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Initial Framework to Design Lifeline Infrastructure for Post-earthquake Functional Recovery

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This publication is intended to capture perspectives from external experts related to NIST efforts to enhance standards and measurement for disaster risk mitigation. These external perspectives can come from industry, academia, government, and other organizations. This report was prepared as a product of collaborative interactions; it is intended to document diverse perspectives and does not represent official NIST position on topics discussed herein.

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ABSTRACT

Services provided by lifeline infrastructure systems are critical to the recovery of social functions after an earthquake. Lifeline infrastructure includes water, wastewater, drainage, electric power, communications, gas and liquid fuels, solid waste, and transportations systems. They are large, complex, geographically distributed systems built with specialized components made of many different materials over long periods of time. This publication is a companion volume to NIST SP 1310 report that presents frameworks for assets and organizational actions for lifeline systems. This volume documents a detailed application of the assets framework to water, wastewater, and electric power systems and how the organizational actions framework supports the development of functional recovery for these systems. The systems were not originally designed and built for resilience or functional recovery. It is difficult to prevent damage and potential service outages after earthquakes, but the loss and recovery of services can be managed to meet societal needs. The managing of lifeline infrastructure system service losses and recoveries requires (1) the establishing of practical objectives to ensure social needs can be met in a post-earthquake environment, and (2) efficient design and operation of the systems to allow basic service recovery times to meet societal needs. A lifeline infrastructure system is considered functionally recovered when all users have their basic services restored. The recovery objectives must first be defined in terms of when the basic services are needed by customers having different levels of importance to communities during a disaster. The recovery objectives are then used as input to an assets framework and an organizational actions framework. Both the assets and organizational actions frameworks target restoring the lifeline infrastructure system services being restored in a post-earthquake timeframe meeting the defined recovery-based objectives.

Lifeline systems provide services through the built infrastructure operated with human interaction. The assets and organizational actions frameworks are iterative and interactive. The water, wastewater, and electric power system examples provide the following outputs:

- Component- and system-level designs enhancing ability to functionally recover
- Target post-earthquake restoration objectives established consistent with asset designs and organizational policies, plans, and strategies
- Identifying potential measures to mitigate asset and organizational deficiencies to improve functional recovery
- Information for improving the system planning process and useful for decision makers to prioritize funding for mitigation measures

KEYWORDS

Functional recovery; water system; wastewater system; electric power system; infrastructure; interdependencies; lifelines; basic services; recovery objectives; restoration time; seismic design.

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1. INTRODUCTION

This report serves as a companion volume to NIST SP 1310 [NIST, 2024] that presents a framework to guide the reader through steps to achieve system level functional recovery of lifeline infrastructure systems exposed to earthquake hazards. The proposed framework presented in Volume 1, published as NIST SP 1310, comprises two constituent parts, one framework for assets and one for organizational actions. This report presents examples for applying the assets framework described in Volume 1 Ch. 4 to water, wastewater, and electric power systems and how the organizational actions framework described in Volume 1 Ch. 5 supports the development of functional recovery for the three infrastructure systems.

1.1. Purpose and Scope

The purpose of this volume is to show how the framework described in Volume 1 can be used practically for three interdependent lifeline infrastructure systems and consistent with NIST-FEMA [2021]. The framework is flexible and scalable, and the examples are developed using hypothetical systems to show how the framework can be used for different infrastructure having a range of diverse characteristics.

The example systems provide services to Centerville [Ellingwood et al., 2016], a testbed community developed by the Center for Risk-Based Community Resilience Planning, a NIST-funded Center of Excellence, documented by van de Lindt et al. [2015]. Centerville is a hypothetical city intended to represent a typical mid-sized urban population in the United States but does not represent any specific location or community. The water, wastewater, and electric power systems are also hypothetical. They reflect typical infrastructure operated in the United States but do not represent any specific system. Centerville does not have a community resilience plan that the lifeline infrastructure system operators can utilize to identify resilience goals. As a result, the water, wastewater, and electric power system operators must develop their own post-earthquake service recovery goals to use as input to utilize the framework.

The example lifeline infrastructure systems focus on the specialized interlinking components making up the systems. Although the systems include buildings among their assets, the examples in this Volume 2 do not address the specifics of building functional recovery. Buildings can be addressed using Cook et al. [2022] or other methodologies, and the criteria for their roles in the infrastructure systems are identified in Volume 1 Ch. 4 that describes the assets framework.

Volume 1 Ch. 3 notes how the assets framework can be used for the design of an individual component, then assess the overall system performance, or to layout and/or assess the entire infrastructure system and how it may perform during earthquakes to identify any components in need of improvement. Both processes reach the same end goal of creating systems for functional recovery. The former is employed for the water and electrical power systems in Chapters 3 and 5, respectively. The latter is employed, in part, for the wastewater system in Ch. 4 by identifying improvements needed to vulnerable components and including these upgrades in the assessment.

All three example systems utilize a common earthquake event defined in Ch. 2. The wastewater system example in Ch. 4 provides a streamlined and limited set of impacts on the infrastructure to easily reveal how the framework steps can be applied. The water and electric power examples in Chapters 3 and 5, respectively, identify a larger and more complex set of impacts on the systems revealing the reality of how the organizational actions interact with the assets and overall system response and recovery.

The assets framework requires the component preliminary design to be checked against acceptance criteria defined within the framework. The water and electric power systems provide example component designs that meet the acceptance criteria, while the wastewater system example shows how to proceed when the design does not meet the acceptance criteria.

The water and electric power system examples identify how to incorporate recovery time objectives for systems having multiple subsystem owners and operators.

All three examples incorporate the importance of communications with other agencies and address dependencies with other system services and the importance of transportation systems to their operations. The wastewater system example identifies damages that are oriented around exposing the effects of dependencies on post-earthquake service recovery.

The water system example incorporates important aspects of organizational actions, such as needing buildings to function to allow essential groups to undertake their duties, access of staff and employees to their work locations, mutual aid and assistance, and other aspects.

The electric power example incorporates concepts on how regional systems are affected and manages the loss and recovery of services in a localized area within their larger service areas. The water and wastewater examples show how local municipal agencies and companies manage the loss and recovery of services within their networks.

1.2. Intended Audience

The primary audience for this Volume is designers and analysts for water, wastewater, and electric power infrastructure systems. Other disciplines that may benefit from these examples include designers and analysts of other lifeline infrastructure systems as well as lifeline infrastructure systems managers, resilience officers, asset managers, emergency managers, and community planners. It is anticipated that the primary intended audience of Volume 1, which is identified as owners and operators of lifeline systems, may charge designers and analysts on their staff to implement the framework steps.

1.3. Findings

Application of the proposed framework to water, wastewater, and electric power systems resulted in the following findings:

- The framework can be applied to multiple lifeline infrastructure systems.
- The framework is flexible and allows the intricacies of each lifeline infrastructure system to be incorporated.

- Organizational actions are important for preparing lifeline infrastructure systems to functionally recover.
- Dependencies and interdependencies between systems are critical aspects of service recovery.
- The framework process is set so that even when a single component is designed, it triggers a systems-level assessment. When the system level assessment is performed, it may result in the identification of other vulnerable components that need to be mitigated to meet recovery-based objectives.

1.4. Study Limitations

The examples presented are limited to water, wastewater, and electric power systems having the specific characteristics identified for the hypothetical Centerville city and the identified earthquake scenario. There are many different configurations for these types of systems and the interaction with other lifeline infrastructure systems can change the results.

The organizational actions framework was only partially implemented into these examples. The examples include dependencies and interdependencies between the water, wastewater, and electric power systems but do not undertake a full evaluation of their interactions and how the service recovery time objectives affect component or system-level results. Studies incorporating more lifeline infrastructure systems exposed to different earthquake hazards with a more comprehensive evaluation of interdependencies will be useful for improving the understanding of what steps are most important for functional recovery.

The assets framework attempts to comprehensively incorporate the numerous factors that need to be addressed for functional recovery. These numerous factors make the framework difficult to implement. The examples do not identify how the framework steps may be simplified to allow lifeline organizations to make incremental improvements toward functional recovery, but additional efforts toward this goal will be useful.

1.5. Report Organization

This is Volume 2 of two reports; Volume 1 is published as NIST SP 1310. This volume is organized as follows:

- Chapter 2 presents the hypothetical setting for Centerville and the earthquake event scenario,
- Chapter 3 presents the example water system application of the framework
- Chapter 4 presents the example wastewater system application of the framework
- Chapter 5 presents the example electric power system application of the framework
- Appendix A presents information for pipe networks to support functional recovery useful for understanding aspects of the water and wastewater systems applications of the framework

A list of references is provided at the end of the report.

The examples documented in Chapters 3 to 5 align directly with the steps described for the assets framework in Volume 1 Ch. 4 and utilize the same notation, e.g., Step A4. Selected key information, such as repair time increments, are directly referenced from Volume 1, thus it is recommended to utilize both volumes simultaneously. All references to any portion of Volume 1 from this Volume 2 will identify those portions as being from Volume 1; for example, Volume 1 Ch. 4 refers to Ch. 4 in Volume 1; whereas reference to Ch. 4 in Volume 2 will not identify this volume number.

2. EXAMPLE COMMUNITY AND LIFELINE INFRASTRUCTURE SYSTEMS

This chapter describes the hypothetical community, example water, wastewater, and electric power lifeline infrastructure systems, and the earthquake event scenario. The community, its lifeline systems, and earthquake event scenario are used in Chapters 3, 4, and 5 to show how the assets framework described in Volume 1, published as NIST SP 1310 [NIST, 2024] can be applied and supported by the organizational actions framework.

The Centerville virtual community was developed as a testbed for the NIST-funded Center of Excellence for Community Resilience [van de Lindt et al., 2015] to have the essential physical components that describe a community to examine procedures and methodologies [Ellingwood et al., 2016]. Ellingwood et al. [2016] provide the original description of Centerville, including its infrastructure systems and hazards to which it is exposed. The descriptions in this chapter deviate from some of the original descriptions to meet the purposes of the example applications of the framework.

2.1. Centerville

A schematic of Centerville is shown in Fig. 2-1. The virtual testbed community of Centerville is a typical midsize community in the United States with a population of about 50,000 people. The population of Centerville is growing at approximately 1.5 % annually. It is a typical middle-class city in most respects, with a median household income that is close to the U.S. average, although there are pockets of low-to-moderate income residents. The Centerville economy is reasonably well diversified, and consists of light manufacturing and industrial facilities, commercial/retail, finance and professional services, health care, education, public services, and tourism. The climate conditions at Centerville are moderate and generally free from extreme heat or cold or precipitation. The community is moderately socially active. Most businesses and people engage with the community in different forms through sports, social clubs, religious centers, and volunteering.

Centerville has common utility and mobility lifeline infrastructure systems including potable water, wastewater, stormwater drainage, electric power, natural gas, liquid fuels, solid waste, and transportation systems. The water, wastewater, and electric power systems are described in detail in Sec. 2.4.

The major community transportation features are shown in Figures 2-1 and 2-2 and include:

- Arterial streets
- A railway line that follows the east side of the river
- Interstate Highway I-99 that is oriented north-south near the west side of the city
- State Highways that are located along the south perimeter of Centerville (HW0) and southwest of Centerville (HW1)

The Centerville Department of Transportation manages the local transportation network and coordinates closely with the County Transportation Department that owns and operates HW0 and HW1 and the State Transportation Department that owns and operates I-99. All three transportation departments have their headquarters collocated in a common building. Each department has an operation and maintenance yard; all three yards are collocated near the headquarters building south of the I-99 and HW0 intersection as shown in Fig. 2-1.

The Centerville building portfolio contains about 30,000 buildings that are assigned residential, commercial, and industrial occupancy, as well as critical facilities such as fire stations, hospitals, schools, and government offices. These are distributed in seven residential zones designated Z1 to Z7, two commercial zones designated Z8 and Z9, and two industrial zones (one light and one heavy industry) designated Z10 and Z11. All sectors are essential to the health and welfare of the community and play a significant role in overall resilience, regardless of the community size or its location.

There are 19,684 households in seven residential neighborhoods designated as either low-density (LD) or high-density (HD), high-income (HI), middle-income (MI), or low-income (LI). A high-income/low-density (HI/LD) development abuts the western hills, and a mixture of middle-income (MI) and low-income (LI) residential areas around and east of Interstate Highway I-99. There is a mobile home park (zone Z7) in the north part of town adjacent to the light industrial zone Z10 and the flood plain. Half of the households are owner occupied and half are renter occupied.

Local government facilities are in the older center of town, near the river. This includes City Hall. The Centerville emergency operations center is housed in City Hall. The stream which bifurcates from the river passes through the area where the government facilities exist, making the community center residing on a portion of the island made by the river flow path.

The Centerville economy is reasonably diversified and consists of light manufacturing and industrial facilities, commercial/retail, finance and professional services, health care, education, public services, and tourism. Centerville has two commercial/retail districts, one of which is along I-99 and the second is along Main Street. There are two large stores near the intersection of I-99 and HW0 in a newly developed area in the southern part of the city. There are two relatively large industrial facilities, each of which employs upward of 250 to 300 people. The first is a manufacturing plant for a national marketer of light-frame steel storage buildings commonly used for industrial and agricultural storage, airports, and other repair facilities. The second is a storage and trans-shipment facility for an international shipping company. There are several other smaller industrial facilities. Many of these are located along the Rock River or the railroad. One industrial facility located in the southeast corner of the heavy industry zone Z11 uses and stores highly explosive materials.

The hospital is a relatively large facility, which serves Centerville and the surrounding county and employs approximately 475 professional and support staff. There are four public elementary schools, two middle schools, and one high school. There are no higher education facilities in Centerville, although one of the State universities is located approximately 80.5 km (50 miles) away.

The open areas on the island made by the river flow and north of the Community Center zone, west of the high school, are developed as recreational park land. West of the high school is a large recreational facility which is also prepared to serve as an emergency shelter for the community. The high school and middle school gyms are also designated to serve as emergency shelters when needed.

Centerville has two fire stations, one on each side of the river. East of the river the fire station is located near the light industry, on the east side of the railroad tracks, between the mobile home park and the low-income/high-density residential zone. West of the river the fire station is located on the west side of the medium-income/high-density residential zone.

