9. Water and Wastewater Systems

9.1. Introduction

Water and wastewater systems represent essential infrastructure for sustaining the economic and social viability of a community. Although these systems provide basic public health and safety to homes, businesses, and industry, they are often taken for granted because of the high level of service and reliability provided by water and wastewater utilities. The importance of these systems is not recognized until a water main break or other disruption in service occurs. This chapter addresses disaster resilience of public water and wastewater systems.

While some utilities are already taking steps to improve the resilience of their systems, capital improvement programs and many others often focus on performing emergency repairs, increasing system capacity to meet population growth, or making system improvements to satisfy public health and environmental regulations. Replacing 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 with future/planned retrofits or replacements of old infrastructure, to improve the resilience of water and wastewater infrastructure. This chapter focuses on the water and wastewater infrastructure itself. However, the water and wastewater industry faces challenges beyond just the infrastructure performance. Water quality and environmental impact are two of the biggest concerns. For example, if water of poor quality is delivered to customers, there is significant risk that the public may become ill from consumption. The wastewater industry operates within strict environmental constraints that have and will likely continue to become more stringent. These restrictions prevent excessive pollution that contribute to environmental damage and, ultimately, impact the health of the humans and animals. Although this chapter touches on such challenges, its main focus is how to build a more resilient infrastructure system that will deliver good quality water with fewer disruptions and limit damage to wastewater systems, making spills less frequent.

9.1.1. Social Needs and Systems Performance Goals

Water services are essential to our daily lives. Using USGS data, Aubuchon & Morley (2012) calculated the average consumption of water across all U.S. states to be 98 gallons per person per day. However, water consumption varies by community and by customer. Personal uses include water for drinking and cooking, personal hygiene, flushing toilets, laundry, landscape irrigation, and many others. Many businesses and industries also depend on a continual supply of potable water and wastewater collection services. Absent functioning drinking water and wastewater systems, the operation of restaurants, child care facilities, hotels, medical offices, food processing plants, paper mills, etc., significantly compromised, if not completely impossible. Additionally, water systems in urban and suburban areas provide water supply for fire suppression. Chapter 2 discusses this societal dependence on water and wastewater systems and other infrastructure systems in more detail.

In the United States, communities generally accommodate to short-term (on the order of a few days) disruptions in water and wastewater services resulting from man-made or natural hazard events. However, longer-term disruptions are less tolerable. The Oregon Resilience Plan (OSSPAC, 2013) indicated a business that cannot reoccupy facilities (including functioning water and wastewater systems) within one month would be forced to move or dissolve. This timeline likely varies depending on community needs and the severity of the event. 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’ status in relation to those goals, and then develop strategies to close the identified resilience gaps. Flow, pressure, and water quality should be considered in those performance goals.

9.1.2. Interdependencies

As discussed in Chapter 4, water system operations are interdependent with other infrastructure systems, both for day-to-day operation and restoration following a hazard event. Electric power is one of the most important services necessary for maintaining pumping and treatment operations. Transportation is critical to allow access for inspection and repairs after the event, as well as maintaining the supply chain. Figure 9-1 presents some interdependencies of the water infrastructure system with other infrastructure systems.

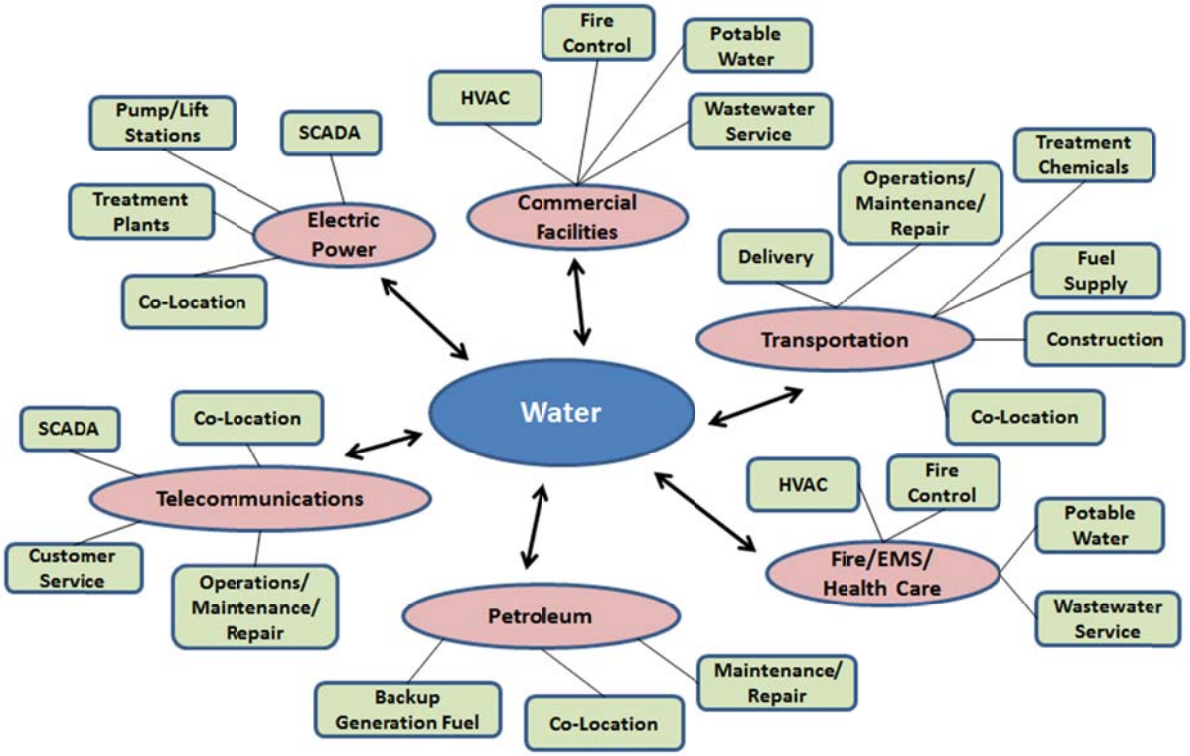

Figure 9-1. Water Interdependencies with Other Infrastructure Systems (Morley 2013)

Some of the most important dependencies for the water and wastewater infrastructure systems include:

1. ***Energy/Power (Electric and Fuel/Petroleum) –*** Water and wastewater utilities rely on commercial electricity to run pumps, treatment processes, and lab and office operations. Some of these functions may have standby power, but overall power demands make it impractical for most water and wastewater systems to run entirely on standby generators. However, short-term power loss events are often mitigated by standby generators supported to maintain water and wastewater operations. These emergency conditions are dependent on sustained fuel supply for standby generators to support utility vehicles and equipment. Disruption in fuel production, storage, or delivery may severely impact a water utility's ability to sustain operations on standby generator power and perform repairs.
2. ***Transportation (Staff, Supplies, Pipelines) –*** Staff at water and wastewater facilities depend on roadway and bridge transportation systems for access. Damage to transportation infrastructure potentially complicates and lengthens repair times or even prevents repairs until roadways and bridges are usable. Water and wastewater utilities generally keep a limited stock of pipe, fittings, and other repair materials to use in response and recovery operations. However, depending on the size of the event, this stock may be quickly depleted due to supply chain disruptions. Such disruptions may also impact the available support from relief equipment and personnel. Utilities also rely on a semi-regular delivery of treatment process chemicals essential for meeting water quality regulations.

Water and wastewater buried pipelines are often co-located with other buried infrastructure 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 during repairs. Therefore, the transportation system, particularly the roadway system, is dependent on the performance of the water and wastewater infrastructure systems.

3. ***Communications and Information –*** Water and wastewater utilities often rely on cellular networks to communicate to operations staff and contractors. If the cellular network is down for an extended period, complications and delays in repairs can occur. Additionally, supervisory control and data acquisition (SCADA) networks are used extensively within both water and wastewater systems to monitor and control widespread components and equipment.

