and Wastewater Agency Response Network (WARN) is an established intrastate contractual relationship for sharing resources necessary to respond to a disaster. The WARN system is currently limited to intrastate mutual aid. However, disasters such as a potential Cascadia Subduction Zone earthquake in the Pacific Northwest have potential to significantly impact multistate regions and overwhelm local resources. It is recommended that the WARN system be expanded to facilitate easier sharing of resources across state lines.

Regulatory Compliance: Communities should work with regulatory agencies before a disaster to establish acceptable practices and operational standards for use during the disaster response phase. Planning should address questions like, “Will it be acceptable to discharge raw sewage to receiving bodies of water?”

Temporary Sanitary Services: Communities should work with utilities and public health agencies to identify, before the event, who will be responsible for temporary sanitation services (e.g., portable toilets).

Temporary Water Supply: Communities should work with utilities to plan for water supply at key distribution points for firefighting and distribution of emergency drinking water. This may require installation of valves and hydrants prior to the event to improve access after the event.

Public and Business Community Education: The general public and business community need to be educated about the potential risks and expected downtime for water and wastewater systems resulting from a disaster. Utility customers need to understand the potential economic consequences of inaction before they will be willing to support potential rate increases to pay for resilience improvements to water and wastewater systems.

Emergency Kit: It should be recommended that community members and employers maintain emergency kits with water and personal sanitation supplies adequate for the expected duration of service interruption.

Business Continuity Plan: Utilities should develop business continuity plans that include on-call contracts or agreements with contractors, consultants, and essential suppliers (fuel, equipment, repair materials, process chemicals, etc.). Utilities should evaluate if current emergency response contingency funds are adequate for the level of damage predicted by an analysis of the system for the disaster scenarios adopted by the community and modify funding levels as appropriate.

9.9. References

ASCE (2013). *Seismic Evaluation and Rehabilitation of Existing Buildings*. Reston, VA: American Society of Civil Engineers.

AWWA (1994). *Minimizing Earthquake Damage, A Guide for Water Utilities*. Denver, CO: American Water Works Association.

AWWA (2013). *J100-10 (R13) Risk and Resilience Management of Water and Wastewater Systems (RAMCAP)Earthquake Damage, A Guide for Water Utilities*. Denver, CO: American Water Works Association.

Ballantyne, D., & Crouse, C. (1997). Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Following Earthquakes. Gaithersburg, MD: National Institute of Standards and Technology.

Eidinger, J. (2012). Performance of Water Systems during the Maule Mw 8.8 Earthquake 27 February 2010. *Earthquake Spectra*, Vol. 28, No. S1, S605-S620.

Eidinger, J., & Tang, A. (2014). *Christchurch, New Zealand Earthqake Sequence of Mw 7.1 September 04, 2010 Mw 6.3 February 22, 2011 Mw 6.0 June 13, 2011: Lifeline Performance.* Reston, VA: American Society of Civil Engineers.

Elliott, T., & Tang, A. (2009). *Pacific Northwest Storms of December 1-4, 2007 Lifeline Performance.* Reston, VA: American Society of Civil Engineers.

EPA (2010). *VSAT – Risk Assessment Tool for Water Sector Utilities.* Washington, D.C.: Environmental Protection Agency.

EPA (2014). *Water Health and Economic Analysis Tool Version 3.0, Consequence Analysis Tool for Water Utilities.* Washington, D.C.: Environmental Protection Agency.

FEMA (2012). *Hazus-MH 2.1 User Manual.* Washington, D.C.: Federal Emergency Management Agency.

FEMA (2013). *Mitigation Assessment Team Report Hurricane Sandy in New Jersey and New York Building Performance Observations, Recommendations, and Technical Guidance* . Washington, D.C.: Federal Emergency Management Agency.

Matsuhashi, M., Fukatani, W., Yokota, T., Ozaki, M., & Horie, N. (2012). The Damage of Sewage Treatment Systems Caused by the Great East Japan Earthquake. *International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan.

Miyajima, M. (2012). Damage to Water Supply System Induced by the 2011 Great East Japan Earthquake. *International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan.

NYCDEP (2013). *New York City Wastewater Resiliency Plan: Climate Risk Assessment and Adaptation Study.* October 2013. New York City Department of Environmental Protection.

NIST (1996). *The January 17, 1995 Hyogoken-Nanbu (Kobe) Earthquake: Performance of Structures, Lifelines, and Fire Protection Systems.* Gaithersburg, MD: National Institute of Standards and Technology.

O'Rourke, T. (2014). *Resilient Lifeline Systems*, ASCE TCLEE LeVal Lund Lecture, April 2, 2014, California Institute of Technology, Pasadena, CA.

OSSPAC (2013). *The Oregon Resilience Plan, Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami*. Salem, OR: Oregon Seismic Safety Policy Advisory Commission.

SFPUC (2006). *General Seismic Requirements for Design of New Facilities and Upgrade of Existing Facilities.* San Francisco, CA: San Francisco Public Utilities Commission.

Schiff, A. (1997). *Northridge Earthquake: Lifeline Performance and Post-Earthquake Response.* Gaithersburg, MD: National Institute of Standards and Technology.

Tang, A., & Edwards, C. (2014). *Tohoku, Japan, Earthquake and Tsunami of March 11, 2011 Lifeline Performance.* Reston, VA: American Society of Civil Engineers.