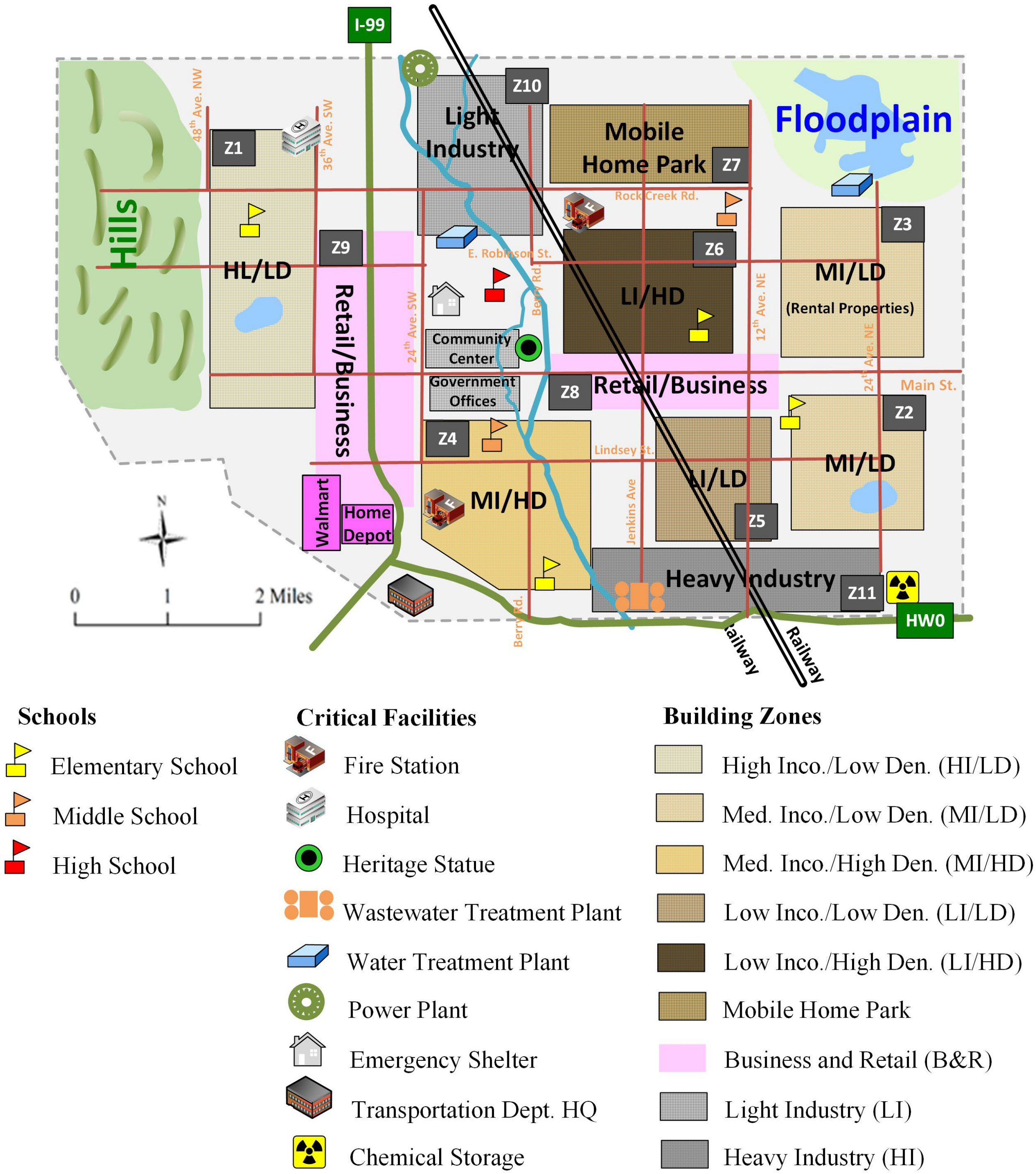

Fig. 2-1. Plan of Centerville (modified from Ellingwood et al. [2016]). Residential zones are labeled Z1 through Z7, and business and industry zones are labeled Z8 through Z11.

The city is approximately rectangular in shape, 13 km by 8 km (8 miles by 5 miles) in dimension. The western side of the city is hilly. The Rock River flows from north to south through the center portion of the city. In the middle of town, the river bifurcates with a smaller stream to the west, then converges back to the river a little further south, creating a small island where the Heritage Statue is located. A lake exists northeast of the city, within a floodplain area.

The geology around Centerville consists of rock making up the hills to the west and sedimentary soils from the bottom of the hills to the east. The sediments are mostly sandy-type soils. The soil is made of very young deposits along the river with some silty particles. In the floodplain the surface soils are also very young and mainly sandy particles with interlayers of silts and clays. The higher elevations between the river and the floodplain consist mainly of older soil deposits, except for some local areas around the small lakes and ponds. The groundwater depths range from zero to about 1.82 m (6 feet) below the ground surface; it is very shallow along the river, around the smaller lakes and ponds, and in the floodplain. The groundwater increases in depth below ground surface in the older sediments between the river and floodplain. The hills on the west side of Centerville have mostly stable and relatively steep slopes. There are a few locations of landslides. The young soil sediments have the potential to liquefy when subjected to earthquake shaking. An earthquake fault exists to the west of Centerville.

2.2. Regional Context

As shown in Fig. 2-2, Centerville is at the center of a set of cities and small towns within a larger region. Other communities located about 80.5 km (50 miles) from Centerville are Northville, Southville, Eastville, and Westville. Centerville is larger than the other communities and serves as a hub for many amenities like healthcare, shopping, and manufacturing. Northville is the second largest community, about half the size of Centerville, and hosts the State universities. The other towns are much smaller than Centerville and mostly serve as community sites for local agriculture and light manufacturing. Centerville is connected to Northville via Highway I-99 and to Eastville via Highway HW0. Westville and Southville are connected via Highway HW1, which intersects with I-99 to connect with Centerville. The railroad mainly runs north-south but cuts through Centerville diagonally parallel to Rock River. An earthquake fault and wider seismogenic zone are located west of Centerville, which traces the ground surface in a roughly north-south direction.

Seismic activity in the region has been documented since initial human habitation in the region. Earthquakes large and small occur as periodic reminders. Geologic investigations identify the earthquake fault as having the potential to create about a magnitude M_w 7.8 earthquake with a recurrence interval of around 500 years. The geologic evidence identifies the last known M_w7.8 earthquake to have occurred about 300 years ago. Buildings are designed and constructed to meet code requirements at the time they are built. However, few buildings meet current code requirements due to the age of the building inventory described in Sec. 2.3. Components of the lifeline infrastructure systems are designed and constructed to meet codes and common seismic standards. Few designs incorporate more than standard ground motion parameters (e.g., peak or spectral accelerations). Buried pipelines and conduits, retaining structures, and many types of equipment are not commonly evaluated for seismic effects.

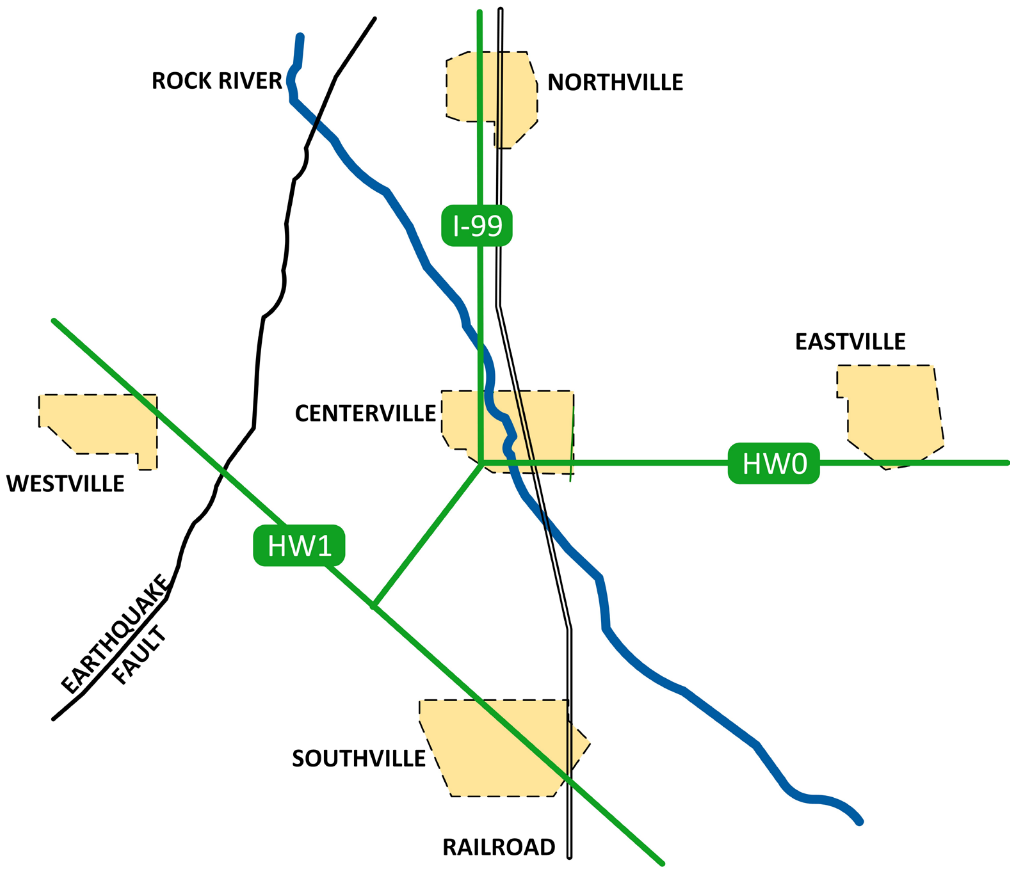

Fig. 2-2. Regional map.

2.3. Centerville Building Inventory

The building inventory in Centerville is summarized in Ellingwood et al. [2016] and Lin and Wang [2016] and covers a wide array of construction. Table 2-1 summarizes the building inventory by occupancy, showing a total of 15,283 buildings. Although the older section of town adjacent to the river dates to early in the twentieth century, most of the current construction dates from the post-WWII era or later, and a significant amount of retail and residential development has occurred around the perimeter of Centerville since 1980. There was a large construction push in the decade following WWII, especially in single-family residences. The majority of buildings are three stories or less; in the retail and industrial sectors, these include steel braced frames, ordinary reinforced concrete frames and reinforced masonry bearing wall buildings. The older section of town around the river contains a significant stock of one- and two-story unreinforced masonry buildings, many of which have been converted to residential lofts during the past 20 years as people have begun to migrate back to the center of the city.

Table 2-1. Building Occupancy and Number of Units [Ellingwood et al., 2016]

Occupancy Type	Number of Units
Single-family with 1 dwelling unit per structure	13,436
Multi-family with 48 dwelling units per structure 102	102
Total residential	13,538
Commercial/retail/government	800
Retail establishments	250
Professional/personal/financial services	450
Entertainment	100
Industrial	125
Special/miscellaneous	10
Grade schools	4
Middle schools	2
High school	1
Regional hospital	1
Fire stations	2

2.4. Centerville Lifeline Infrastructure Systems

2.4.1. Water System

Fig. 2-3 shows the Centerville potable water system. Guidotti et al. [2016] describe the Centerville potable water system. This example provides a more detailed description with some modifications to Guidotti et al. [2016]. The water system is made up of supply, treatment, transmission, and distribution subsystems.

Centerville's major source of water is the Rock River. Water is pumped from Rock River near the north end of the city, where it is treated and stored for transmission and distribution to customers. The Rock River pumping station and treatment plant have the capacity to supply the entire city and can be expanded to meet future city demand. It treats 50 million gallons on average each day. A well field located north-east of Centerville in the floodplain provides a second source of water, but only has the capacity to meet about half of the city normal demand (e.g., 25 million gallons per day). The well field pumps groundwater into a collection line running to a treatment plant. Both treatment plants have large finished water reservoirs.

Water is pumped from the finished water reservoirs into trunk lines which transmit the treated water to two storage tanks. One storage tank is in the hills on the west side of the city. The other is located on the southeast side of the city. The two tanks are at the same elevation and can store about the same amount of water. The tank in the southeast is elevated. The treatment system includes chlorination stations near the outlets of the two tanks to keep the water disinfected. From the storage tanks, water is transmitted in trunk lines to distribution areas. Figure 2-3 shows the trunk lines but not the distribution mains. Water from the well-field finish water reservoir may also be pumped directly to distribution areas through the transmission system. A booster pumping station is located on Main Street, west of Rock River, in the retail/business district to lift water coming from the east side to the storage tank in the hills. There is a direct connection from a trunk line to the power generating station located on the north end of the city. The distribution areas correlate with the different zones Z1 to Z11 shown in Fig. 2-1. Water distribution mostly operates as a single pressure zone, with the water head regulated by the two storage tanks.

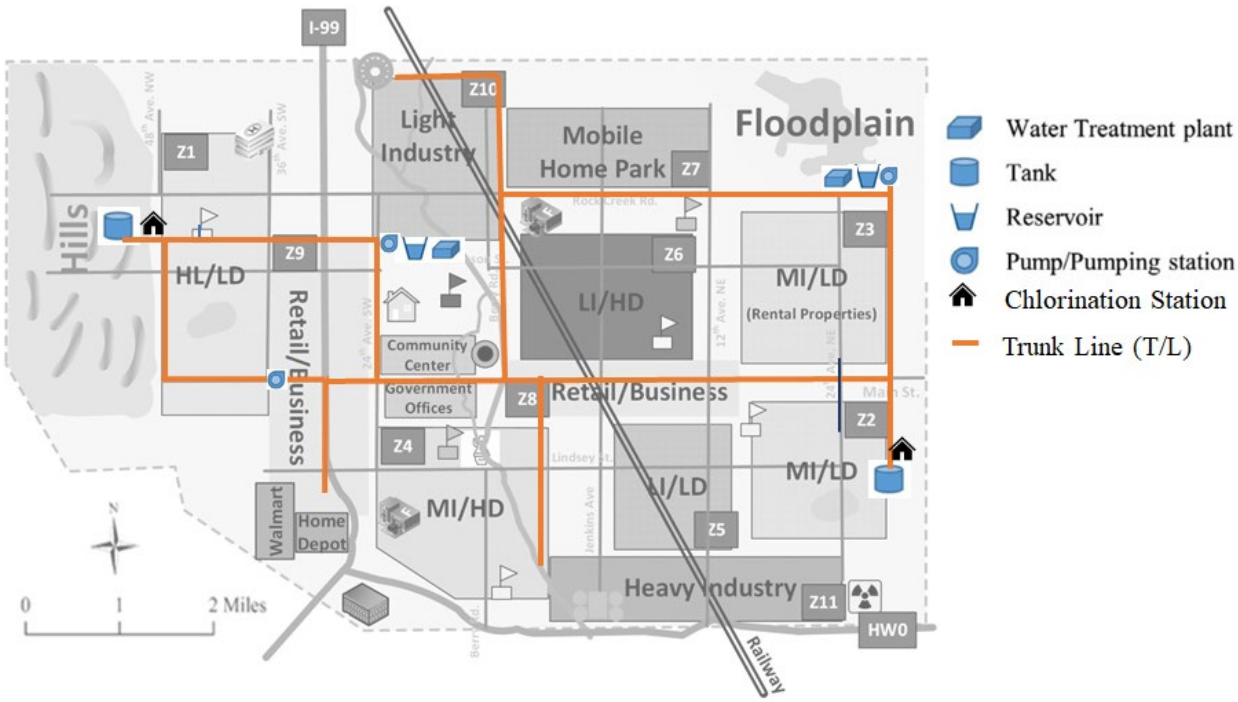

Fig. 2-3. Centerville potable water system (gray shaded base map modified from Ellingwood et al. [2016]).

There are approximately 56.3 km (35 miles) of buried transmission pipelines and 418.4 km (260 miles) of buried distribution pipe making up the potable water system. The transmission pipe is made up of welded steel, ductile iron, and older cast iron pipelines ranging from 60.96 cm to 91.44 cm (24 in to 36 in) in diameter. The distribution pipe is made up mostly of cast iron and ductile iron, ranging from 10.16 cm to 30.48 cm (4 in to 12 in) in diameter, connected using unrestrained bell and spigot rubber gasket joints. The transmission and distribution pipelines are buried under the streets. The distribution pipe grid resembles the surface street grid in each of the zones Z1 to Z11. The transmission pipelines are equipped with a few valves allowing portions to be isolated for normal operational changes. The distribution network has many valves placed at connections to the trunk lines and throughout the grid. Fire hydrants are connected to the distribution pipelines and located about every 91.4 m to 152.4 m (300 ft to 500 ft). Every service connection is made with a service lateral from the water main in the street to a water meter at the property line. The customer is responsible for piping and connections beyond the meter.

The Centerville Water Department (CWD) is part of the Centerville Public Works Department and owns and operates the potable water treatment, transmission, and distribution system. A privately owned company called the Centerville Water Supply Company (CWSC) holds all the water rights in the area. The CWSC owns and operates the Rock River pumping station and pipeline, and the floodplain groundwater wells and collection line; they also own the pipeline running to the treatment plants. They have supply meters located at the entrance to the treatment plants. The CWSC owns and operates all infrastructure from the sources up to and including the supply meters. The CWD owns all infrastructure downstream of the supply meter to the meters connecting to customer service connections. The CWD purchases the water from the CWSC.

The CWD has its headquarters in the government buildings within the older part of the city. The CWD has two operation and maintenance (O&M) yards collocated with the water treatment plants. The Rock River O&M yard is relatively small. Most of the field personnel, equipment, and supplies are operated out of the well field treatment plant O&M yard. The CWD has its own emergency operations center located in its headquarters and it also positions staff in the City's emergency operation center in City Hall.