   The communications system infrastructure also depends on water infrastructure. For example, air conditioning system cooling towers that support communications require water to keep sensitive electronic equipment in Central Offices at safe operating temperatures. Furthermore, technicians cannot enter Central Offices to maintain or repair functionality of the communications system if its water and wastewater systems are not functioning.

4. ***Buildings (Critical, Commercial, General Public) –*** Water and wastewater utilities rely on customers (e.g., critical facilities, commercial facilities, and households) to pay bills as a continued source of capital. Utilities will potentially experience significant capital expenditures in the aftermath of a disaster and customers may not have the ability to pay bills (i.e., loss of personal income from loss of wages or breakdown of electronic or posted payments), placing a large financial burden on the utilities. Water and wastewater utilities also operate administrative buildings. New Orleans Water & Sewer Board's treatment, distribution, collection, and administrative operations were severely impacted following Hurricane Katrina. The administration's disruptions included the loss of customer billing and other records due to significant flooding. During this same event, Children's Hospital of New Orleans was forced to evacuate when the hospital lost water pressure and was unable to maintain the HVAC system needed by patients in critical care units.

   Commercial and other public buildings need water supply with adequate flow and pressure for fire suppression, as well as sanitation. Industrial facilities need functional water and wastewater systems for developing, processing, and manufacturing materials and products. The public relies on water and wastewater services for overall health of the community.

9.2. Water and Wastewater Infrastructure

This section describes basic components of water and wastewater systems. Performance observations from past disaster events characterize some key hazard vulnerabilities in water and wastewater systems. Water and wastewater infrastructure are vulnerable to a number of hazards: buried pipelines are vulnerable to breaks during earthquakes, water and wastewater treatment facilities are vulnerable to flood hazards. Facilities are often designed to be in or near flood hazard areas, given their functional dependency on natural water resources. To become more resilient, each individual community will have to consider its own hazards when implementing plans. Additionally, as discussed in the previous section, system interdependencies (e.g., loss of commercial electrical power in a high wind event) can have a significant impact on operability of water and wastewater systems (Elliott, T. and Tang, A., 2009).

9.2.1. Water Infrastructure

Water sources include groundwater and surface water, treated to satisfy public health standards and distributed to consumers by a network of pipelines. Some water utilities have their own supplies and treatment infrastructure, while others buy wholesale water from neighboring agencies.

Water systems are composed of six general infrastructure categories: 1) Supply, 2) Transmission, 3) Treatment, 4) Pumping, 5) Storage, and 6) Distribution. The basic function of each category and infrastructure system (electric power, transportation, communication) interdependent of the water system can be impacted by a variety of hazards, as shown in Table 9-1. Some examples of damage to water infrastructure seen in past events are discussed in the following subsections.

***Table 9-1. Hazard Impacts on Water Infrastructure System** (AWWA M19: Emergency Planning for Water Utilities)*

System Components – Likely damage, loss, or shortage due to hazards	Earthquakes	Hurricanes	Tornadoes	Floods	Forest or Brush Fires	Volcanic eruptions	Other Severe Weather	Waterborne Disease	Hazardous Material	Structure Fire	Construction Accidents	Transportation Accidents	Nuclear	Vandal, riots, Strikes
Administration/operations														
Personnel	◆	◆					◆	◆			◆	◆	◆	◆
Facilities/equipment	◆	◆	◆	◆	◆	◆				◆			◆	◆
Records	◆	◆	◆	◆	◆					◆				◆
Source Water														
Watersheds/surface		◆		◆	◆	◆		◆	◆				◆	◆
sources	◆	◆		◆				◆	◆				◆	◆
Reservoirs and dams				◆				◆	◆				◆	
Groundwater sources	◆	◆	◆	◆		◆	◆	◆	◆					◆
Wells and galleries														
Transmission														
Intake structures	◆		◆	◆		◆	◆					◆		◆
Aqueducts	◆										◆	◆		
Pump stations	◆		◆	◆	◆	◆	◆			◆	◆	◆		◆
Pipelines, valves	◆	◆					◆				◆			◆
Treatment														
Facility structures	◆	◆	◆	◆	◆	◆	◆			◆	◆	◆	◆	◆
Controls	◆	◆	◆	◆	◆	◆	◆			◆	◆	◆		◆
Equipment	◆	◆	◆	◆	◆					◆	◆	◆	◆	◆
Chemicals	◆	◆	◆	◆	◆					◆				◆
Storage														
Tanks	◆	◆	◆		◆	◆	◆	◆	◆	◆		◆	◆	◆
Valves	◆						◆					◆		◆
Piping	◆						◆							
Distribution														
Pipelines, valves	◆	◆					◆	◆	◆		◆			◆
Pump or PRV stations	◆	◆	◆	◆	◆	◆	◆			◆	◆	◆		◆
Materials	◆	◆		◆	◆					◆				◆
Electric power														
Substations	◆	◆	◆	◆	◆		◆			◆	◆	◆	◆	◆
Transmission lines	◆	◆	◆	◆	◆		◆			◆	◆	◆		◆
Transformers	◆	◆	◆	◆	◆	◆	◆			◆	◆	◆		◆
Standby generators				◆						◆				◆
Transportation														
Vehicles		◆	◆	◆	◆		◆				◆	◆		
Maintenance facilities	◆	◆	◆	◆	◆		◆			◆		◆		◆
Supplies		◆		◆	◆					◆				◆
Roadway infrastructure	◆			◆		◆	◆				◆	◆		◆
Communications														
Telephone	◆	◆	◆	◆	◆		◆			◆	◆	◆		◆
Two-way radio														◆
Telemetry	◆		◆	◆	◆	◆								◆

9.2.1.1. Supply

Water supply can come from groundwater or surface water, as described below.

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. 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 structures in lakes or rivers and diversion dams then direct water to a pipeline inlet along the shoreline. All of these systems would generally include screens to keep large debris and fish from entering the treatment plant.

Just as with water and wastewater infrastructures, the water supply is particularly vulnerable flooding and earthquakes. The most significant hazard is contaminated water; flooding can cause contamination of surface and groundwater sources. Additionally, inundated well heads at the surface can introduce contaminants to well systems and groundwater. Floodwaters and generally carry contaminants like petroleum, nutrient/organic matter, bacteria, protozoa, and mold spores that pose significant health risks. Contamination can also result from tank or vehicle discharge in the watershed. In 2014, in West Virginia, 4-methylcyclohexanemethanol (MCHM) was released into the Elk River, contaminating water serving 300,000 people. It took months to restore full water service.

Although not often considered for their impact on water quality, wildfires can also lead to water contamination. Wildfires can burn watersheds, destabilizing the ground cover, which can cause landslides that contaminate the water when subsequent rains occur. Denver Water experienced wildfires in significant parts of their watershed in 1996 and 2002 that burned 150,000 acres of land, releasing one million cubic yards of sediment into one of their reservoirs.

Reservoirs behind dams often also serve as water supply features, but dam failure can present a secondary hazard in the wake of earthquakes, heavy rainfall, and flood events. Concentrated precipitation and flooding most commonly causes overtopping of the dam. While dams can reduce flooding, older and improperly designed and maintained dams are not equipped to contain large volumes of quickly accumulating water runoff. Landslides, caused by liquefaction from earthquakes can also lead to dam failure. These types of dam failures are rare, but present a significant risk to anyone’s life downstream of a dam. Dams are critical infrastructure components that need to be designed to withstand extreme events.

9.2.1.2. Transmission

Large diameter transmission pipelines carry raw water from source to treatment plant, and treated water to storage facilities before branching out into smaller distribution pipelines. Depending on the system, these can range from one foot to several tens of feet in diameter. Transmission pipelines are constructed of welded steel, reinforced concrete, concrete cylinder, or ductile iron (historically cast iron).