2.4.2. Wastewater System

Figure 2-4 shows the Centerville wastewater system. Ellingwood et al. [2016] did not describe a wastewater system when introducing Centerville. In this work, one is developed to be applied in the Ch. 4 example. The wastewater system consists of collection, conveyance, treatment, and disposal subsystems. It operates separately from the stormwater collection system, however, infiltration of groundwater through holes, cracks, joint failures, and faulty connections, plus the inflow of stormwater via roof drains, and foundation drains are part of the collection capacity.

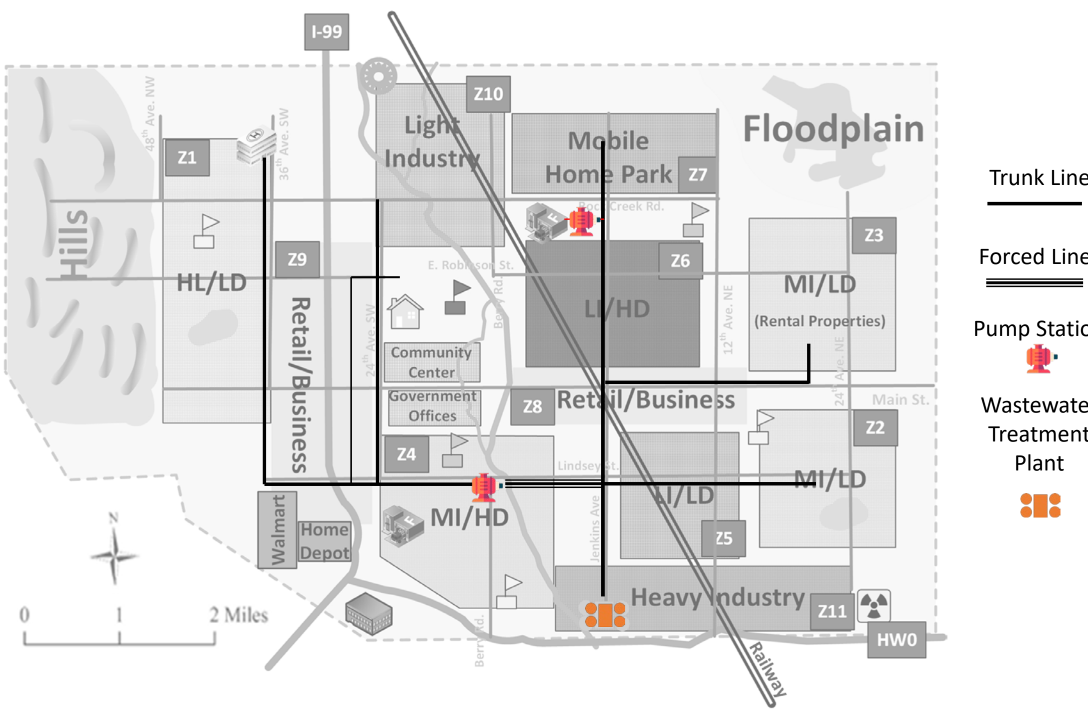

Fig. 2-4. Centerville wastewater system (gray shaded base map modified from Ellingwood et al. [2016]).

The collection system consists of approximately 418.4 km (260 miles) of buried property service connections (PSCs), lateral, and main sewers; there are approximately 56.3 km (35 miles) of buried trunk lines. The lateral and main sewer lines are made of PVC pipelines ranging from 15.24 cm to 30.48 cm (6 in to 12 in) in diameter. The trunk lines are made of concrete, ranging from 45.72 cm to 81.28 cm (18 in to 32 in) in diameter. The PSC, lateral, and main sewer lines follow the surface street grid in each of the zones Z1 to Z11; they are buried at least 3.05 m (10 ft) horizontally and 1.53 m (5 ft) vertically below the water mains. Manholes are positioned at sewer sanitary junctions and where the variation of the sewer pipe size is required. Isolation valves, check valves, and force main valves are used in pump stations and throughout the collection system.

The Centerville Department of Sanitation (CDS) is part of the Centerville Public Works Department and owns and operates the wastewater system. The CDS headquarters is in the same government building as the water department. The CDS has an operation and maintenance yard collocated with the wastewater treatment plant in the south of Centerville. The CDS has its own emergency operations center located in its headquarters and it also positions staff in the City's emergency operation center in City Hall.

As illustrated in Fig. 2-4, wastewater is conveyed to the treatment plant in the south of Centerville. This facility treats an average daily wastewater flow of 50 million gallons per day, serving over 50,000 residents of Centerville. The treated wastewater is discharged into the river.

Given the topology of Centerville, the entire collection network consists of gravity sewers, except the trunk line running between zones Z4 to Z5. The collection networks in Z1, Z4, Z9, and Z10 have the capacity to service the population in these zones. The pumping station and the pressurized trunk from zones Z4 to Z5 have the capacity to handle the throughput from zones Z1, Z4, Z9, and Z10. The entire water treatment system can provide for Centerville and can be expanded to meet future city demand.

The proper working of several wastewater system components, and consequently the wastewater system itself, depends on services from other lifelines. Specifically, the pumping station in zone Z4 depends on the electric power system. The wastewater treatment plant depends on several services, including electric power, transportation (the off-ramps from HW0, the overpass on the railroad), and delivery of chemicals (depending on the manufacturing factories and facilities). The working of the entire wastewater system depends on the water system.

2.4.3. Electric Power System

Figure 2-5 shows the electric power system in Centerville used as an example to demonstrate the proposed framework. Guidotti et al. [2016] originally described the Centerville electric power system. This example provides a more detailed description with some modifications to Guidotti et al. [2016]. The electric power system consists of generation, transmission, and distribution subsystems. For simplicity, low voltage circuits and drops to users are not represented in Fig. 2-5. The electric power network serving Centerville is connected to a regional transmission grid shown in Fig. 2-6.

Figure 2-5 shows the main components in Centerville include a power plant, two passing transmission lines, and the distribution grid. The two transmission lines connect Centerville to other towns and cities served by the same regional power grid, including the four towns surrounding Centerville shown in Figures 2-2 and 2-6. Thus, loads in Centerville can be powered from the local power plant or through transmission lines from power plants located at long distances away. The distribution grid follows a radial architecture. Transmission line TL1 serves three distribution substations D1, D2, and D3 from a main substation M. D1 and D2 are also served through a sub-transmission substation SS. TL1, D1, D2, D3, M, and SS are shown in Figure 2-5. Most of the power infrastructure in Centerville and its neighboring region is overhead, which is less vulnerable to the damaging effects of earthquakes compared to underground cables and other equipment. Still, there are two underground distribution lines, UDL1 and UDL2 shown in Fig. 2-5, that are used to power loads from D3 and D1, respectively. The distribution line UDL1 uses the bridge along Main St. to cross the river passing through Centerville and power the government building and community center at the center of the town. The other underground line UDL2 powers the heavy industry zone south of Centerville where some industries handle toxic materials.

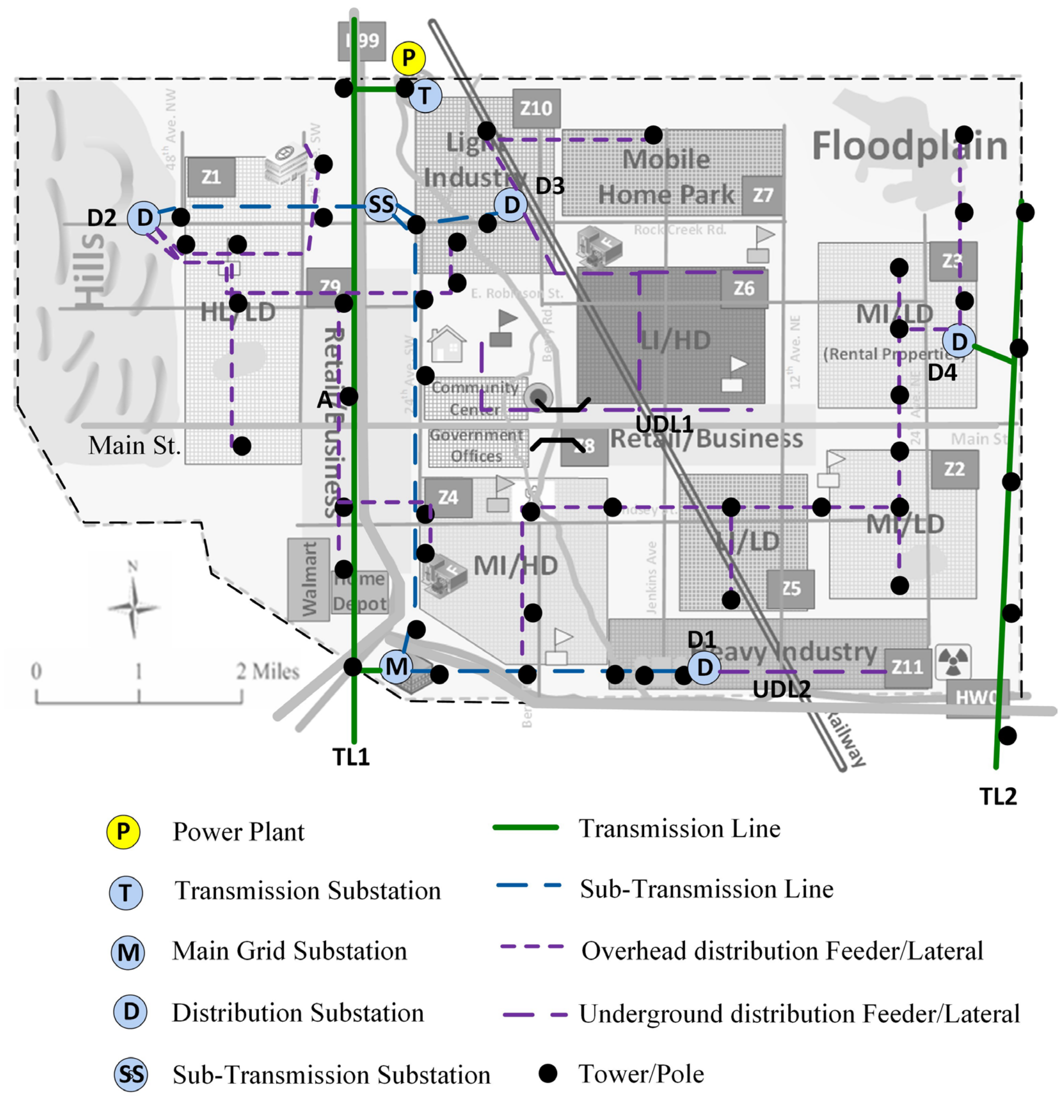

Fig. 2-5. Centerville electric power system (gray shaded base map modified from Ellingwood et al. [2016]).

Energy use statistics in the United States from 2022 indicate that 332 million people in the U.S. consumed 4 trillion kWh of electricity, thus it is reasonable to assume an average power consumption per capita in Centerville is about 70 MW. However, peak power consumption could be estimated as approximately 50 % higher than this value or about 100 MW. The power plant in Centerville is assumed to be a natural gas station with a total capacity of 200 MW. In addition to natural gas for fueling its turbines, this power plant requires limited amounts of water for cooling. The relative relevance of power plants needs to be examined also at a system-wide level. Although in this example, the capacity of the power plant in Centerville is relatively low and, thus, its loss is unlikely to cause system-wide effects, in a more general case, although the loss of service of a large power plant may still not necessarily lead to system-wide outages, it may more likely affect service in areas away from where the large power plant is located. In this Centerville example, the immediate neighboring region has another power plant, seen to the southwest in Fig. 2-6. This power plant is assumed to be a 500 MW coal-fired power plant. Centerville can also receive electric power from two 69 kV transmission lines, one running parallel to I-99 and the other one running in the north-south direction on the eastern side of the town. These lines are assumed to be relatively short with a power capacity of about 90 MW each. Other transmission lines in the region around Centerville are shown in Fig. 2-6. For simplicity in the figures, the private communication network used to connect all necessary electric grid sites and components are not shown in Figures 2-5 and 2-6.

There is only one electric power utility that distributes power in Centerville, and it is owned by the city and operated by the Centerville Electric Power Department (CEPD). The CEPD also owns and operates the 200 MW natural gas generating plant located in Centerville and has its headquarters located in the government buildings within the older part of the city near the building housing the CWD and CDS. It has an operation and maintenance yard collocated with the electric power generation plant. The electric power company has its own emergency operations center located in its headquarters and it also positions staff in the City's emergency operation center in City Hall.

The 500 MW coal-fired power plant is owned and operated by a privately owned company named the Regional Power Generation Corporation (RPGC). The RPGC owns and operates many different electric power generation plants in the region. The transmission lines in the region are owned by a conglomerate named the Power Transmission Agency (PTA). Power generation is managed and coordinated through a regional power dispatch. Power transmission is managed and coordinated through a regional systems operator. The regional power generation dispatch center and regional systems operation facility are collocated at the headquarters of the CEPD, which are situated at the community center facility in the middle of Centerville.

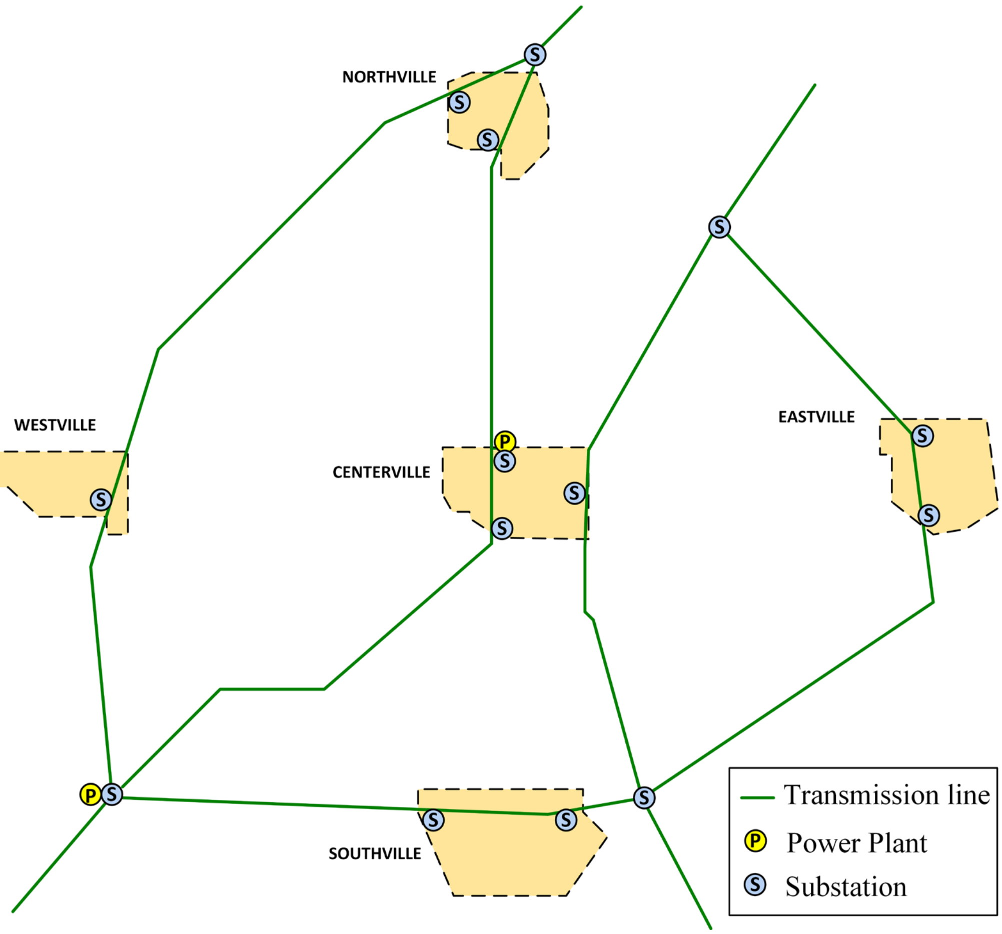

Fig. 2-6. Electric power transmission grid in the region around Centerville.

2.5. Critical Users in Centerville

To apply the assets framework, each component within the lifeline infrastructure systems is assigned a criticality category. The criticality category is a function of the type of customer and user the component helps to provide services to and the level of component redundancy. Table 2-2 defines the Critical User type category levels for Centerville using the definitions given in Volume 1 Sec. 4.4 and the guidance provided by FEMA P-2234 [FEMA, 2024]. These user definitions are applied to the water, wastewater, and electric power system examples respectively in Chapters 3, 4, and 5. It is noted that Ch. 3 provides an example of a water treatment plant that is not a Criticality Customer A, using the equivalency defined in Volume 1 Sec. 4.4.

Other types of customers that are not specifically addressed in this example include hotels, restaurants, grocery stores, nursing homes, medical clinics, gas/fueling stations, telecommunications central offices and others described in FEMA P-2234.

Table 2-2. List of Centerville User Types and Critical Customer/User Category Assignments

User Type	Critical Customer / User Category (A, B, C)
Hospital	A
Emergency operations facilities (located in City Hall)	A
Emergency shelters (recreational facility, high school and middle school gymnasiums)	A
First responders (police/fire stations)	A
Jail (in government center)	A
Elementary schools	B
Home Depot	B
Walmart	B
Storage building manufacturer[a]	B
International shipping company[a]	B
Industrial/manufacturing facility (toxic/explosive, southeast corner of Z11)	A
All other industrial/manufacturing facilities (non-toxic or non-explosive)	C
Single-family residential zone	B
Multi-family residential zone	B
Electric power generation[b]	A
Electric power converter, switching, … sites/facilities[b]	A
Water/wastewater treatment, pump, … facilities[b]	A

[a] Not specifically evaluated in the water, wastewater, and electric power system examples.

[b] Unless defined otherwise by the infrastructure owner/operator. For example, a lifeline infrastructure system may define a critical component to a lower level as explained in Volume 1 Sections 4.4 and 4.5.

2.6. Earthquake Hazards in Centerville

Centerville is near a large fault capable of generating earthquakes up to about magnitude 7.8. The fault is part of a larger seismogenic zone which creates a band of about 24.1 km (15 miles) on each side of the fault trace. This zone poses the greatest earthquake source threat to Centerville. Expected earthquakes of any magnitude up to 7.8 may have a hypocenter somewhere within this seismogenic zone.

Within Centerville other transient and permanent ground deformation earthquake-related hazards exist. Transient ground shaking is expressed in terms of peak ground acceleration (PGA) and peak ground velocity (PGV). Permanent ground deformations include the potential for liquefaction, landslides, and differential settlement. The entire Centerville area is exposed to potential transient ground shaking. Only portions of Centerville are exposed to the potential for permanent ground deformation. The hills on the west side may experience seismic-induced landslides. The saturated sandy soils along Rock River, in the flood plain, and around the smaller lakes and ponds may experience liquefaction; these areas have respectively very high, high, and moderate susceptibility to liquefaction triggering. These areas are also prone to liquefaction-induced lateral spreading, which results in the ground moving horizontally and differentially settling. Liquefaction may also result in differential vertical movement without any lateral spreading. There may be other types of permanent ground movements, but these will not be addressed in this example. There is no expected potential exposure to surface fault rupture within Centerville, but this type of permanent ground deformation is expected to occur within the seismiogenic zone when there is an earthquake.

Volume 1 Sec. 4.4 describing Step A2 in the assets framework identifies the component earthquake hazard design basis. Table 2-3 summarizes the hypothetical scenario hazard intensity values for each of the component Criticality Categories and earthquake hazards that exist in Centerville. The values in Table 2-3 are site-specific and identified for the hypothetical example applied to Centerville; they do not apply to any other location. The range in PGA and PGV identifies the low and high values across the city. The formations making the hillside are relatively consistent so each site can utilize the same potential landslide displacements. The potential for lateral spreading displacements is relatively consistent along Rock River and as a result each site location along the river can use the displacements identified in Table 2-3 for each return period; similarly for the potential lateral spreading displacements in the floodplain and around each lake/pond location. The lateral spread values in Table 2-3 are peak values occurring near the sloping face along the waterfront. The permanent ground displacements from the lateral spread dissipate linearly with distance from the peak to zero over a 152.4 m (500 foot) length.

Table 2-3. Intensity Measures for each Earthquake Hazard[a] in Centerville for each Criticality Category, based on Volume 1 Table 4-2

Criticality Category	Hazard Return Period *T* (years)	PGA (g)	PGV (cm/s)	Landslide Displacement cm (in)	Lateral Spread Displacement cm (in)		
					Rock River	**Floodplain**	**Lake/Pond**
I	72	0.1 to 0.2	12.7 to 17.8	0	0	0	0
II	475	0.3 to 0.4	50.8 to 63.5	10.16 (4)	15.24 (6)	10.16 (4)	5.08 (2)
III	975	0.5 to 0.6	114.3 to 127	20.32 (8)	60.96 (24)	25.4 (10)	10.16 (4)
IV	2,475	0.8 to 0.9	203.2 to 254	30.48 (12)	91.44 (36)	45.72 (18)	22.86 (9)

[a] Minimum values dictated by existing codes and regulations must be met. For example, if the building code requires a different design ground motion, then the building code values are to be used.

2.7. Earthquake Scenario

2.7.1. Earthquake Event Scenario

The example scenario has an earthquake event of magnitude 6.5 with an epicenter approximately 25 km southwest of Centerville. This event has an estimated recurrence of about 400 years and therefore is very close to and represents a Level II earthquake event scenario as identified in Volume 1 Table 2-3 (see footnote for Volume 1 Table 2-3). As documented by Guidotti et al. [2016], the PGV in Centerville ranges from about 16 to 20 cm/s and the PGA ranges from about 0.25 g to 0.3 g.

The shaking triggers liquefaction along the riverbanks, in the floodplain, and around the smaller lakes and ponds. Lateral spreading occurs along the riverbanks moving toward the river centers with peak displacements of 0.30 m to 1.52 m (1 ft to 5 ft) on each side. This raises the river bottom by about 0.61 m (2 ft) from compression bulging. Ground cracking and differential settlement of a few cm to over 30 cm occurs on the east and west side of the river. The area is covered with sand ejected from the ground. The horizontal movement extends distances of around 100 m from the riverbank. The permanent ground displacements from the lateral spread commonly dissipate linearly with distance from the peak to zero over a 152 m (500 ft) length. The island in the river severely liquefies and spreads into both sides of the river; the island elevation lowers by about a meter. Lateral spreading occurs in the floodplain resulting in over 30 cm of horizontal movement and several cm of differential settlement across ground cracks. There are numerous sand boils resulting from water and subsurface materials being ejected from the ground. Lateral spreading occurs in limited amounts around the ponds and lakes in the city with a few sand boils.

The shaking triggers a few landslides in the hills. Rockfalls deposit boulders near the foot of the slopes. Some mass block slide movements displace the slopes leaving head scarps of several feet and compression bulges along the toe of the slope.

The shaking and permanent ground deformations identified for the scenario earthquake event use mean values. Thus, the parameters defining the scenario are very plausible and do not represent unlikely or extreme values.

2.7.2. Effects of Earthquake Hazards

The earthquake event and resulting cascading hazards have a significant effect on the built environment. Ground shaking results in damage to the building and bridge inventory. Some of the older government buildings experience significant structural, non-structural, and content losses. This includes the CWD, CDS, and CEPD headquarter buildings. The commercial/retail and industrial zones have the heaviest losses in terms of dollars, while multifamily and high-income residential zones have the highest direct loss relative to their appraised values [Lin and Wang, 2016]. The mobile home park has the most significant impact relative to the other zones, just from shaking impacts. This is compounded by damage to natural gas connections being broken and igniting fires that burn many of the mobile homes. The impacts result in many businesses being unable to function and many residents being displaced from their homes. The residential damage and social displacements impact employees of the lifeline infrastructure systems.

Liquefaction and lateral spreading along the river results in some severe impacts to government buildings within about 60.96 m (200 feet) of the river and also many buildings near the river in the light industry zone Z10, the western portion of heavy industrial zone Z11 and the east side of the high-density residential zone Z4. School buildings are not damaged by permanent ground deformation due to their distance from the river. Permanent ground deformation does affect the transportation system and subsequently impacts the delivery of chemicals to the water and wastewater treatment plants.

The shaking results in damage to some bridges along HW0 and at the interchange with I-99. The permanent ground deformation along the river displaces bridge abutments toward the river, severely damaging almost all the surface roadways near the river and resulting in bridges crossing the river being impassable. This cuts off important access between the east and west sides of Rock River. As a result, injured people on the east side of Rock River have difficulties accessing the hospital on the west side of Rock River. Similarly, the government center, emergency operations center, and the emergency evacuation center at the park and high school have limited to no access to the people located on the east side of the river.

Landslides in the hills block access to the roadway at the bottom of the slopes.

The shaking and permanent ground deformation damage buried pipes and conduits (further explained in Chapters 3, 4, and 5). Additionally, some natural gas pipelines were damaged and released gas into the atmosphere igniting fires. Damaged bridges crossing the river brought about damage to pipelines and electric power conduits that are attached to the bridge for crossing the river. The damaged water pipeline resulted in pressurized water ero ding soil at the abutment, further damaging the roadway and collocated buried utilities and delaying the ability to make repairs.

Liquefaction and lateral spreading along the river also damage portions of the water treatment plant. Fortunately, the liquefaction did not directly affect the wastewater treatment plant. Liquefaction and lateral spreading in the floodplain also damage the water treatment plant at that location.

Other specific damages to the water, wastewater, and electric power systems are described in Chapters 3, 4, and 5 respectively.

3. WATER SYSTEM EXAMPLE

3.1. Introduction

3.1.1. Purpose of Example

This chapter presents an application of the proposed assets framework presented in Volume 1, published as NIST SP 1310 [NIST, 2024], Ch. 4 to a fictional water system providing services to the Centerville community described in Ch. 2. The chapter also identifies how the proposed organizational actions framework presented in Volume 1 Ch. 5 supports the assets framework to achieve functional recovery.

Section 3.1 presents preliminary information and an overview of the water system. Section 3.2 establishes the basic service recovery time objectives. Sections 3.3 through 3.13 are coordinated with the steps presented in Volume 1 Ch. 4 for the assets framework to illustrate the application for each individual step. As part of this process, some portions of the steps are developed for general use to any water supply and delivery system while illustrating how the framework steps are implemented specifically for the example fictional Centerville water system.

3.1.2. Water System Overview

The purpose of a water system is to provide affordable, safe, and reliable water supply to the communities they serve. Water systems provide potable water supply for:

- Domestic, commercial, and industrial uses, including critical services, emergency operations and shelter centers, and other lifeline infrastructure systems.
- Firefighting, cleaning, flushing, cooling, irrigation, recreation, and environmental quality, and as an energy source. These uses do not require potable water, but the potable supply is commonly used for these purposes.

In general, a potable water system consists of four main water subsystems and the components presented in Table 3-1. Table 3-1 provides a relatively comprehensive list of potential components that may make up each subsystem within any water system. The following notes apply to Table 3-1:

- Pump stations and treatment systems have their own site-specific subsystems made up of mechanical, electrical, and civil engineered subsystems and components.
- Instrumentation and monitoring are integrated into all subsystems. Supervisory Control and Data Acquisition (SCADA) systems are used to monitor and operate water systems.
- Buildings and facilities, including central headquarters, operation and maintenance yards, pump station housings, treatment and disinfection system housings, and other components are also a part of the systems.

Table 3-1. Major Water Subsystems and Typical Components (Modified from NIST [2016] and Davis and O'Rourke [2011])

Subsystems	Description	Typical Facilities / Components
Raw water supply systems	Systems providing raw water for local storage or treatment including local catchment, groundwater, rivers, natural and manmade lakes and reservoirs, aqueducts.	Pump stations, wells, bar screens, intakes, pipelines, canals, reservoirs, tunnels, gates and valves, dams, levees; may also include desalination plants and wastewater treatment plants as water sources. Some systems include power plants, and other energy dissipating structures such as regulating stations or cascading channels.
Treatment systems	Systems for treating and disinfecting water to make it potable for safe use by customers.	Treatment plants, filtration systems, screens, settling basins, ultraviolet processes, chlorination stations, chloramination stations, and other chemical stations (fluoridation, hypo-chlorination, chloramine, etc.).
Transmission systems	Systems for conveying raw or treated water. Raw water transmission systems convey water from a local supply or storage source to a treatment point. Treated water transmission systems, often referred to as trunk line systems, convey water from a treatment or potable storage point to a distribution area.	Medium to large diameter pipes, tunnels, reservoirs and tanks, pumping stations, valves, regulating stations, pressure relief stations. Some systems include power plants and other energy dissipating components.
Distribution systems	Networks for distributing water to domestic, commercial, business, industrial, and other customers.	All pumping stations, regulating stations, pressure relief stations, tanks and reservoirs, valves, and piping that are not defined as part of another subsystem and form a network from connections at the transmission systems to points of service. Includes service laterals, hydrant laterals and fire hydrants, and meters.

3.1.3. Centerville Water System

Consistent with the summary description of the Centerville potable water system in Sec. 2.4.1, the Centerville water system consists of the same four main water subsystems presented in Table 3-1, but with a subset of components. Table 3-2 presents the subsystems and components making up the Centerville water system. The Centerville water system aims to represent realistic conditions but is intentionally simplified to illustrate how the proposed framework in Volume 1 may be implemented.

The raw water supply system in Centerville is operated by the Centerville Water Supply Company (CWSC), a private organization who owns the local water rights and draws the water from the river and groundwater basin. The raw water is pumped to a treatment facility where it is purchased by the municipal water agency, the Centerville Water Department (CWD). At the treatment facility, the water is purified and disinfected before it is transported in bulk through large diameter pipelines to distribution networks, then distributed to customers for use. The main features, important characteristics, and the subsystem owners and operators for the Centerville water system example are as follows.

Supply subsystem (owned by CWSC):

- Water sources are Rock River and groundwater wells in the floodplain.
- Raw water pumping is provided for each source, including a pumping station at Rock River with inlet screens, and a well field and collection line in the floodplain.
- Rock River can provide enough supply to meet all demands in the city; groundwater can meet 50 % of the city’s normal demand.

Treatment subsystem (owned by CWD):

- Treatment plants and finished water reservoirs are located at Rock River and the flood plain. Treatment plants operate by splitting the water flow in half and treating each side independently so that half the plant can operate under normal conditions while the other can undergo maintenance and backflushing the filters. Treated water is temporarily stored in finished water reservoirs.
- Chlorination stations are located at outlets to each storage tank.

Transmission subsystem (owned by CWD):

- Pumping stations are located at the finished water reservoir outlets.
- Approximately 56.3 km (35 miles) of buried transmission pipelines.
- Two storage tanks.
- Booster pump station.
- Valves in pipe network for flow control.
- Bulk service is provided to the power generation station.

Distribution subsystem (owned by CWD):

- Approximately 418.4 km (260 miles) of buried distribution pipelines.
- 11 main distribution areas in zones Z1 to Z11, plus other local service connections.
- All zones have about the same pressure; pressure is regulated by the two storage tanks.
- All fire service is provided by water mains. Hydrants are spaced at about 91.4 m to 152.4 m (300 ft to 500 ft) distances along streets.
- Valves in pipe network provide flow control.
- Service lateral and meters are provided for every customer connection.

The treatment plants, pumping stations, and chlorine stations have some of their equipment seismically anchored, but most are not anchored to the ground or structures.