Typically, these pipelines are buried, making them difficult to inspect and expensive and disruptive to repair. Burial reduces pipelines’ vulnerability to hazards, such as high wind events; however, hazards that cause landslides, such as earthquakes, floods, long-term heavy rain, and wildfire, can damage transmission lines. Figure 9-2 shows a transmission pipeline bridge demolished in the Bull Run Canyon in a landslide event induced by heavy rains.

***Figure 9-2. Water Transmission Pipeline Bridge Damaged by Landslide** (Courtesy of Portland Water Bureau)*

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. The processes used depend on the raw water source, removing pathogens, organic or inorganic contaminants, chemicals, and turbidity. The treatment process commonly includes pretreatment, flocculation, sedimentation, filtration, and disinfection with variations of these processes in some modern plants. 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.

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 by flood inundation, leading to loss of functionality and service outages. In 1991, the Des Moines, Iowa Water Treatment Plant was submerged by riverine flooding, resulting in 19 days without potable water for the city of Des Moines.

Loss of power at water treatment plants from high wind events (hurricanes, tornadoes), severe storms, or other hazards can severely impact the system by preventing proper treatment prior to transmission and distribution. As a result, potable water may not be available and boil water notices necessary. While standby power systems are usually incorporated into a water treatment plant's design, they need to be well-maintained, tested regularly, and adequately connected, installed, supplied, and protected from hazard events to be reliable and function properly.

Earthquakes also cause damage to water treatment plants and their components. In 1989, the Loma Prieta earthquake in California heavily damaged the clarifiers due to sloshing water at the Rinconada Water Treatment Plant in San Jose, California, greatly curtailing its 40 MGD capacity (Figure 9-3). In the 2011 Tohoku earthquake in Japan, liquefaction resulted in differential settlement between pile-supported structures and direct-buried pipe at water treatment plants, as shown in Figure 9-4.

Figure 9-3. Santa Clara Valley Water District, Rinconada Water Treatment Plant Clarifier Launders Damaged due to Sloshing, 1989 Loma Prieta Earthquake (Courtesy of Don Ballantyne)

Figure 9-4. Liquefaction Caused Differential Settlement Between Pile-Supported Structures and Buried Pipe during the 2011 Tohoku Earthquake (Courtesy of 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.

Similarly to water treatment plants, loss of commercial electrical power due to any type of hazard event prevents operation of pumps if there is no standby power supply. Furthermore, floodwater can inundate electrical equipment and controls at pump stations located wholly or partially below grade and/or in flood-prone areas. Figure 9-5 shows a pump station adjacent to the Missouri River damaged by flood inundation.

Figure 9-5. Bismarck, ND Pump Station Damaged by Flood Inundation from Adjacent Missouri River (Courtesy of FEMA)

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 daily water demand is stored to satisfy increased demand from fire suppression or other emergency needs. Reservoirs are often constructed by damning a valley with a concrete or earthen dam. If they are being used for treated water, they can be lined with asphalt or concrete and covered.

Modern steel storage tanks are either ground-supported, taller standpipes, or elevated tanks supported on a frame or pedestal. Reinforced concrete tanks are typically at grade or buried. Circular concrete tanks can be reinforced with wire wrapping or tendons.

Storage tasks are vulnerable to a number of hazards. 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, suddenly releasing their contents. In hurricanes, high winds present a higher hazard in coastal areas (than further inland) and are often accompanied by storm surge. Figure 9-6 shows a collapsed water tank in Buras, Louisiana near Hurricane Katrina's landfall that was likely caused by a combination of high winds and storm surge.

***Figure 9-6. Collapsed Water Tank in Buras, LA near Hurricane Katrina Landfall Location** (Courtesy of David Goldbloom- Helzner)*

At-grade or partially-underground storage tanks are more susceptible to flood damage (from hurricane storm surge, riverine flooding, or tsunamis), particularly if located in or near flood-prone areas. Tank damage or failure can be caused by both hydrostatic forces from standing or slow moving water, or hydrodynamic forces imposed by higher velocity flows or wave action. Buoyancy forces can cause uplift of empty subgrade tanks if the soil becomes saturated. Figure 9-7 shows two liquid fuel tanks in the foreground that were floated and toppled by tsunami wave inundation after the 2011 Tohoku, Japan tsunami. The tank in the background was on higher ground and does not appear to be damaged.

***Figure 9-7. Steel Tanks Damaged Due to Tohoku, Japan Tsunami in 2011** (Tang & Edwards 2014)*

Earthquakes can damage storage tanks due to lateral loads (shaking) and permanent ground deformation due to liquefaction and landslides. Water sloshes in storage and process tanks imparting extreme loads on tank walls and baffles. In the 1994 Northridge earthquake, a Los Angeles Department of Water and Power (LADWP) tank moved, severing piping, as shown in Figure 9-8. The utility just north of LADWP suffered elephant's foot buckling in a steel tank as shown in Figure 9-9.

***Figure 9-8. Tank Moved, Severing Connecting Pipe in 1994 Northridge Earthquake** (Courtesy of Los Angeles Department of Water and Power)*

***Figure 9-9. Steel Tank "Elephant's Foot" Buckling in 1994 Northridge Earthquake** (Courtesy of Donald Ballantyne)*

9.2.1.6. Distribution

Smaller diameter distribution pipelines carry treated water from transmission pipelines to neighborhoods commercial and industrial areas. Service connections with meters 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. The system is controlled with manually operated valves distributed at most pipeline intersections. Distribution systems have fire hydrants located every 300 feet along the pipeline. Distribution pipelines are commonly made with ductile iron (historically cast iron), welded steel, PVC, or asbestos cement.

Leaks and breaks are two main concerns for distribution pipelines. A leak commonly refers to relatively minor damage to a pipe barrel or joint that causes minor to moderate water loss, but does not significantly impair the distribution system's function. However, breaks commonly refer to major damage to a pipe barrel or joint that causes major water and pressure loss in a zone or drains nearby tanks. When there are breaks in the water distribution system, it can lead to depressurization of the system. Depressurization can result in sediment accumulation within the pipelines affecting the potability of the water, contamination and loss of potability means boil water orders should be issued. Before water can be considered potable again, the distribution systems must be fixed and the water quality monitored and tested continuously to meet public health standards.

Breaks of distribution pipelines can result from a number of hazards. Floods cause erosion, exposing, possibly breaking pipelines (see Figure 9-10).


Figure 9-10. Exposed and Broken Distribution Lines Resulting from Flooding in Jamestown, CO (Courtesy of David Goldbloom-Helzner)

Earthquakes can cause liquefaction or permanent ground deformation, causing pipeline breaks. In the 1994 Northridge earthquake, the Los Angeles Department of Water and Power had approximately 1,000 pipeline breaks, primarily in cast iron pipe. While there was only limited liquefaction, ground motions were very strong. A year later, the Kobe earthquake caused approximately 1,200 pipeline failures due to extensive liquefaction. Most of the system was constructed of ductile iron pipe, which primarily failed by joint separation as seen in Figure 9-11.

Figure 9-11. Joint Separation in Ductile Iron Pipe due to Liquefaction during 1995 Kobe Earthquake (Courtesy of Kobe Water Department)

High wind events, such as hurricanes or tornadoes, can result in damage to distribution lines, though not directly cause by high winds, but by uprooted trees. For example, during Hurricane Andrew, there was extensive damage to the water distribution systems in Southern Florida primarily caused by tree roots that had grown and wrapped themselves around the water mains and service lines. When these trees were uprooted by hurricane force winds, (Hurricane Andrew was a Category 5 on the Saffir-Sampson scale when it made landfall in Dade County, Florida) they pulled the lines too. Similar damage to water transmission and distribution systems occurred during Hurricanes Katrina and Rita in Louisiana (Allouche, 2006). As stated above, no matter the cause of damage, pipeline breaks resulting in a depressurized system contaminate the pipelines, affecting the potability of the water and requiring additional recovery time.