Table 3-2. Centerville Water Subsystems and Components

Subsystems (Owner / Operator)	Description	Typical Facilities / Components
Raw water supply systems (CWSC)	Systems providing raw water for local treatment from the Rock River and groundwater from the floodplain.	Rock River: Pump station (3 electric pumps, 1 diesel powered emergency back-up at 50 % capacity), bar screens, inlet channel, stilling basin and sump, outlet line, flow meter. Floodplain: wells, collector line, flow meter.
Treatment systems (CWD)	Treatment plants at Rock River and the floodplain. Chlorination stations for disinfection at two tank outlet lines.	Two of each: treatment plants, filtration systems, screens, settling basins, chlorination stations.
Transmission systems (CWD)	Trunk line systems conveying bulk treated water from the finished water reservoirs located at the treatment plants to distribution zones.	Two finished water reservoirs, 56.3 km (35 miles) of 60.96 cm to 91.44 cm (24 in to 36 in) diameter pipes (welded steel, ductile iron, and older cast iron), two steel storage tanks: one on-ground and one elevated, two pumping stations at the finished water reservoirs, one booster pumping station, valves, pressure relief station near Rock River.
Distribution systems (CWD)	Networks for distributing water to domestic, commercial, business, industrial, and other customers in Centerville.	Pipes, valves, service laterals, hydrant laterals and fire hydrants, and meters forming a network from connections at the transmission systems to points of service. The pipes include 418.4 km (260 miles) of cast iron and ductile iron, ranging from 10.16 cm to 30.49 cm (4 in to 12 in) in diameter.

3.1.4. Water System Basic Service Categories

Table 3-3 describes four Basic Service Categories (BSCs) identified for domestic water systems. The system or portion of system meeting the service description in Table 3-3 for each category is considered to have the BSCs provided to the customer after an earthquake. Water systems normally provide many additional levels of service (e.g., IPWEA, 2015; LGAM, 2019) on a daily basis, in addition to those presented in Table 3-3. If services are lost due to damage caused by an earthquake, the primary objective is to restore the BSCs given in Table 3-3.

Identification of BSCs for water systems considers how an earthquake may cause sufficient damage to the network which may result in complete loss of water delivery to some or all customers. For water delivered through the infrastructure networks, water delivery is the first step in service restoration to the customer’s service connection and is a prerequisite for meeting the quality, quantity, and fire protection services. The quality, quantity, and fire protection service restorations may be accomplished in any order and possibly along with water delivery restoration but cannot be restored in advance of water delivery. Water quality, quantity, and fire protection services may be lost even if water delivery services are maintained.

Table 3-3. Water System Basic Service Categories [Davis, 2014a, 2014b; NIST, 2016]

Basic Service Category	Description of Service
Delivery	The system can distribute water to customer service connections, but water delivered may not be continuous or meet quality standards (requires water advisory/purification notice), pre-event volumes (requires water rationing), fire flow requirements (impacting firefighting capabilities), or pre-event functionality (inhibiting system performance reliability).
Quality	The water quality at service connections meets pre-event standards. Potable water meets health standards (water use/purification notices removed), including minimum pressure requirements to ensure contaminants do not enter the system.
Quantity	Water flow to customer service connections meets pre-event volumes (water rationing removed).
Fire Protection	The system can provide pressure and flow of a suitable magnitude and duration to fight fires.

The quality basic service is achieved when the minimum potable requirements are met, even if prior to an event the minimum requirements were exceeded. The goal for meeting the quality BSC definition can simply be to report when pre-event minimum conditions are re-established. This will allow users to know when the product is safe to use for their purposes. This should be pronounced by the water distributor in agreement with public health officials.

Quantity is limited by the capacity of the water system. Capacity is designed to meet the domestic, commercial, industrial, agricultural, and firefighting demands. Capacity and hydraulic grade are considered simultaneously. In terms of BSCs, the system may be able to deliver water but not meet its design capacity, user demands, or pre-event amounts. Once the system is restored sufficiently to meet its pre-event amounts for a customer, it then meets the water quantity basic service. The goal is to restore flow (instantaneous and long-term) meeting pre-event conditions, or as near as possible, for all customers. The instantaneous flow is based on local storage and pressure and applies to users over a duration of minutes, hours, or days. The long-term flow is based on total supply volume over timeframes covering days, weeks, months, or years. Rationing may be required if instantaneous or long-term flows are not met.

The fire protection basic service requires a minimum quantity to be provided at a minimum sustained pressure and flow rate for a minimum duration for the purpose of extinguishing structure fires. The water supply available must be adequate to battle the fire threat from the building and contents [Benfer and Scheffey, 2014]. The American Water Works Association [AWWA, 1989] defines the required fire flow as "the rate of water flow, at a residual pressure of 20 psi and for a specified duration that is necessary to control a major fire in a specific structure." This means the flow rate and duration defining the minimum quantity are a function of different structures and building uses, which varies across the city, indicating different zones may have different requirements using this criterion. The firefighting water supply can come from the municipal water supply or other sources [Benfer and Scheffey, 2014; Hickey, 2008]. The Fire Protection Research Foundation [Benfer and Scheffey, 2014] explain the numerous fire flow methodologies used in the United States, each methodology defining the objective of the required fire flow differently. As a result, regulations for fire flow from water distribution systems vary across the Nation. In terms of BSCs, it may not be necessary to track all these parameters or variations in methods for fire flow and obtaining firefighting water supply. The goal for meeting the firefighting basic service can simply be to re-establish pre-event minimum regulatory conditions pertaining to the location being assessed for use by the public. Further, this BSC is a system-wide service intended for protection of all people and property within the service area and therefore should not be thought of as a service for one specific customer, the fire department, even though the fire department may be the local regulator for the provision of this basic service. Specific property owners receive continuous benefit from this basic service, e.g., through automatic fire sprinklers. Further, firefighting water supply is a regionally distributed supply and does not always provide service directly to a specific property or building. Instead, fire-fighting water basic services are provided to hydrants and specific buildings defined by use type (usually industrial use, mid- or high-rise).

Quality, quantity, and fire protection are the services provided by most all water systems and functional recovery does not require these three services to be restored at the same time. Further, resilient water systems can deliver water to at least some users in advance of meeting the quality, quantity, and fire protection services. Delivery allows users to use the water for some purposes (e.g., flushing, self-purification, irrigation, etc.) in advance of full water service recovery and these interim uses improve community resilience.

Davis [2014a, 2014b, 2021], NIST [2016], and FEMA P-2234 [2024] provide additional information about water system basic service categories.

The Centerville potable water system has the same BSCs as presented in Table 3-3.

3.2. Identify System Performance and Recovery Time Objectives

The system-level performance includes all the objectives and criteria necessary to accomplish normal operations (i.e., operating pressure, flow rate, water quality) and provides the services to each customer. The assets framework provides for the inclusion of a system-level seismic performance objective. A system-level seismic performance objective could be specified using parameters such as a maximum number of service losses and/or a recovery rate, a total number of damaged locations, post-earthquake leakage rate, or other parameters, all of which are conditioned on the seismic event associated with the performance objective. However, there are no existing guidelines for how to establish these types of parameters for a system-level performance objective. FEMA P-2234 proposes future work to investigate the usefulness of preparing system-level performance criteria in terms of a number of customer service losses and recovery rate. Further research is needed to identify how to develop system-level seismic performance objectives for water systems.

Since there are no existing guidelines for how to establish system-level seismic performance objectives, none are specified in this water system example. Instead, the system-level performance is identified as an outcome of the system layout including redundancy and isolation capabilities and the performance of the individual components making up the built networks. The system-level performance is identified through the assessment process in Step A11 as the level of performance for the earthquake event defined in Ch. 2 necessary to achieve the target service recovery times defined in Table 3-4a in combination with all the recovery time factors.

FEMA P-2234 presents a framework for identifying target system-level recovery time objectives based on the earthquake event scenario size and available user adaptations. Table 3-4a presents the water system recovery time objectives for the BSCs given in Table 3-3 for the Level II earthquake event scenario described in Ch. 2 having an approximate 400-year return period based on an example application in FEMA P-2234. This is one of several recommended sets of earthquake event scenarios and associated service recovery time objectives a water system should investigate as defined in Volume 1 Sec. 2-5 and FEMA P-2234. Only one earthquake event scenario and associated service recovery objectives are selected for this example.

The target basic service recovery times in Table 3-4a apply to end users and are therefore intended for use by the Centerville CWD.

Table 3-4a. Target Water System BSC Recovery Times for a Level II Earthquake Event Assuming User Adaptations are Applied where Basic Services are Applicable to Distribution of Water to end Customers and Users

BSC	Service Description	Target Recovery Time
Delivery	Restore to all customers	7 days
Quality	Restore to all customers	15 days
	Restore to 50 % of all customers	3 days
	Restore to 100 % of all Critical A Users	3 days
	Restore to 100 % of all Critical B Users	7 days
Quantity	Restore to high-volume Commercial, Industrial, and Institutional Users	7 days
	Restore average winter day demand to all customers	20 days
	Restore to pre-event normal demand (rationing removed)	30 days
Fire Protection	Restore to all hydrants within 0.81 km [a] (1/2 mile) of Critical A Users and multi-resident users; within 1.61 km [a] (1 mile) of any other area requiring fire protection.	3 days
	Restore to Critical A & B Users having fire service at main service connections	3 days
	Restore to 90 % of hydrants	10 days
	Restore to all hydrants	20 days

[a] This criterion may change with local fire department capability to relay water over distance. Consult local Fire Department authorities. This criterion is acceptable for this example because the Centerville Fire Department has the capability to relay firefighting water up to 1.61 km (1 mile).

The fire protection basic service in Table 3-4a is provided to some customers at specific locations having built-in fire service connections and for large areas where buildings and open land do not have a fire service directly as part of their connection (instead water for fire protection is provided through hydrants spaced throughout a zone). The target fire protection basic service recovery time assumes that all spatially distributed hydrants are not required to supply firefighting water immediately after the earthquake. Instead, the concept incorporates the use of firefighting equipment to relay water from usable hydrants, which potentially may be located at distances further than under normal conditions. This requires certain lines to be sufficiently robust to provide post-earthquake firefighting water within distances so that the local fire department can rapidly relay water from a pressurized hydrant to a fire ignition using their existing equipment. An example describing how this can be achieved is presented in Appendix A.

As described in Volume 1 Sections 2.3.6.2 and 3.4, coordination with the CWD is necessary to identify service recovery time targets for the CWSC water supply. Using Step O3 in the organizational actions framework in Volume 1 Ch. 5, the two organizations should coordinate to identify the target CWSC service recovery times in Table 3-4b. The CWSC provides raw water with the quality as withdrawn from Rock River and the groundwater in the floodplain. As a result, only the delivery and quantity basic services apply to the CWSC.

Table 3-4b. Target Water System BSC Recovery Times for a Level II Earthquake Event Assuming User Adaptations are Applied where Basic Services are Applicable to Water Supply Provided to the Centerville Water Department

BSC	Service Description	Target Recovery Time
Delivery	Restore to CWD	1.5 days
Quantity	Restore average winter day demand to CWD	5 days
	Restore to pre-event normal demand (rationing removed)	25 days

The target service recovery time objectives in Tables 3-4a and 3-4b assume the following user adaptations can be implemented; these are in addition to any adaptations made to the system. As a result, it is essential that the organizational actions incorporate the needed activities to ensure these user adaptations can be implemented throughout the service area by including them in the proper plans, coordinating with the correct agencies who can ensure they can be implemented (i.e., Volume 1 Ch. 5 Step O3), and including them in emergency exercises. The user adaptations assumed to be implemented include:

- Reducing consumption, including rationing water that may be implemented system wide
- Delaying consumption
- Temporary relocation (e.g., residents going to hotel or a friend’s or relative’s house or a medical facility)
- Use a regionally redundant facility (e.g., alternate hospital, schools, grocery store having water service)
- Cancel activities
- Any alternate source in bottles, buckets, trucks
- Portable toilets and hand washers
- Portable showers
- Bottled water meeting public health standards
- Trucked water meeting public health standards
- Bottled water (not necessarily potable)

- Trucked water (not necessarily potable)
- Relayed water sources for firefighting from other parts of network, ocean, rivers, lakes/reservoirs, swimming pools, cisterns. Some of these sources may also be local to the fire (e.g., swimming pool)
- Truck brigades for firefighting
- Fire watch (requires fire department approval and their ability to use other adaptations)

The component-level performance and recovery time objectives are identified in Step A4. The component-level recovery time is a function of many locally specific factors described in Volume 1 Table 4-7.

3.3. Step A1: Define System Layout and Operational Characteristics

The Centerville potable water system is described in Sec. 2.4.1 and the major components making up the supply, treatment, transmission, and distribution systems are outlined in Sec. 3.1.3. Figure 2-3 shows the water system major components and transmission connectivity. Figure 3-1 is a plan of the water system showing the layout of the major components making up the supply, treatment, and transmission subsystems. Not shown in Fig. 3-1 due to scale issues are most of the distribution pipelines, but the distribution system is described in more detail later in Sections 3.4 and 3.5 as part of Steps A2 and A3, respectively.

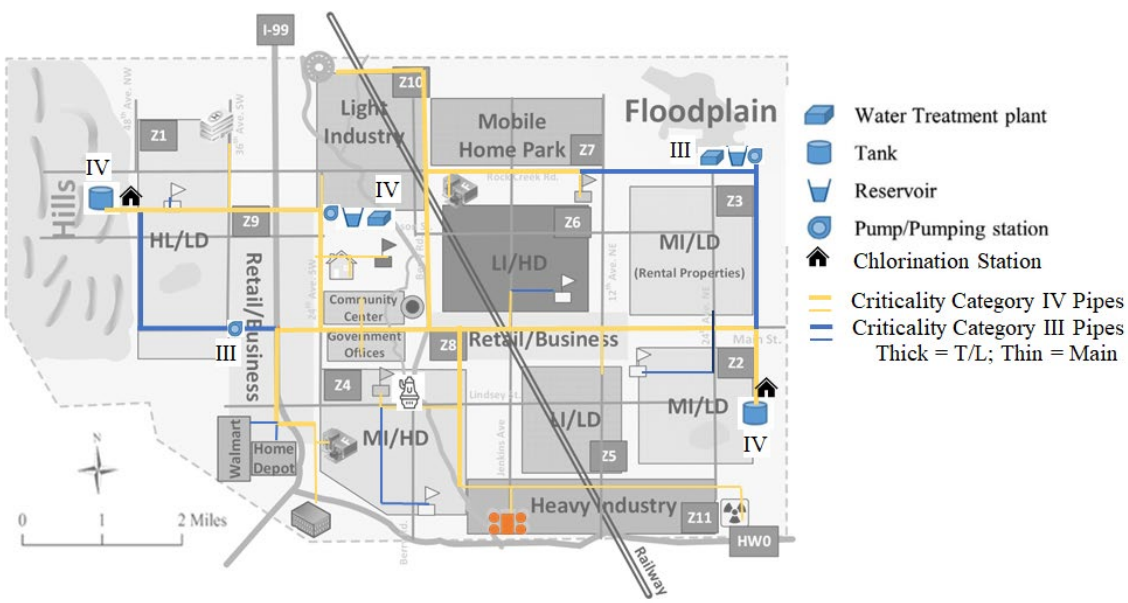

Fig. 3-1. Centerville water system layout and assigned component Criticality Categories.

3.4. Step A2: Define Criticality Category and Earthquake Design Basis for System Components

The components making up the water system described in Step A1 are all assigned a Criticality Category based on the importance of the customers and users the components are utilized to serve. The Criticality Categories are defined in Table 3-5 and are considered applicable to all water systems. Volume 1 Table 4-2 is used to establish the recommended earthquake design basis. Figure 3-1 shows the assigned component Criticality Categories for the Centerville water system, except for most of the distribution mains, which are described in more detail in Appendix A.

Table 3-5. Water System Component Criticality Categories (adapted from Davis [2005; 2008] and ALA [2005])

Criticality Category	Description
I	Components, in the event of failure, present very low hazard to human life, no damage to property, and little to no effects on user's ability to perform their post-earthquake activities or functions. These components are not needed for post-earthquake system performance, response, or recovery. They typically serve for non-essential agricultural or irrigation usage, certain temporary facilities, or minor (non-water) storage facilities which do not have a significant role in the economy. Pipelines may provide potable water supply for a few isolated service connections but are not required for any level of fire suppression following a significant earthquake and have easy access for repair.
II	All components not identified in Criticality Categories I, III, and IV. These typically are normal and ordinary components not used for water storage, pumping, treatment, or disinfection. This includes nonhazardous material storage, commercial, some non-commercial, and industrial buildings not needed for essential emergency response or initial recovery.
III	Components providing water services that represent a substantial hazard or mass disruption to human life in the event of failure, including significant levels of property damage. An extended operational outage for these components may result in significant social or economic impacts and cause significant effects on users' ability to perform their activities or functions. Operational disruption of these components causes long delays in post-earthquake system response or recovery. These components are needed to provide water to Critical B Customers/Users. Buildings and structures necessary for interacting with customers and users like customer service offices.
IV	Components providing water services to essential facilities for post-earthquake response, public health, and safety. This includes components needed for primary post-earthquake firefighting. These components are intended to remain operable during and following an earthquake. These also include all components in the water supply chain, including mechanical and electrical equipment, to Critical A Customers/Users. Additionally, this category includes components, if rendered inoperable, that may result in secondary disasters potentially impacting life safety or public health, impeding emergency response and operations, impeding evacuation routes, or disruption to other lifeline infrastructure systems. Buildings and structures necessary for performing essential and support functions by the lifeline infrastructure system organization, and facilities containing hazardous chemicals.

Applying Table 3-5 to the layout in Fig. 3-1 identifies the Criticality Categories shown in the Fig. 3-1 legend. The Rock River treatment plant and pumping station and all the trunk lines leading to the storage tanks are assigned Criticality Category IV because they are necessary for public health and safety. The trunk line feeding the power generation plant is Criticality Category IV because the power plant is designated as Criticality Category IV in Ch. 5. The main lines to the hospital, emergency shelters (recreation facility, high school, and middle schools), government center, fire stations, hazardous chemical storage, the wastewater treatment plant, and other lifeline infrastructure system headquarters and operation and maintenance (O&M) yards are assigned

Criticality Category IV. In the Centerville community center, most of the buildings are linked to critical government operations during a disaster and utility headquarters and therefore the water pipelines and all components feeding them are assigned Criticality Category IV.

The floodplain treatment plant and pumping station is not a fully redundant source because it only has capacity to supply about 50 % of the city normal demand. The descriptions in Table 3-2 allow these facilities to be assigned at least as Criticality Category III because water supply after an earthquake is considered essential. Since the city can function with reduced volumes by conserving, the floodplain treatment plant is taken as redundant for emergency purposes and using Volume 1 Table 4-3 is assigned Criticality Category III. The booster pumping station is similarly assigned Criticality Category III. The trunk lines from the floodplain treatment facilities and the booster pumping station are also assigned Criticality Category III. The main lines connecting from the trunk lines to the elementary school, Home Depot, and Walmart are assigned Criticality Category III.

An alternative perspective for assigning the Criticality Category to the flood plain treatment plant, appurtenant components, and linked trunk lines is to claim the great importance of water supply and ascribe them Criticality Category IV. This is reasonable if the cost for the increased level can be afforded. This approach was not taken in this example for the primary purpose of showing how redundant components can be managed using the framework.

The mainlines required to provide fire protection basic service during a disaster are assigned Criticality Category IV. This requires all main lines feeding into each zone Z1 to Z11 to be assigned Criticality Category IV. In accordance with Table 3-4a, the fire protection basic service needs to be provided within 0.81 km (0.5 mile) to Critical A users and multi-residential buildings. To accomplish this and distinguish between main lines designated as Criticality Categories II, III, and IV, the branch lines and isolation capabilities need to be defined as described in Step A3. In the absence of defining branch lines and isolation to ensure firefighting capability all main lines in the service zones end up being assigned Criticality Category IV. This is discussed further in Appendix A to show how most main lines can be assigned a lower Criticality Category.

Table 2-3 defines the intensity measures for each earthquake hazard in Centerville for each component Criticality Category.

3.5. Step A3: Check Multiple Use, Continuity, and Redundancy

The components shown in Fig. 3-1 are assigned the highest Criticality Category for the customers and users they provide service to, except for the redundant components. The redundant components at the floodplain groundwater wells, collection line, treatment plant, finished water reservoir, and pumping station are considered redundant to the primary supply source at Rock River, as described in Sec. 3.4 Step A2, and are reduced by one Criticality Category level in accordance with Volume 1 Table 4-3 as shown in Fig. 3-1. The transmission pipelines conveying water from the flood plain finish water reservoir are similarly reduced by one Criticality Category level as shown in Fig. 3-1. In accordance with the equivalency defined in Volume 1 Sec. 4.4, the Criticality Category III flood plain groundwater wells, treatment plant, and pumping station, along with the booster pumping station, are defined as Critical Customer/Users B to the wastewater and electric power systems.

For continuity, all the mainlines connecting from the trunk line and distributing to zones Z1 to Z11 are designated Criticality Category IV because they are used to provide the fire protection basic service. As shown in Fig. 3-1, all trunk lines transmitting water to these zones have continuity with Criticality Category IV components to the Rock River water source. Appendix A describes how the distribution network may be composed of Criticality Category I to IV pipelines depending on the range of customers within the different zones.

3.6. Step A4: Establish Component Objectives - Maximum Level of Damage and Return to Operation Time

3.6.1. Target Maximum Component Damage

Volume 1 Table 4-4 defines the component-level performance objective in terms of tolerable component damage. Table 3-6 provides guidance descriptions of the expected damage levels related to the terms identified in Volume 1 Table 4-4. These represent the acceptance criteria for newly designed and constructed or retrofitted components in a potable water system. These damage descriptions follow the general descriptions given in Volume 1 Table 4-5 and can be applied to any water system.

Table 3-6. Water System Damage Levels and Summary Descriptions

Damage Level	Summary Description
Minor	Minimal to no perceivable damage to water system components. Limited to no effects on water system operations; able to continue essential emergency operations and most normal operations. For facilities[a], this damage level is equivalent to the Immediate Occupancy Structural Performance Level and Operational Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the minor level buildings and structures that are a part of the water system have minimal to no damage to their structural and essential nonstructural components. Buildings are safe to occupy and able to continue essential emergency operations. Injuries to building occupants are minimal in number and minor in nature. Nonstructural systems, including mechanical and electrical equipment, needed for normal building use and emergency functions are fully operational, but may require adjustments for external utilities (e.g., water, wastewater, power, communications), which may need to be provided from alternative emergency services. Damage to building contents is minimal in extent and minor in cost. Minimal hazardous materials are released to the environment. Pumping, treatment, and disinfection facilities remain operable and may require some minor repairs. There is little to no damage to mechanical and electrical equipment. Tanks, dams, levees, and reservoirs have minor damage which may warrant investigation due to safety precautions, but do not result in safety concerns or any significant limitations to operations. Trunk lines and their appurtenances have minor to no perceivable damage and transmission operations are not affected. Water distribution pipelines and appurtenances have minor damage, resulting in very few leaks and breaks which are easy to repair and impact a small number of customers. Tunnels and channels have minor to no damage requiring little to no repair (e.g., minor concrete cracking).

[a] Buildings and facilities that are part of the water system.

Table 3-6. Water System Damage Levels and Summary Descriptions (continued)

Damage Level	Summary Description
Moderate	Damage is repairable. There may be some delay in re-occupying buildings[a]. Essential emergency functions are fully operational. Emergency systems remain fully operational. For facilities[a], this damage level is equivalent to the Damage Control Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the moderate level, for buildings that are a part of the water system, structural damage is repairable, and some delay in re-occupying buildings is expected. Nonstructural systems needed for building use and essential emergency functions are fully operational, although some cleanup and repair may be required. Emergency systems remain fully operational. Injuries to building occupants may be locally significant but are generally moderate in number and in nature; the likelihood of a single life loss is low and the likelihood of multiple life loss is very low [ICC, 2022]. Some hazardous materials are released to the environment, but the risk to the community is minimal. Pumping, treatment, and disinfection facilities may be damaged requiring temporary removal from operation for limited repairs, but not on an emergency basis (i.e., can remain operable following the earthquake, but a temporary shutdown may be warranted within days to weeks after the event). Similarly, there is limited damage to mechanical and electrical equipment, but not to the extent water system operations are seriously impacted (e.g., some equipment may require repairs but can be undertaken without serious disruption to operations). Tanks, dams, levees, and reservoirs may have some damage which may warrant immediate investigation due to safety precautions and some repairs but have limited to insignificant impacts to operations. Trunk lines and appurtenances may have minor leaks which require shutdown and repairs, but no serious structural damage, breaks, or significant flooding from the pipelines. Critical and essential mainlines will behave similar to trunk lines. Water distribution pipeline networks may have several leaks and breaks, potentially locally impacting services provided to customers. Tunnels and channels have moderate to minor damage requiring little to some limited repair (e.g., concrete patching), but no serious structural defects requiring immediate shutdown.
High	Significant damage is expected. Structural damage to components may be repairable. For facilities[a], this damaging level is equivalent to the Life-Safety Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the high level, for buildings that are a part of the water system, significant damage to building structural elements, but no large falling debris, is expected. Repair of the structural damage is possible, but significant delays in re-occupancy can be expected. Nonstructural systems needed for normal building use are significantly damaged and inoperable. Emergency systems may be significantly damaged but remain operational. Injuries to building occupants may be locally significant with a high risk to life but are generally moderate in number and nature. The likelihood of a single life loss is moderate, and the likelihood of multiple life loss is low [ICC, 2022]. Hazardous materials are released to the environment and localized relocation is required [ICC, 2022]. Pumping, treatment, and disinfection facilities may be significantly damaged removing them from operation until repairs are completed. Similarly, damage to mechanical and electrical equipment may require extensive repairs or replacement. Tanks, dams, levees, and reservoirs may show observable and significant damage warranting immediate investigation and potential removal from use due to safety precautions, but do not pose a threat of a catastrophic release of water. Trunk lines and appurtenances may have significant structural damage, but either retain their pressure boundaries or have limited leakage, requiring them to be shut down for repairs. Critical and essential mainlines will behave structurally similar to trunk lines but may be drained due to other distribution pipe damages. Water distribution pipeline networks may have many leaks and breaks, potentially locally impacting services provided to customers. Tunnels and channels can have serious damage requiring them to be removed from use for repair.

[a] Buildings and facilities that are part of the water system.

Table 3-6. Water System Damage Levels and Summary Descriptions (continued)

Damage Level	Summary Description
Severe	Substantial damage is expected. Repair may not be technically feasible. For facilities[a], this damaging level is equivalent to the Collapse Prevention Structural Performance Level and Hazard Reduced Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the severe level, for buildings that are a part of the water system, substantial building structural damage is expected, and repair may not be technically feasible, though all significant structural components are intended to continue carrying gravity load demands. Partial or total collapse is possible [ASCE, 2023]. The building is not safe for re-occupancy because re-occupancy or aftershocks could cause collapse. Nonstructural systems for normal building use may be inoperable, and emergency systems may be substantially damaged and inoperable. Injuries to building occupants may be high in number and significant in nature. Significant hazards to life may exist. The likelihood of life loss is high. Significant amounts of hazardous materials may be released to the environment and relocation beyond the immediate vicinity is required [ICC, 2022]. Pumping, treatment, and disinfection facilities are severely damaged, and unlikely operable; required repairs are extensive and may not be feasible. Mechanical and electrical equipment is not usable. Tanks, dams, levees, and reservoirs have signs of severe distress and may be leaking or even releasing large volumes of water; they require immediate drainage of any retained water to ensure safety of downstream properties. Trunk lines and appurtenances have ruptures requiring immediate shutdown for repairs and releasing significant amounts of water onto the ground surface. Distribution pipeline networks have a great number of leaks and breaks, impacting services provided to a large number of customers. Tunnels and channels can have substantial damage where repairs may not be feasible, requiring complete reconstruction.

[a] Buildings and facilities that are part of the water system.

HAZUS [FEMA, 2022] uses damage descriptions for None, Slight, Moderate, Extensive, and Complete as part of their fragility functions. Their descriptions can be correlated to the Minor, Moderate, High, and Severe descriptions above which are based on the damage descriptions by ICC [2022].

3.6.2. Target Return to Operation Time

The target time increments for returning components to operation within the Centerville water system are identified in Volume 1 Table 4-6.

To aid the preliminary design in Step A6, each physical component should have a potential repair time estimated, and then added to any expected or assumed time increment after the earthquake to initiate work plus lead times as described in Volume 1 Sec. 4.6.2. In Step A7 the resulting estimated time is compared to Volume 1 Table 4-6. For example, consider a trunk line buried deeply (e.g., 6 to 9 meters) below a very narrow and busy street and all repairs must be made external to the pipeline due to internal access constraints. If the trunk line experiences moderate damage in an earthquake, it may take a week or more to make the repair. This time increment is longer than what is identified for a Criticality Category III component experiencing a 975-year return period earthquake hazard per Volume 1 Table 4-6. As a result, a Criticality Category III pipeline having these specific site conditions may need to be designed to a higher-level standard.

The repair time increment objectives therefore represent another type of acceptance criterion for newly designed and constructed or the retrofit of existing components in a potable water system. The default acceptance criteria fall along the diagonal of Volume 1 Table 4-6 from upper right to lower left. The repair time increment objectives may be taken strictly during component design or incorporated into a broader system-level analysis in Step A9. Following a system analysis, if the basic service recovery times are shown to be met, even if the component recovery time increment exceeds the target duration in Volume 1 Table 4-6, then the component design may be deemed acceptable.

Due to simplifications, recovery time increments for all components in the Centerville example are not prepared, and the preliminary design in Step A6 conforms with Volume 1 Table 4-6. Water systems are recommended to consider specific component conditions when applying the framework.

3.7. Step A5: Identify Dependent Services

The water system is dependent upon services from other lifeline infrastructure systems identified in Table 3-7. These dependencies are identified for the Centerville example. Additional dependencies unique to each individual water system should be identified.

Table 3-7. Water System Component Dependencies

Component/Activity	Dependent upon services from system
Pumping station	Electric power
Treatment plant and chlorination stations	Electric power and chemical deliveries via rail and ground transport
Distribution subsystem	Wastewater
Emergency generators	Liquid fuels
Vehicles (damage inspection and repair)	Transportation Gas fuels Liquid fuels

3.8. Step A6: Develop Preliminary Design

This example of the Centerville water system uses a hypothetical existing system which has already been constructed, and for the most part, the system-level and each component were not designed for functional recovery. Because the aforementioned is a common expectation across the country, this example will utilize the existing designed and constructed system that has not been modified for functional recovery to carry out the remainder of the framework.

To carry through with the framework, this example identifies an older, buried pipeline that has deteriorated and needs replacement. This line is a 1.61 km (1 mile) long stretch of trunk line on Main Street east of Rock River in the retail/business district zone Z8. The hydraulic conditions have not changed from the original design. As a result, the new pipeline only needs to include the current seismic design and all other aspects of the design remain the same as for the existing pipe.

As shown in Fig. 3-1, this trunk line has a Criticality Category IV. The geographic location does not have any exposure to permanent ground deformations (i.e., it is located outside the potential liquefaction hazard zones). As a result, this pipeline is to be designed to withstand peak ground acceleration of PGA = 0.85g and peak ground velocity of PGV = 228.6 cm/sec (90 in/sec), in accordance with Table 2-3. Using ALA [2005], the PGV will drive the seismic design and result in relatively large pipe strains. The design procedure results in using a seismic resilient pipe system that can accommodate the large strains and the CWD chooses to put out for bid, a construction project allowing the contractor to select either a welded steel pipe, a ductile iron hazard resilient pipe (or sometimes called an earthquake resistant ductile iron pipe), or a high-density polyethylene pipe (HDPE). These three pipe systems were found during the design process to meet the normal operating and the seismic demands on this stretch of trunk line.