9.2.2. Wastewater Systems

Wastewater systems collect domestic and industrial liquid waste products and convey them to treatment plants through collection and conveyance systems and pump stations. After separation of solids, biological processing and disinfection, treated wastewater is discharged as effluent into a receiving body of water or alternatively, may be reused for irrigation or other purposes. Some utilities have separate collection systems for wastewater and storm water; other utilities have collection systems combine collected wastewater and storm water in the same pipelines.

Pipeline system failure can discharge raw sewage into basements, on to city streets, and into receiving waters, resulting in public health issues and environmental contamination. Standard wastewater systems are composed of five general categories of infrastructure: 1) Collection, 2) Conveyance, 3) Pumping, 4) Treatment, and 5) Discharge. The basic function of each of these categories is briefly described in the following subsections. Apart from standard systems, pressure and vacuum systems are used on occasion. Pressure systems require a grinder pump at each house that pump the sewage through small diameter pipe to a larger pipe collector, and often times to a gravity sewer. Vacuum systems work in a similar manner, except a vacuum pump and tank pull sewage through shallow small diameter pipe to a central location.

9.2.2.1. Collection

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. This is usually accomplished using gravity sewers. In some instances pumps convey wastewater through pressurized force mains. 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. A variety of pipe materials are commonly found in collection systems, including:

- Vitrified clay – smaller diameter collection
- PVC – smaller diameter collection
- Asbestos cement – historically smaller diameter collection
- Reinforced concrete – larger diameter interceptors
- Steel – force mains or siphons
- Polyethylene – force mains or siphons
- Ductile iron (or historically cast iron) – collection or force mains
- Brick – larger capacity interceptors
- Fiberglass or FRP
- ABS

Gravity systems have manholes at regular intervals allowing access for cleaning and maintenance. Manholes are usually constructed with concrete, although historically manholes were often constructed with brick.

Wastewater collection pipes have similar causes of damage to those of water distribution and transmission pipelines. Wastewater collection pipelines can be exposed and damaged because of landslides, erosion, or scour, which damages or breaks the pipelines. Furthermore, wastewater collection pipelines can be damaged in high wind events by uprooted trees with root systems grown around the pipelines.

In the collection and conveyance system, pipelines are damaged by earthquake shaking, but more extensively due to liquefaction and associated lateral spreading. Sewer pipes can be damaged by shaking, which can cause joints to crack, but most remain operable. These cracks will ultimately have to be repaired to control infiltration. Liquefaction can result in pulled joints and displaced pipe. Another cause of failure is pipe flotation, occurring when a partially-filled gravity sewer is surrounded by liquefied soil.

Flooding can also damage wastewater collection pipelines in a number of ways. Pipelines that are co-located on bridges experience damage caused by 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. In the New Orleans area after Hurricane Katrina, the most common damage to buried wastewater pipelines observed by clean-up crews was separation of pipe joints, leaks, and breaks. This damage was believed to be the result of floodwaters supersaturating soils then draining, leading to soil shrinkage and subsidence. Without support of the soils, the rigid pipelines broke and fractured (Chisolm, 2012). Increased flow and pressurization of the wastewater collection systems as the result of inflow and infiltration during flood events can also damage pipelines, particularly in cases where pipes are composed of materials such as vitrified clay. For example, during the 1997 Red River Flood in Grand Forks, North Dakota, pressurization caused breaking of vitrified clay pipe and hairline cracks increased the rate of overall pipe deterioration (Chisolm 2012).

9.2.2.2. Conveyance

The conveyance system for the wastewater network is similar to the transmission system in a water system. The conveyance pipelines are larger in diameter, and are often times deeper underground. In many instances, these conveyance systems were installed in the early to mid-1900s as the United States began to clean up its waterways. The conveyance systems are designed to collect sewage from the collection system and move it to the wastewater treatment plant. Like collection systems, it may include pump stations. Recently, the EPA is pushing wastewater utilities to minimize discharge of raw sewage to receive water runoff during heavy rain events. This often resulted in cities having sewers that carried both sewage and storm water. As a result, many conveyance systems now have a built-in large storage capacity, taking the form of a wide point in the line and, in some cases, simplified wastewater treatment facilities.

9.2.2.3. Pumping

Gravity feed systems use pump or lift stations 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. The pumps can be located in a building (typically wetwell-drywell layout) or a large manhole (submersible). Pump stations are required to have standby generators to enable continued operation when the commercial power supply is interrupted.

Pump stations are vulnerable to a number of hazards, most notably earthquakes and flooding. Unless designed to be submersible, floodwater inundating pumps can disable and damage the pumps and their motors. This was a common cause of pump station failure in New York City during flood inundation from Hurricane Sandy (NYCDEP, 2013). Damage is even worse if salt water flooding is involved, leading to corrosion. Loss of commercial electrical power prevents operation of pumps if adequate standby power is not provided or these generators are not refueled in a timely manner. Earthquakes can cause liquefaction, resulting in buried wastewater collection wells at pump stations to float and tilt. This movement likely damages connecting piping and renders the pump station inoperable. Manholes and pump stations can float as well, when founded in liquefied soils, which changes the grade, making the sewer unusable or difficult to maintain.

9.2.2.4. Treatment

Wastewater treatment plants process raw sewage from household and industrial sources so the resulting effluent discharge meets public health and environmental standards. The typical process is: 1) Pretreatment using screens and grit chambers, 2) Primary treatment in a sedimentation tank, 3) Secondary treatment using biological treatment and clarifiers, and 4) Disinfection using chlorine or other disinfectants. In some cases, the effluent is further treated at a higher level to be used for irrigation. Solids drawn off from the four processes are further treated in digesters and solidified using presses or centrifuges. These processes require an extensive mechanical and electrical equipment and piping.

Wastewater treatment plants are susceptible to damage from several natural hazards, particularly flooding. Wastewater treatment plants are often located in or near flood-prone areas because they return treated water to naturally occurring bodies of water via gravity. Therefore, they can be vulnerable to flood inundation or storm surge and wave action from coastal sources, causing damage and loss of functionality to buildings, equipment, and electrical and mechanical systems. The New York City Department of

Environmental Protection (NYC DEP) noted in a recent study that all 14 of the wastewater treatment plants (WWTP) it owns and operates are at risk of flood damage (NYCDEP, 2013).

WWTPs in non-coastal regions of the United States are often located adjacent to rivers. With the projected sea level rise continuing through the 21st century, the frequency of these facilities flooding will increase. Some recent examples of WWTP riverine flooding include: 1) Nine days of lost functionality due to flooding of Valdosta, Georgia WWTP in 2009; 2) Flooding of the Pawtuxet River in Warwick, Rhode Island in 2010; and 3) Shut down of the Palmyra, Indiana WWTP in 2011 due to rising water levels.

In areas where wastewater treatment facilities are elevated or protected by levees, flooding can still lead to access issues. While the treatment facility itself may not be inundated, flooding around the facility can limit both ingress and egress of vital staff. This was the case for several WWTPs located along the Missouri and Mississippi Rivers during the 1993 flood. Access to facilities was only possible by boat, while roads inundated by the flood were not considered stable enough for larger vehicles, such as those that carried supplies for the plants (Sanders, 1997).