The repair time increment is specifically reviewed for this design project and found to fall within the criteria identified in Volume 1 Table 4-6. The new design is not expected to be damaged in an earthquake, but if it were, the repair time increment is within a few hours.

The trunk line has no dependencies because it has no appurtenant components requiring power, chlorination, or anything else. Since the proposed trunk line design and construction are not expected to be damaged, this design does not incorporate repair time, or any direct or indirect costs associated with putting this 1.61 km (1 mile) stretch of pipe back into service as explained in Volume 1 Sec. 4.8 (Step A6).

3.9. Step A7: Assess Component Performance and Repair Time, Compare with Target Objectives

The pipeline design described in Step A6 is not expected to be damaged for the design level transient ground motions, even when performing a series of assessments to transient motions exceeding the design level PGV. In addition, even though the buried pipeline is not expected to be subjected to permanent ground deformations, the design can handle small ground movements up to several cm of horizontal and vertical displacements without damage. Evidence providing support for this is given in Davis et al. [2019].

Volume 1 Table 4-4 identifies the newly designed trunk line should not sustain more than moderate damage. According to Table 3-6, trunk lines and appurtenances with moderate damage may have minor leaks which require shutdown and repairs, but no serious structural damage, breaks, or significant flooding from the pipelines. The default acceptance criteria in Volume 1 Table 4-5 indicates the trunk line should be repairable within a few hours to days. These criteria are identified based solely on the design criteria of Volume 1 Table 4-2 and the component Criticality Category (i.e., this is independent of any intensity measures associated with an earthquake event scenario). As a result, the newly designed 1.61 km (1 mile) long stretch of buried trunk line is expected to exceed the target performance and recovery time criteria and path ‘Yes’ is followed in Volume 1 Fig. 4-1a. This allows a system-level evaluation to be performed using Volume 1 Fig. 4-1b.

3.10. Step A8: Identify Recovery Time Factors

The recovery time factors described in Volume 1 Sec. 4-10 are reviewed. They are all applicable to the Centerville water system and will be assessed as part of Step A9. No additional dependencies to those listed in Table 3-7 were identified.

3.11. Step A9: Assess System Performance and Recovery Time

The Centerville water system assessment uses the earthquake event scenario described in Sec. 2.7 to evaluate expected basic service disruptions and recovery times using metrics that allow the results to be compared with the information provided in Tables 3-4a and 3-4b. The assessment covers all the subsystems in Table 3-2 and how they interact, regardless of who owns or operates them.

3.11.1. Effects of the Earthquake Hazards on the Centerville Water System

The scenario earthquake event and hazards are described in Sec. 2.7.1. This assessment is streamlined for the purpose of illustrating how to implement the framework. Actual systems may experience more or less damage than described in this assessment. Figure 3-2 shows 19 damage locations, identified as D1 to D19 in Table 3-8. Damage to the distribution system are not shown in Fig. 3-2 or included in Table 3-8. This damage is experienced by the existing infrastructure that was not designed to the Criticality Category levels identified in Fig. 3-1 and shown in Volume 1 Table 4-2. Fragility and recovery functions given in FEMA [2022] were used to aid in understanding the effects of the earthquake event on the water infrastructure. The effects of the earthquake hazards on the Centerville water supply, treatment, transmission, and distribution subsystems are described in the following subsections. The descriptions identify the damage number in Fig. 3-2 and Table 3-8 in brackets as [**Dx**].

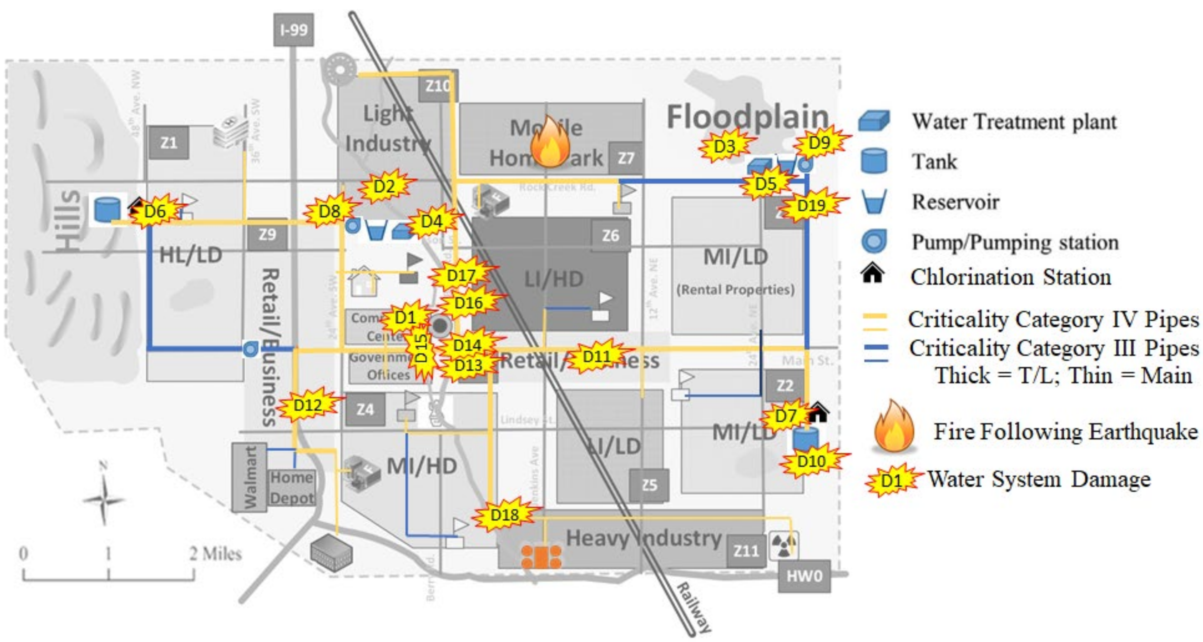

Fig. 3-2. Centerville water system damage locations, except for the water distribution pipelines leaks and breaks.

The CWD headquarters building was highly damaged from shaking and lateral spreading [**D1**] and is unusable until repaired. The O&M yard buildings and structures had minor damage which did not significantly inhibit operations.

Table 3-8. Summary of Expected Damages to Water System

No.	Component	Damage	Repair Time[a]	Repair Description
D1	HQ Building	Moderate building structural damage	2 yrs	Repair structural and nonstructural
D2	Rock River supply pump station	Electric cabinets, inlet channel, sump, building structure, 2 pumps unusable, outlet pipe.	2 days; 1 yr	Partial repair at 2 days; Temporary repair to elect. equip, and pipe. 1 year to repair channel, structure, sump, replace pumps
D3	Floodplain supply pump and collection line	1 pump unusable, collection line break	1 day; 45 days	Collection line coupling welded by CWD at 1 day. Pump replaced at 45 days.
D4	Rock River treatment plant	½ of plant: Equipment, baffles, pipe connections to basins	90 days	Repair concrete, damaged pipes, electrical cabinets, etc.
D5	Floodplain treatment plant	½ of plant: Equipment, baffles, pipe connections to basins	60 days	Repair concrete, damaged pipes, electrical cabinets, etc.
D6	West chlorine station	Equipment and chlorine tanks	4 days	Temporary repairs
D7	East chlorine station	Equipment and chlorine tanks	4 days	Temporary repairs
D8	Rock River transmission pump station	Electrical equipment	1 day	Temporarily repair wiring around toppled cabinets
D9	Floodplain transmission pump station	Electrical equipment	2 h	Temporarily repair wiring around toppled cabinets
D10	East elevated water tank	Inlet line break	4 days	Weld new section
D11	Main St. trunk line (TL)	Leak	3 days	Weld damaged joint
D12	TL to Home Depot	Leak	3 days	Weld damaged joint
D13	Main St. TL	Break at Bridge	12 days	Cut-out and weld-in new section
D14	Main St. TL	Break at Tee	12 days	Cut-out and weld-in new section

[a] The time the repairs were completed (i.e., how long it took to complete the repairs after the earthquake struck).

Table 3-8. Summary of Expected Damages to Water System (continued)

No.	Component	Damage	Repair Time[a]	Repair Description
D15	Main St. TL	Break west of river	12 days	Cut-out and weld-in new section
D16-D17	TL to Z10	Breaks next to river	12 days	Cut-out and weld-in new section
D18	TL to Z11	Break next to river	5 days	Cut-out and weld-in new section
D19	TL to and from floodplain	Break	3 days	Cut-out and weld-in new section

[a] The time the repairs were completed (i.e., how long it took to complete the repairs after the earthquake struck).

3.11.1.1 Raw Water Supply

Raw water supply from the Rock River and floodplain groundwater are impacted by ground shaking and lateral spreading.

The Rock River supply pumping station electric cabinets toppled from shaking [**D2**]. Lateral spreading damaged portions of the inlet channel, sump, and rendered two electric power pumps unusable, leaving the station at 80 % of its normal capacity when using the back-up fuel powered pumps. The pump station building structure and sump were moderately to highly damaged but remain structurally stable and can be safely entered. The outlet pipe connection to the pumping station manifold used an unrestrained mechanical coupling which pulled apart resulting in a severe break and eroded a large hole in the access roadway.

One of the groundwater wells in the flood plain was rendered unusable and must be replaced. All other wells remain usable, and the site can produce 75 % of its normal supply volume. The permanent ground deformation broke the collection line to the treatment plant [**D3**].

3.11.1.2 Treatment

The two water treatment plants [**D4** and **D5**] were damaged from shaking and lateral spreading. In both cases, half of the plant was severely damaged while the other half received minor to moderate damage. Wave sloshing in the basins damaged the baffles throughout both plants. Unanchored equipment slid and toppled immediately removing the ability to operate any portion of both treatment plants. Differential ground movement broke several buried pipe connections to concrete structures.

The chlorination stations [**D6** and **D7**] were moderately damaged from the shaking. The building structures had minor damage and remained safe to use. Unanchored equipment and chlorine tanks disrupted the disinfection operations.

The treatment plants and disinfection stations are dependent upon chemical deliveries and are therefore sensitive to damage in the multimodal transportation system. This issue is not specifically addressed in this example but is covered in the wastewater system example in Ch. 4.

3.11.1.3 Transmission

The finished water reservoirs were relatively undamaged. The collocated pumping stations were moderately damaged, mostly from unanchored equipment, and can be returned to operation after completing a few repairs [**D8** and **D9**]. The inlet line to the elevated storage tank on the east side of town pulled apart and drained the tank [**D10**].

There was a total of two leaks from ground shaking [**D11** and **D12**] and 12 breaks from permanent ground deformation [**D13** and **D25**] in the trunk line system. The trunk line running down Main Street crosses Rock River in a pipe connected to the transportation bridge [**D13**]. The bridge was damaged as explained in Section 2.7.2 and resulted in a large break in the trunk line. At this location there is a tee connection to another trunk line running north to the power plant. This tee connection was severely damaged [**D14**] from lateral spreading. These pipe breaks at the bridge and the tee resulted in pressurized water eroding soil at the bridge abutment, damaging the roadway and collocated buried utilities. These two trunk lines also experienced a combined 4 additional breaks [**D15** to **D18**] from permanent ground deformation (6 total) along the Rock River as shown in Fig. 3-2 and Table 3-8. One trunk line in the northeast portion of the system, near the finished water reservoir, also had a break from the permanent ground deformation in the floodplain [**D19**].

3.11.1.4 Distribution

There were a total of 20 leaks and 5 breaks in the distribution system from transient ground shaking that were scattered around the zones. The permanent ground deformation along the Rock River, in the floodplain, and around the lakes and ponds resulted in an additional 75 breaks in the distribution network. There were a total of 100 distribution pipe repairs. Additionally, there were 60 service line breaks resulting from permanent ground deformation.

3.11.1.5 Dependencies

The impacts to the electric power system as described in Ch. 5 resulted in power service losses at all pumping stations, treatment plants, and chlorination stations for up to four days. Damage to the bridges inhibited the ability of the CWD and the CWSC staff and consultants to respond to the earthquake for emergency response and longer-term repairs.

3.11.1.6 Service Losses

Damage to the water system eliminated the ability to deliver water to nearly all customers soon after the earthquake, mainly due to pipe damage from the supply sources. Some customers being served by the storage tank in the hills, including the hospital, were able to continue receiving water for many hours following the earthquake, until the tank drained; the tank drainage resulted because of water leaking from pipes and water consumption by customers. The lack of fire service seriously inhibited the fire department from extinguishing fires ignited following the earthquake, for example at the mobile home park. There are many repairs required to restore the water delivery basic service.

3.11.2 Response and Service Restoration

As a result of damage to the water system the mayor immediately issued throughout the City a boil water notice and a water rationing requirement. The water rationing required nonessential customers to cut back water usage by 75 % of normal for those getting water delivery.

Impacts to the road network significantly impacted the ability for the water system field groups to respond to perform inspections and to initiate repairs and restore operations. This was especially serious on the west side of Rock River because the crews, materials, and equipment were stationed at the floodplain O&M yard, and access cross the river was seriously delayed due to damages to bridges crossing the river and erosion of soil under the roads from the pipe breaks.

Due to damages from the CWD headquarters building, they had to relocate to an alternative building at the Rock River treatment plant until it can be repaired and retrofitted. The CWD primary emergency operations center is in the headquarters building. The back-up emergency operations center is at the Rock River treatment plant. The Rock River treatment plant has an administration building capable of accommodating the core management and their staff who normally work in the headquarters building but does not have enough space to manage all normal work. Some CWD groups are relocated to other offsite buildings at various locations throughout Centerville.

Immediately after the earthquake, the Fire Department placed an urgent request for firefighting water to be provided to the mobile home park zone Z7. As a result, the CWD staff initiated work on the floodplain transmission pumping station to make repairs to [**D9**] and isolated the damaged trunk line [**D19**]. Within about two hours the floodplain transmission pumping station was able to resume pumping from water stored in the finished water reservoir to recover the fire protection basic service to the mobile home park zone Z7. Existing emergency generators in the flood plain transmission pumping station were used to power the pumps since the electric power system could not provide the delivery basic service. This operation also required shutting valves to isolate breaks [**D16**] and [**D17**]; the water delivery and fire protection basic services were also restored to the power plant and zones Z3, Z6, and Z10NE. Water supply is able to be maintained by using the workable groundwater wells, repairing [**D3**] within 1 day and bypassing the damaged floodplain treatment plant [**D5**] using the existing bypass pipeline. The collection line is owned and operated by the CWSC, but they were unable to provide crews rapidly to the site so the CWD agreed to make the repairs under their mutual aid agreement so that water supply could be restored to their system.

Similar repairs were required for the Rock River transmission pumping station but took up to one day since groups and suppliers had difficulty accessing the site because they could not easily cross the river. After 1 day [**D8**] was repaired and water was able to be pumped from the finished water reservoir into the system. Existing emergency generators in the Rock River transmission pumping station were used to power the pumps since the electric power system could not provide the delivery basic service. The leak at [**D12**] and break at [**D15**] had to be isolated by shutting off valves in the trunk lines. This allowed water delivery to be restored to zones Z1, Z9, Z10SW, the community center, the high school, and the recreational center. The high school and recreational center have been converted to emergency shelters. The fire protection service is not able to be restored to these areas because the storage tank in the hills is unable to remain at the minimum volume.

Temporary and partial repairs were able to be completed to the Rock River supply pumping station [**D2**] within two days to utilize the working pumps. Diesel fuel is required to be delivered every three days to keep the back-up pumps running. This work was required to be completed before the two days of storage in the finished water reservoir was depleted of storage or the delivery service to zones Z1, Z9, Z10SW, and the community center would stop. This operation also required utilizing the bypass pipeline around the damaged [**D4**] Rock River treatment plant. When completed, the fire protection basic service is restored to zones Z1, Z9, Z10SW, the community center, the high school, and the recreational center.