Release of untreated sewage is relatively common during major flood events when inflow and infiltration can overtax wastewater collection systems or when there are combined sewer overflows. During Hurricane Sandy, over 560 million gallons of untreated and diluted sewage, mixed with storm water and seawater, was released into waterways. This instance of sewage release was caused by infiltration of floodwaters into the sewer system, flood inundation of plant facilities, and power outages (NYC DEP, 2013). After Hurricane Sandy, electronic controls were inundated and damaged in many wastewater treatment facilities, which significantly delayed the facilities' recovery times (FEMA 2013). Similarly, after Hurricane Rita in 2005, the City of Lake Charles had a citywide power loss that affected the wastewater treatment plant serving two-thirds of the city, releasing raw sewage into a nearby lake for over a week, until power was restored.

While discharge or raw sewage contaminates the receiving water, chemical contamination of sewage can impact the WWTP treatment process itself. For example, in the 1989 Loma Prieta earthquake in California, the East Bay Municipal Utility District (EBMUD) WWTP biological treatment process failed due to a spill in the collection system contaminating the treatment plant influent. Coupled with the spill, EBMUD lost power and were unable to pump oxygen into the treatment system, resulting in the secondary treatment system being inoperable for several weeks.

WWTPs are at a low point in the elevation of the system. Though flooding from different hazard events (hurricane storm surge, coastal and riverine flooding, and tsunamis) is a primary concern, earthquakes can damage facilities by shaking, permanent ground deformation, and liquefaction. Shaking is particularly problematic in process tanks and digesters where the hydraulic load from sloshing sewage impacts the tank walls. Liquefaction-induced permanent ground deformation often causes process tank joint separation, damage to pipelines, pipe racks, etc. Even if treatment structures are pile-supported, direct-buried piping can settle differentially and break. In the 2011 Christchurch earthquake in New Zealand, clarifiers settled differentially rendering them inoperable. In the 1995 Kobe Earthquake, the Higashinada WWTP site settled differentially as much a one meter, and moved laterally as much as two meters due to liquefaction heavily damaging non-pile-supported structures. The resulting damage is shown in Figure 9-12. Figure 9-13 shows the Higashinada influent channel that was offset one meter by liquefaction during the 1995 Kobe earthquake.

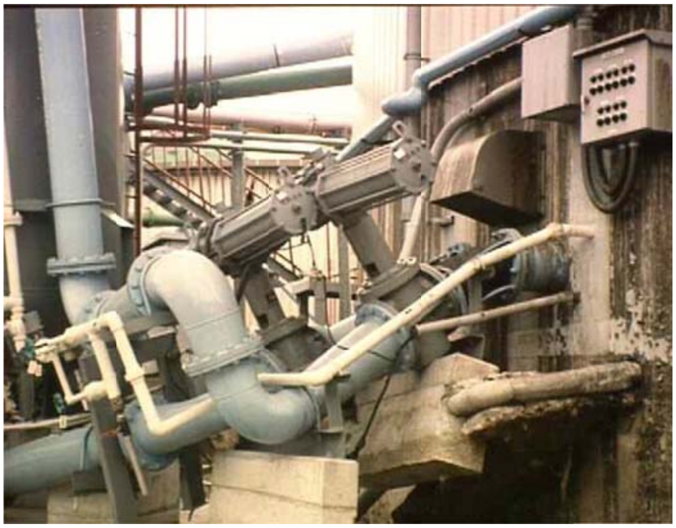

***Figure 9-12. Non-Pile Supported Structures Failed Due to Liquefaction in 1995 Kobe Earthquake** (Courtesy of Donald Ballantyne)*

***Figure 9-13. Higashinda WWTP Channel Offset by Liquefaction in 1995 Kobe Earthquake** (Courtesy of Donald Ballantyne)*

Strong earthquakes can produce tsunamis that structurally damage treatment plant facilities due to lateral hydraulic loading and can inundate facilities, causing damage to electrical gear. The 2011 Tohoku earthquake in Japan caused heavy damage to the Sendai WWTP Effluent Pump Station's east wall, as shown in Figure 9-14. Much of the treatment plant's process tank equipment required replacement because of the large amount of damage, as shown in Figure 9-15.

***Figure 9-14. Sendai WWTP Effluent Pump Station Damaged by Tsunami in 2011 Tohoku Earthquake** (Courtesy of Donald Ballantyne)*

***Figure 9-15. Sendai WWTP Equipment and Piping Damage from 2011 Earthquake** (Courtesy of Donald Ballantyne)*

9.2.2.5. Discharge

Effluent from the treatment plant is discharged to a receiving body of water through an outfall. Outfalls are composed of a pipeline with a diffuser at the end discharging the water hundreds or thousands of feet away from the shoreline, at a depth that will minimize impact on the environment.

9.3. Performance Goals

The large and distributed nature of water and wastewater systems, combined with their interdependence on other infrastructure systems, limits the practicality of maintaining 100 percent operational capacity in the aftermath of a major natural disaster. This section provides an example of performance goals for water and wastewater systems in the fictional community of Centerville, USA.

Performance goals 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 community. Water and wastewater stakeholder engagement is critical in establishing a community-specific level of service performance goals for each of the three different hazard levels (*routine*, *expected*, and *extreme*) defined in Chapter 3. Stakeholders should include representation from the following organizations as applicable:

- Residential customers
- Business owners
- Industry representatives
- Water wholesale customers
- Hospital representatives
- Fire department officials and crew
- 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 infrastructure system operators (power, liquid fuel, transportation, etc.)

Establishing performance goals involves a discussion amongst the stakeholders about their expectations for the availability of water and wastewater systems following a hazard event in the short, intermediate, and long term phases for different hazard levels (e.g., *routine*, *expected*, and *extreme*). The assumed expectation of the public is that for *routine* hazard events 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. While examples are provided in Table 9-2 through Table 9-7 (pages 16 through 21), it is anticipated that actual goals will vary by community and are dependent on community priorities, as determined during the development of the goals and through outreach to and discussion among stakeholders.

There may be variability for an individual community's goals depending on the specific hazard being addressed. For example, if a community is subject to both seismic and wind hazards, they may determine that the damage to major collection lines within a wastewater system from an extreme seismic event is more likely and requires more restoration time, compared to damage from an extreme wind event.

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

Interdependencies of water and wastewater systems with other infrastructure 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 standby generators and impacts repair crew's vehicles and equipment. In turn, delivery of liquid fuels depends on the status of the highway and bridge transportation network.

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.

The infrastructure components in the example performance goals tables are not intended to be an exhaustive list. Some of the system components may not exist in all communities. For instance, in the water system performance goals, some communities may have the ability to distinguish between the general water supply and distribution and water supply for fire suppression. However, most systems are integrated and will not have a means to separate general supply and distribution from that needed for fire suppression. Additionally, some communities might have wholesale users – a system component listed in the performance goals – meaning their water system supplies all of the water used by other nearby, smaller communities. Wholesale users are treated as a critical part of the distribution system within the example, but are not a consideration for all communities. Each community will need to review these components to determine which ones to incorporate into their systems.

Similarly, communities may want to add certain system components to these goals that are not already captured here, to provide additional detail and allow for distinction between restoration timeframes. There may also be system components that are unique to a community that require special consideration. While the lists presented in the examples generally capture significant system components, it is recognized that communities may have additional infrastructure assets to consider.

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 certain concepts.

- Prioritizing potential solutions to be implemented over many years to limit disruptions and recovery time rather than implementing them all at once
- Recognizing that there may be both short and long-term solutions capable of decreasing recovery times
- Balancing societal needs with realistic expectations of system performance

Focusing on major system components that form a backbone network capable of supplying key health and safety-related community needs shortly after a hazard event is one way to focus priorities. Recognizing that potentially less costly short-term solutions combined with longer term physical hardening of infrastructure allows for increased resilience would manage community’s expectations and the cost of implementing solutions.

Table 9-2. Example Water Infrastructure Performance Goals for Routine Event in Centerville, USA

Disturbance		
(1)	Hazard	Any
	Affected Area for Routine Event	Localized
	Disruption Level	Minor

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								
			Routine Hazard Level								
			Phase 1 – Short-Term			Phase 2 -- Intermediate			Phase 3 – Long-Term		
			Days			Wks			Mos		
			0	1	1-3	1-4	4-8	8-12	4	4-24	24+
Source		1									
Raw or source water and terminal reservoirs			90%		X						
Raw water conveyance (pump stations and piping to WTP)			90%		X						
Potable water at supply (WTP, wells, impoundment)			90%		X						
Water for fire suppression at key supply points (to promote redundancy)			90%		X						
Transmission (including Booster Stations)		1									
Backbone transmission facilities (pipelines, pump stations, and tanks)			90%		X						
Control Systems											
SCADA or other control systems			90%		X						
Distribution											
Critical Facilities		1									
Wholesale Users (other communities, rural water districts)			90%		X						
Hospitals, EOC, Police Station, Fire Stations			90%		X						
Emergency Housing		1									
Emergency Shelters			90%		X						
Housing/Neighborhoods		2									
Drink water available at community distribution centers				90%		X					
Water for fire suppression at fire hydrants				90%		X					
Community Recovery Infrastructure		3									
All other clusters					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 9-3: Example Water Infrastructure Performance Goals for Expected Event in Centerville, USA

Disturbance		
(1)	Hazard	Any
	Affected Area for Routine Event	Localized
	Disruption Level	Minor

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								
			Expected Hazard Level								
			Phase 1 – Short-Term			Phase 2 -- Intermediate			Phase 3 – Long-Term		
			Days			Wks			Mos		
			0	1	1-3	1-4	4-8	8-12	4	4-24	24+
Source		**1**									
Raw or source water and terminal reservoirs					90%						
Raw water conveyance (pump stations and piping to WTP)						90%				X	
Potable water at supply (WTP, wells, impoundment)			30%		60%	90%			X		
Water for fire suppression at key supply points (to promote redundancy)			90%			X					
Transmission (including Booster Stations)		**1**									
Backbone transmission facilities (pipelines, pump stations, and tanks)			90%					X			
Control Systems											
SCADA or other control systems			30%		60%	90%		X			
Distribution											
Critical Facilities		**1**									
Wholesale Users (other communities, rural water districts)				60%	90%						
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: See Table 9-2, page 16.

Table 9-4: Example Water Infrastructure Performance Goals for Extreme Event in Centerville, USA

Disturbance		
(1)	Hazard	Any
	Affected Area for Extreme Event	Regional
	Disruption Level	Severe

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								
			Extreme Hazard Level								
			Phase 1 – Short-Term			Phase 2 – Intermediate			Phase 3 – Long-Term		
			Days			Wks			Mos		
			0	1	1-3	1-4	4-8	8-12	4	4-36	36+
Source		**1**									
Raw or source water and terminal reservoirs			30%		60%	90%			X		
Raw water conveyance (pump stations and piping to WTP)						60%	90%			X	
Potable water at supply (WTP, wells, impoundment)					30%	60%	90%			X	
Water for fire suppression at key supply points (to promote redundancy)					90%	X					
Transmission (including Booster Stations)		**1**									
Backbone transmission facilities (pipelines, pump stations, and tanks)			30%				60%		90%	X	
Control Systems											
SCADA or other control systems						30%	60%	90%			
Distribution											
Critical Facilities		**1**									
Wholesale Users (other communities, rural water districts)							60%		90%	X	
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					30%	60%	90%		X		
Water for fire suppression at fire hydrants						60%	90%			X	
Community Recovery Infrastructure		**3**									
All other clusters								60%	90%		X

Footnotes: See Table 9-2, page 16.

Table 9-5. Example Wastewater Infrastructure Performance Goals for Routine Event in Centerville, USA

Disturbance		
(1)	Hazard	Any
	Affected Area for Routine Event	Localized
	Disruption Level	Minor

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								
			Routine Hazard Level								
			Phase 1 – Short-Term			Phase 2 -- Intermediate			Phase 3 – Long-Term		
			Days			Wks			Mos		
			0	1	1-3	1-4	4-8	8-12	4	4-24	24+
Treatment Plants											
Treatment plants operating with primary treatment and disinfection					90%	X					
Treatment plants operating to meet regulatory requirements					90%	X					
Trunk Lines											
Backbone collection facilities (major trunkline, lift stations, siphons, relief mains, aerial crossings)				60%	90%	X					
Flow equalization basins				60%	90%	X					
Control Systems											
SCADA and other control systems			90%		X						
Collection Lines											
Critical Facilities											
Hospitals, EOC, Police Station, Fire Stations				90%	X						
Emergency Housing											
Emergency Shelters				90%	X						
Housing/Neighborhoods											
Threats to public health and safety controlled by containing & routing raw sewage away from public				60%	90%	X					
Community Recovery Infrastructure											
All other clusters				60%	90%	X					

Footnotes: See Table 9-2, page 16.

Table 9-6: Example Wastewater Infrastructure Performance Goals for Expected Event in Centerville, USA

Disturbance		
(1)	Hazard	Any
	Affected Area for Expected Event	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								
			Expected Hazard Level								
			Phase 1 – Short-Term			Phase 2 -- Intermediate			Phase 3 – Long-Term		
			Days			Wks			Mos		
			0	1	1-3	1-4	4-8	8-12	4	4-24	24+
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 trunkline, lift stations, siphons, relief mains, aerial crossings)					30%		60%	90%			X
Flow equalization basins					30%		60%	90%			X
Control Systems											
SCADA and other control systems						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: See Table 9-2, page 16.

Table 9-7: Example Wastewater Infrastructure Performance Goals for Extreme Event in Centerville, USA

Disturbance		
(1)	Hazard	Any
	Affected Area for Extreme Event	Regional
	Disruption Level	Severe

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								
			Extreme Hazard Level								
			Phase 1 – Short-Term			Phase 2 -- Intermediate			Phase 3 – Long-Term		
			Days			Wks			Mos		
			0	1	1-3	1-4	4-8	8-12	4	4-36	36+
Treatment Plants											
Treatment plants operating with primary treatment and disinfection						30%	60%		90%	X	
Treatment plants operating to meet regulatory requirements										90%	X
Trunk Lines											
Backbone collection facilities (major trunkline, lift stations, siphons, relief mains, aerial crossings)							30%	60%		90%	X
Flow equalization basins							30%	60%		90%	X
Control Systems											
SCADA and other control systems								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								60%		90%	X

Footnotes: See Table 9-2, page 16.

9.4. Regulatory Environment

9.4.1. Federal

The federal EPA has requirements for drinking water quality defined in the Safe Drinking Water Act and wastewater discharge water quality defined in the Clean Water Act. These acts are amended on an ongoing basis. In most cases, the EPA gives states primacy to enforce these requirements. There are certain prescriptive requirements associated with each.

SDWA Example Requirements

- Filtration of surface water supplies, except in some cases special treatment of particularly clean surface water supplies
- Disinfection of supplies (except a few groundwater supplies)
- Covering of treated water storage

Clean Water Act Example Requirements

- Secondary treatment of wastewater discharges
- Disinfection of wastewater discharges

In general, these regulations all focus on water quality and have limited interest in catastrophic hazard event impacts and planning.

9.4.2. State

State Drinking Water Programs. States typically regulate water quality and require treatment approaches for recycled water. States ensure water systems meet Safe Drinking Water Act standards by ensuring water systems test for contaminants, reviewing plans for water system improvements, conducting on-site inspections and sanitary surveys, providing training and technical assistance, and taking action against non-compliant water systems.

State Water Quality Programs. States also ensure water systems meet Clean Water Act water quality standards using state water quality programs. 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 non-compliant wastewater systems.

Emergency Planning and Community Right-to-Know Act (EPCRA). Facilities that store, use, or release certain chemicals may be subject to reporting requirements to state and/or local agencies through EPCRA. Information in reports then becomes publically available. Treatment chemicals stored and used at water treatment plants often require this type of reporting.

Planning Requirements. Water and wastewater planning and design requirements are generally controlled by states and local governments. States typically require comprehensive plans for water and wastewater system are prepared on a regular basis to assess future system needs (e.g. capacity) and how those needs will be met. The elements of those comprehensive plans are defined by the state. Often times, these plans include requirements to identify hazards to which the system could be subjected, and how the utility will address those hazards. These are typically quite general in nature and do not include detailed design criteria.

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 state and local government are responsible for adopting model building codes, such as the International Building Code (IBC). Model building codes rely heavily on standards, such ASCE-7, *Minimum Design Loads for Buildings and Other Structures.* In many cases, the state will adopt these model codes; in some cases, local jurisdictions modify them to suit their needs. The IBC and ASCE-7 focus on building structure life safety. State and local agencies will also have special requirements for high risk facilities, such as dams. The Federal Energy Regulatory Commission controls designs of hydroelectric generating dams.

The development of design codes is a long and arduous process. Theses codes are updated on a regular basis taking into account performance of facilities since the last code was issued and other developments in the building industry. Once they are finalized, they are voted on by the code committee and finally adopted by state and/or local jurisdictions. Once a code is well vetted, the state and local jurisdictions adopt it.

The following subsections discuss some of the codes, standards, and guidelines that are important to the disaster resilience of water and wastewater infrastructure, the anticipated performance of the infrastructure after an expected hazard event, and the long-term recovery levels of the infrastructure when damage does occur.

9.5.1. New Construction

Design Standards. Developed and adopted by various organizations, the two organizations that have standards most relevant to natural hazard impacts on the water and wastewater industry include:

- **American Concrete Institute –** standards addressing concrete process tanks (ACI 350)
- **American Water Works Association (AWWA) –**
  - Standards addressing design of water storage tanks (AWWA D100, D110, D115), addressing seismic design of water storage tanks
  - Standard AWWA-J100, Risk and Resilience Management of Water and Wastewater Systems, addressing performance of water and wastewater systems when subjected to natural and manmade hazards

AWWA has other standards addressing pipeline design and water quality. However, none of these other standards addresses seismic design for other natural hazards.

For the design of new underground pipelines, there is not a 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 its design practices. While these agency-specific design practices are generally based on industry recommendations, variability in standards used by utilities results in variability in the intended system reliability for natural and man-made hazards.

Some utilities develop their own standards to address significant local hazards specifically. 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, yet ensures the SFPUC achieves its basic level of service performance goal to deliver winter day demand to their wholesale customers within 24 hours after a major earthquake.

Guidelines and Manuals of Practice. A number of organizations have developed guidelines intended for use by the industry to enhance design of the particular product being addressed. Table 9-8 lists some of the model codes, standards, and guidance documents applicable to water and wastewater infrastructure.

This table also shows a matrix of system component to document. This list is not intended to be exhaustive. However, the reader should be aware of these documents that pertain to disaster resilience.

Table 9-8. Codes, Standards, and Guidelines for Hazard Resistance of Water and Wastewater Facilities

Org	Category (1)	Name	General	Pipelines	Pumping	Storage	Treatment
IBC	C	2012 International Building Code or applicable jurisdictional building code	x				
ASCE	S	Minimum Design Loads for Buildings and Other Structures	x				
ACI	S	350 Code Requirements for Environmental Engineering Concrete Structures				x	x
ACI	S	371R-08 Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks				x	
ACI	S	372R-03 Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures				x	x
AWWA	S	D100-11 Welded Carbon Steel Tanks for Water Storage				x	
AWWA	S	D110-13 Wire- and Strand-Wound, Circular, Prestressed Concrete Tanks				x	
AWWA	S	D115-06 Tendon-Prestressed Concrete Water Tanks				x	
AWWA	S	G430-14 Security Practices for Operation and Management	x				
AWWA	S	J100-10 Risk Analysis and Management for Critical Asset Protection Standard for Risk and Resilience Management of Water and Wastewater Systems	x				
AWWA	S	G440-11 Emergency Preparedness Practices	x				
ALA	G	Guidelines for Implementing Performance Assessments of Water Systems	x				
ALA	G	Guidelines for the Design of Buried Steel Pipe (2001)		x			
ALA	G	Seismic Design and Retrofit of Piping Systems (2002)			x		x
ALA	G	Seismic Fragility Formulations for Water Systems (2001)	x				
ALA	G	Seismic Guidelines for Water Pipelines (2005)		x			
ALA	G	Wastewater System Performance Assessment Guideline (2004)	x				
ASCE	G	Guidelines for Seismic Design of Oil and Gas Pipeline Systems (1984)		x			
AWWA	G	Emergency Power Source Planning for Water and Wastewater	x				
AWWA	G	M9 Concrete Pressure Pipe		x			
AWWA	G	M11 Steel Pipe: A Guide for Design and Installation		x			
AWWA	G	M19 Emergency Planning for Water Utilities	x				
AWWA	G	M60 Drought Preparedness and Response	x				
AWWA	G	Minimizing Earthquake Damage, A Guide for Water Utilities (1994)	x				
EPA/AWWA	G	Planning for an Emergency Drinking Water Supply	x				
MCEER	G	MCEER-08-0009 Fragility Analysis of Water Supply Systems (2008)	x				
MCEER	G	Monograph Series No. 3 Response of Buried Pipelines Subject to Earthquakes		x			
MCEER	G	Monograph Series No. 4 Seismic Design of Buried and Offshore Pipelines		x			
TCLEE	G	Monograph 15 Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities (1999)		x			
TCLEE	G	Monograph 22 Seismic Screening Checklists for Water and Wastewater Facilities (2002)	x				
WEF	G	Emergency Planning, Response, and Recovery	x				
WEF	G	Guide for Municipal Wet Weather Strategies	x				
WEF	G	MOP 28 Upgrading and Retrofitting Water and Wastewater Treatment Plants					x
WEF	G	MOP 8 Design of Municipal Wastewater Treatment Plants					x
WEF	G	MOP FD-17 Prevention and Control of Sewer System Overflows	x				

C – Code; S – Standard; G – Guideline or Manual of Practice (MOP)

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, seismic, or other 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, seismic, or other event. By designing for this performance target for the *expected* level event, water and wastewater systems should remain operational under a *routine* level event and may experience moderate to major damage during an *extreme* level event.

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 water or wastewater systems to return to normal operating status following a hazard event 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.). Estimating system recovery times for a specific hazard requires in-depth engineering and operational knowledge of the system.

Table 9-9 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 9-9. 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 was refined over time as the engineering and seismology community's understanding of United States seismicity 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 the hazard used by current codes and standards.

Expected seismic performance of water and wastewater system components is dependent on the hazard level, codes and standards used in original design, and the type of structure. 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 structures' behaviors during earthquakes. 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 are in areas that haven't experienced a significant increase in seismicity are generally expected to perform similar to new construction as described above. However, some types of structures are inherently rugged. For example, many older cast-in-place concrete structures, particularly single story buildings with few opening would be expected to perform well.

Anticipated performance of nonstructural components should be evaluated on a case-by-case basis, as engineers now pay closer attention to seismic design and construction of nonstructural components.

Anticipated 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. Even today, there is no code or standard for seismic design of pipelines.

9.5.2.2. Recovery Levels

In the past, infrastructure systems have not performed to the level that communities would desire with extended recovery times beyond the example performance goals in Section 9.3. There are a number of examples of disaster events that have rendered utilities non-functional for weeks following the event and illustrate importance of considering the interdependencies of water and wastewater systems with other systems of the built environment. A few notable events and their actual recover levels are discussed herein.

Great Flood of 1993. In the Great Flood of 1993, the Raccoon River overtopped its banks and submerged the Des Moines, Iowa WWTP. The water receded and the plant was able to restore non-potable water within 12 days and potable water within 19 days. The water outage disrupted restaurant and hotel operations. The Principal Insurance Company headquarters had to haul in water and pump it into the building to cool computers. AT&T's regional central office came within minutes of losing phone service because of computer cooling issues.

Northridge and Kobe Earthquakes. In the 1994 Northridge earthquake, the Los Angeles Department of Water and Power's distribution system suffered approximately 1,000 pipeline failures, primarily in the San Fernando Valley. With their own forces and mutual aid, they were able to fully restore potable water service to everyone within 12 days. A year later, the 1995 Kobe Japan earthquake suffered 1,200 pipeline failures resulting in lost service to all households for up to 60 days.

Christchurch, New Zealand and Tohoku, Japan Earthquakes. The recent 2011 Christchurch New Zealand, and Tohoku Japan earthquakes both resulted in outages lasting in excess of 40 days. Impacted Japanese cities were assisted by mutual aid from their colleagues from cities in western Japan.

9.6. Strategies for Implementing Community Resilience Plans

Section 9.2 discusses components of water and wastewater infrastructure system. The discussion includes examples from different types of hazards to encourage the reader to think about the different hazards that could impact the communication and information infrastructure in their community. The number, types, and magnitudes of hazards that need to be considered will vary from community to community.

Section 9.3 discusses example performance goals for the water and wastewater infrastructure system in fictional town Centerville, USA. These example performance goals are provided for the routine, expected and extreme event. However, the performance goals should be adjusted by the community based on its social needs.

Section 9.4 and 9.5 outline some of the regulatory levels and issues, and codes and standards that the reader should keep in mind when planning to make upgrades/changes to existing infrastructure as well as building new structures for their water and wastewater infrastructure system. The objective of this section is use the information from Sections 9.2 through 9.5 to provide guidance on how a community should work through the process of assessing their communications infrastructure, defining strategies to make its infrastructure more resilient, and narrowing the resilience gaps.

9.6.1. Available Guidance

The purpose of the assessment is to quantify the anticipated performance and recovery of the overall system to determine whether it meets the performance goals described in Section 9.3. If the system does not meet the objectives, the assessment should identify system facility and pipe deficiencies that should be improved to achieve those performance goals.

Section 9.2.1 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. Information about past disaster performance of similar systems combined with knowledge of current condition and original design standards of the system help a utility estimate the expected level of service they could provide after a hazard event. There is likely a gap in the level of service a system would provide if a hazard event occurred today versus community-established performance goals. It is likely that 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 designing new and upgrading existing infrastructure. To estimate the level of service a water or wastewater system would provide after a given scenario hazard event, an assessment of expected damage to the system and restoration times is required.

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

- ***Tier 1 –*** A high-level assessment of hazards and their performance conducted by persons knowledgeable about the system (chief engineer, operations manager, etc.). This can be accomplished in a workshop setting using system maps and schematics, along with hazard maps of the service area, such as liquefaction susceptibility or flood plain maps. Restoration times will be based on professional judgment of the workshop participants.
- ***Tier 2 –*** A more refined assessment based on published scenario events and hazard zones, system inventory (i.e., facility type, age, condition, and location relative to hazards, and pipe type, length and soil type), site visits, and use of generalized component fragilities, such as those included in HAZUS-MH and ALA documents. Restoration times are based on the extent of damage (e.g., number of pipeline breaks), estimates of the time to repair each category of damage, and crews and equipment available for restoration.
- ***Tier 3 –*** A detailed assessment of all components in a system, specific component fragilities, and the interdependencies of system components. Same as Tier 2, with the addition of detailed

analysis (e.g. geotechnical, structural or hydraulic) of facilities and pipelines determined to be vulnerable and critical, should they fail, significantly impacting the overall system operation.

To characterize the current disaster resilience of water and wastewater systems appropriately, 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. It assists in conducting a Tier 2 analysis and an AWWA J100 analysis as discussed below.

The ANSI/AWWA J100-10 *Standard for Risk and Resilience Management of Water and Wastewater Systems* (AWWA, 2010) provides a methodology for conducting multi-hazard system risk and resilience assessments. The J100 aligns the national homeland security objectives in HSPD-5, PPD-8, PPD-21 and EO 13636. The J100 standard consists of a seven-step process for analyzing and supporting management decisions that maximize risk reduction and/or enhance resilience at the utility and the community it serves.

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

Asset level resilience for specific threats is part of the J100 assessment methodology, which may support a community's process for determining current performance and target performance (Section 9.3). The J100 also includes the Utility Resilience Index (URI), which is a system-level assessment of operational and financial indicators that are essential to resilience and, therefore, an asset's ability to effectively serve a community. The URI serves 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.

Several tools were developed by the U.S. Environmental Protection Agency to support the water utility assessment of risks. The Vulnerability Self-Assessment Tool (VSAT) (EPA 2014) is designed to assist water and wastewater utilities' application of the J100 standard. VSAT is complemented by the Water Health and Economic Analysis Tool (WHEAT), which quantifies three aspects of consequence associated with an adverse event's 1) public health impact, 2) utility-level financial impact, and 3) direct and indirect regional economic impact (EPA, 2014). WHEAT is specifically aligned with step 3 (consequence analysis) of J100 standard.

The EPA's National Homeland Security Research Center (NHSRC) also supported efforts to enhance utility resilience. Collaboration with AWWA resulted in the development of *Planning for an Emergency Drinking Water Supply*, which directly supports a capability assessment based on worst reasonable threats in J100 to determine options for maintaining service.

An example Tier 2 resilience assessment procedure for water systems is outlined in the following.

9.6.1.1. Example Tier 2 Resilience Assessment for Earthquake:

1. Identify the appropriate earthquake scenario or scenarios. Develop or obtain ground motion information for each. The USGS has scenarios available for a suite of earthquakes in the U.S.

Obtain liquefaction and landslide hazard maps available from the state department of geology. Use GIS for all mapping.

For buried pipelines:

2. Compile an inventory of system pipelines including pipe material, joint type, and length.
3. In GIS, superimpose the pipeline distribution system onto maps of the scenario hazard (peak ground velocity, 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 pipeline 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. Use fragility curves found in HAZUS-MH to determine the anticipated performance for a particular facility type for a given ground motion.
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 system performance based on the damage to pipelines and facilities in a workshop format.
10. 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.
11. 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. The tier level of the assessment increases by conducting detailed analyses of each facility and pipeline.

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 characterize the anticipated performance of the system of systems in a hazard event appropriately.

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 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. If no codes exist for a particular category of structure or facility, the designer should investigate guidelines that address hazard-resistant design issues (see Table 9.4). The incremental cost of designing and constructing for improved disaster resilience may be 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 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. In some cases, redundant systems can be justified based on increasing demand requirements. The "new" redundant system could provide on its own an adequate supply to meet an average day's demand until the damaged system was repaired. Whatever is done needs to be part of the day-to-day needs of the utility. That is, if special features added to a system to increase resilience are never used, there is a high likelihood they will not be functional when they are needed.

Once water and wastewater providers and the community establish resilience performance goals and complete baseline resilience assessments, there may be a number of goals not currently met due to the anticipated 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 period) of new construction, retrofit of existing system components to better withstand hazard events, 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. Major resilience improvements that take place on a shorter timeline require a more extensive campaign of public outreach and education.

9.7. References

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