After returning the water supply pumping stations to service, the mayor reduced the water rationing requirement to 80 % of normal use. This restriction is set to remain in place until both supply sources are returned to full capacity. Water rationing is removed for critical facilities and users like the hospital, emergency shelters when activated, fire department, and power plant.

Half of the Rock River treatment plant [**D4**] was restored three days after the earthquake. The electric power to this location was restored four days after the earthquake. This allows potable water to be placed into the pipeline networks on the west side of the river. However, the water quality basic service cannot be restored until the boil water notice can be removed, which requires all the transmission and distribution pipelines to be disinfected with confirmed tests and the chlorination stations to be returned to operation. Thus, the distribution mainlines in each zone also need to be isolated or repaired in advance of disinfecting the network.

Trunk line repairs to [**D19**], [**D11**], and [**D12**] were completed 3 days after the earthquake. Repair for [**D19**] was lengthy due to the extensive amount of pipe damage and offset of pipe from ground displacement. Repair [**D11**] was not identified until the pipe was re-wetted after completing repair at [**D19**]. Once identified [**D11**] was rapidly fixed. After isolating the damaged tank [**D10**] and pipelines [**D13**] and [**D18**], the delivery basic service was restored to zones Z2, Z4E, Z5, and Z8. However, the pumps alone are unable to provide the fire protection service to these zones; repairs to the elevated tank at [**D10**] are necessary to restore the fire protection basic service. Repair to [**D10**] was completed 4 days after the earthquake.

The need for repair at [**D12**] was identified the day of the earthquake but took 3 days to complete due to access limitations by the repair crew from the damaged bridges across the river. Completing this repair restored the delivery and fire protection basic services to zone Z4W and to Home Depot, Walmart, and the transportation department headquarters.

Half of the flood plain treatment plant [**D5**] was restored four days after the earthquake. This allows potable water to be placed into the pipeline networks on the east side of the river. However, as explained for the Rock River treatment plant, this does not allow for restoration of the water quality basic service. The electric power to this location was restored three days after the earthquake.

The chlorination stations [**D6**] and [**D7**] temporary repairs were completed four days after the earthquake to allow resumption of chlorine for disinfecting the water in the pipelines. The electric power to these locations was restored within four days. The process for disinfecting the wetted pipelines initiated soon after returning the chlorination stations to service, but it takes several days to accomplish and validate with laboratory testing results. The water quality basic service category was restored as the boil water notices were removed by zone between 6 and 7 days after the earthquake. The zones were confirmed to be disinfected and approved by the state department of public health in consecutive order from those closest to the treatment plants. Zones Z3, Z7, Z9, Z10W and the community center had the water quality basic service restored 6 days after the earthquake. Zones Z1, Z2, Z4E, Z4W, Z5, Z6, Z8, Z10E had the water quality basic service restored 7 days after the earthquake.

The **[D18**] repair was completed 5 days after the earthquake. This repair restored the delivery and fire protection basic services to zone Z11. After disinfecting the pipelines and testing the boil water notice was removed and the water quality basic service was restored 8 days after the earthquake.

The remaining transmission pipe repairs at [**D13**] to [**D17**] took up to 12 days after the earthquake to complete. Repairs at these locations were extensive because of the level of damage they experienced from ground movement. The completion of these repairs allows resumption of flow between the east and west side of the river allowing both supply sources to be used anywhere in the city.

The distribution pipe repairs follow the restoration of water delivery to the different zones. The small diameter pipe leaks and breaks normally cannot be identified until pressurized water is placed into the system. As a result, the distribution zones Z1 to Z11, community center, and other mainlines do not have repairs initiated until after the transmission lines restore water delivery to the zone and the zone is inspected. After leaks and breaks are identified, repairs are initiated. Priority mainline repairs will be given to those needed to provide service to Critical Customers/Users A, B, and C, respectively. Thus, when the CWD is prioritizing repairs, mainlines serving Critical A Customers/Users may have a higher priority, and repairs completed, before other larger diameter pipelines that are not needed to provide services to Critical A Customers/Users.

The unusable groundwater pump in the floodplain was replaced 45 days after the earthquake, returning full capacity of this source, but the supply could only be used at half capacity until the floodplain treatment plant can be returned to full operation.

Full flow capabilities through the Rock River and floodplain treatment plants were restored 90 days and 60 days, respectively after the earthquake. This allowed the floodplain to return to full capacity. However, the Rock River portion of the system remained limited at 80 % capacity until the Rock River supply pumping station can return to full capacity operation.

The Rock River supply pumping station took more than 12 months to return to full pumping capacity. During this time, diesel fuel was required to be delivered every three days to ensure the back-up pumps were able to run. After returning the Rock River supply pumping station to full capacity, the water rationing requirement is removed for the entire city. As a result, the water quantity basic service is restored 12 months after the earthquake.

The headquarters building repairs to structural and nonstructural components were not completed for about 2 years. In the meantime, groups worked from remote locations.

The recovery times presented in Table 3-9 identify only the basic services and when complete operability is reached. Many of the facilities were temporarily repaired to allow them to be put back into operation. Much more effort and time are necessary to reach full functionality for the system, which is important and should also be assessed, but is beyond the scope of an assessment for establishing performance at the lower functional recovery level.

Table 3-9. Water System Basic Service Restorations

Service Zone	Delivery		Quality		Quantity		Fire Protection	
	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.
Z1	1 d	Repair D8, Isolate D12-15	7 d	Repair D4, D6, Disinfect pipes	1 yr	Repair D2, D3	2 d	Temp. repair D2, bypass D4
Z2	3 d	Repair D19, D11, isolate D10, D13	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	4 d	Repair D10
Z3	2 h	Repair D9, isolate D19, Bypass D5	6 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Z4E	3 d	Repair D19, D11, isolate D10, D13	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	4 d	Repair D10
Z4W	3 d	Repair D12	7 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	3 d	Repair D12
Z5	3 d	Repair D19, D11, isolate D10, D13	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	4 d	Repair D10
Z6	2 h	Repair D9, isolate D19, bypass D5	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Z7	2 h	Repair D9, isolate D19, bypass D5	6 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Z8	3 d	Repair D19, D11, isolate D10, D13	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	4 d	Repair D10
Z9	1 d	Repair D8, isolate D12-15	6 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	2 d	Temp. repair D2, bypass D4
Z10NE	2 h	Repair D9, isolate D19, bypass D5	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Z10SW	1 d	Repair D8, isolate D12-15	6 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	2 d	Temp. repair D2, bypass D4
Z11	5 d	Repair D18	8 d	Repair D5, D7, D18, disinfect pipes	1 yr	Repair D2, D3	5 d	Repair D18
Community Center and Government Offices	1 d	Repair D8, isolate D12-15	6 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	2 d	Temp. repair D2, bypass D4
Hospital	1d	Repair D8, isolate D12-15	7d	Repair D4, D6, disinfect pipes.	2d	Temp. repair D2, D3	2d	Temp. repair D2, bypass D4

Table 3-9. Water System Basic Service Restorations (continued)

Service Zone	Delivery		Quality		Quantity		Fire Protection	
	Dur.	**Descr.**	**Dur.**	**Descr.**	**Dur.**	**Descr.**	**Dur.**	**Descr.**
Northern Fire Department	2 h	Repair D9, isolate D19, bypass D5	7 d	Repair D5, D7, disinfect pipes.	2 d	Temp. repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Southern Fire-Department	3 d	Repair D12	7 d	Repair D4, D6, disinfect pipes.	2 d	Temp. repair D2, D3	3 d	Repair D12
Home Depot/ Walmart	3 d	Repair D12	7 d	Repair D4, D6, disinfect pipes.	1 yr	repair D2, D3	3 d	Repair D12
Power Plant	2 h	Repair D9, isolate D19, bypass D5	7 d	Repair D5, D7, disinfect pipes.	2 d	Temp. repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Wastewater Treatment Plant	5 d	Repair D18	8 d	Repair D5, D7, D18, disinfect pipes.	2 d	Temp. repair D2, D3	5 d	Repair D18
High School	1 d	Repair D8, isolate D12-15	6 d	Repair D4, D6, disinfect pipes.	2 d[a]	Temp. repair D2, D3	2 d	Temp. repair D2, bypass D4
Northern Middle School	2 h	Repair D9, isolate D19, bypass D5	6 d	Repair D5, D7, disinfect pipes	2 d[a]	Temp. repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Southern Middle School	3 d	Repair D12	7 d	Repair D4, D6, disinfect pipes	2 d[a]	Temp. repair D2, D3	3 d	Repair D12
Eastern Elementary School	3 d	Repair D19, D11, isolate D10, D13	7 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	4 d	Repair D10
Western Elementary School	1 d	Repair D8, isolate D12-15	7 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	2 d	Temp. repair D2, bypass D4
Center Elementary School	2 h	Repair D9, isolate D19, bypass D5	7 d	Repair D5, D7, disinfect pipes	1 yr	Repair D2, D3	2 h	Repair D9, isolate D19, bypass D5
Southern Elementary School	3 d	Repair D12	7 d	Repair D4, D6, disinfect pipes	1 yr	Repair D2, D3	3 d	Repair D12
Recreational Center (Emergency Shelter)	1 d	Repair D8, isolate D12-15	6 d	Repair D4, D6, disinfect pipes	2 d[a]	Temp. repair D2, D3	2 d	Temp. repair D2, bypass D4

[a] When emergency shelter is activated.

Table 3-9. Water System Basic Service Restorations (continued)

Service Zone	Delivery		Quality		Quantity		Fire Protection	
	Dur.	**Descr.**	**Dur.**	**Descr.**	**Dur.**	**Descr.**	**Dur.**	**Descr.**
Transportation Department	3 d	Repair D12	7 d	Repair D4, D6, disinfect pipes.	1 yr	Repair D2, D3	3 d	Repair D12
Chemical Storage Location	5 d	Repair D18	8 d	Repair D5, D7, D18, disinfect pipes	1 yr	Repair D2, D3	5 d	Repair D18

3.12 Step A10: Compare System Assessment Results with Target Objectives

3.12.1 Comparing Assessed and Target Recovery Times

Tables 3-10a and 3-10b compare the basic service recovery times in Table 3-9 with the target recovery times given in Table 3-4a and 3-4b. As seen in the Tables 3-10a and 3-10b right columns, some of the target basic service recovery times are met and some are not. Additionally, given the uncertainty in the type of assessment undertaken in Step A9, the recovery times just reach the limits of the target times and with a little difference in an actual response the basic services may not meet the community needs.

As a result, path ‘No’ is followed in Volume 1 Fig. 4-1b and modifications are needed so that the basic service recovery time objectives may be achieved in future earthquakes which may strike Centerville.

3.12.2 Making System Modifications and Framework Iterations

Since not all the target service recovery time objectives were met, Volume 1 Fig. 4-1b shows the next part of the process is to revise the system recovery time factors in Step A8 and/or the performance and service recovery time objectives in Tables 3-4a and 3-4b. It is most important to focus on how to first modify the recovery time factors to identify cost-effective ways to improve the system performance and recovery before attempting to change (i.e., lengthen) the service recovery time objectives. The service recovery time objectives target societal needs for the water system services so extending these durations results in potentially not meeting the needs of the community. Therefore, this example will proceed with investigating how to modify the system assets and organizational actions while maintaining the target service recovery time objectives in Table 3-4a and 3-3b.

Reviewing the assessment identifies many needed modifications to the Centerville water system, including portions owned by the CWSC and CWD. Seismic improvements include, but are not limited to:

- Anchoring of equipment and tanks in all buildings and facilities.
- Strengthening the Rock River water supply pumping station and the floodplain wells and collector line against permanent ground deformation.

Table 3-10a. Comparison of Basic Service Recovery Times from System Assessment with Target Recovery **T**imes in Table 3-4a

BSC	Service Description	Target Recovery Time	Is Target Met?
Delivery	Restore to all customers	7 days	Yes
Quality	Restore to all customers	15 days	Yes
	Restore to 50 % of all customers	3 days	No
	Restore to 100 % of all Critical A Users	3 days	No
	Restore to 100 % of all Critical B Users	7 days	No
Quantity	Restore to high-volume commercial, industrial, and institutional users	7 days	No
	Restore average winter day demand to all customers	20 days	Yes
	Restore to pre-event normal demand (rationing removed)	30 days	No
Fire Protection	Restore to all hydrants within 0.81 km (0.5 mile) of Critical A Users and multi-resident users; within 1.61 km (1 mile) of any other area requiring fire protection.	3 days	No (not met for wastewater treatment plant and chlorination stations)
	Restore to Critical A & B Users having fire service at main service connections	3 days	Yes (in Z8, Z9, Z10, Z11, and community center and government offices)
	Restore to 90 % of hydrants	10 days	Yes
	Restore to all hydrants	20 days	Yes

Table 3-10b. Comparison of Basic Service Recovery Times from Supply Subsystem Assessment with Target Recovery Times in Table 3-4b

BSC	Service Description	Target Recovery Time	Is Target Met?
Delivery	Restore to CWD	1.5 days	No
Quantity	Restore average winter day demand to CWD	5 days	Yes
	Restore to pre-event normal demand (rationing removed)	25 days	No

- Strengthening the Rock River and floodplain water treatment plants against permanent ground deformation
- Strengthening the Rock River and floodplain transmission pumping stations against permanent ground deformation
- Strengthening the chlorine stations to resist shaking
- Improving lateral bracing for the elevated storage tank

- Developing seismic resilient transmission and distribution pipe networks [Davis, 2018] to support functional recovery similar to that described in Appendix A.
- Improving the water system headquarters building.

All the components should be designed to meet the Criticality Categories shown in Fig. 3-1. Additionally, more resilient pipelines need to be constructed across Rock River. The system is too vulnerable with only one transmission line crossing the river to provide the primary supply source to the east side of the city. This may most easily be accomplished by extending the east-west running trunk line in Rock Creek Road to the west side of the river and connecting it to the outlet line of the Rock River transmission pumping station. The asset modifications to meet the target basic service recovery times entail the improvement of component-level performances through robustness and some system layout modification to create more redundancies.

Additionally, some organizational actions may be modified to improve performance and service recovery times. Example modifications of organizational actions by the CWSC and CWD would include, but not be limited to:

- Improving emergency response plans incorporating how to manage activities on each side of Rock River when there are access constraints
- Undertaking emergency exercises using the earthquake event scenario described in Ch. 2, including multi-system exercises (i.e., involving water, wastewater, electric power, and other systems)
- Improving communications between other lifeline infrastructure systems and emergency management organizations
- Assessing the human resources for all aspects of the organizations to ensure they are adequate in number and sufficient in training to undertake their duties during a disaster, including ability to report to assigned locations on each side of Rock River
- Assessing materials, supplies, and finance capabilities for use during a disaster, including supply chain management during a disaster (e.g., fuel and chemical replenishment after an earthquake)
- For known vulnerabilities requiring post-earthquake repairs (e.g., distribution pipelines), identifying and practicing prioritization, adaptation, and repair strategies that can reduce the time to recover services
- Incorporating the Criticality Categories and redundant components into the CWSC and CWD asset management program so that they are embedded into all future reviews and evaluations
- Developing other plausible earthquake event scenarios to assess

It is beyond the scope of this example to provide detailed guidance on how to modify the assets and organizational actions to meet the performance objectives. The main point is to show that once the comparison of service recovery time objectives is made and system modifications are needed, the process is iterated to identify which changes may be made to portions of the assets and organization. These are then designed in accordance with the framework and another assessment and comparison made. The process is continued until the performance and recovery time objectives are met. If in special cases, after investigating all options for modifying the assets and organizational actions, some objectives cannot be met for cost or logistical reasons, they may be revisited, coordinated with the community and all critical customers, and modified if appropriate as described in Volume 1 Chapters 3, 4, and 5.

3.13 Step A11: Report System Assessment Results

The system assessment along with the results are documented and filed in a safe place for future reference and use by the CWSC and CWD. An important aspect of reporting is to ensure all the appropriate findings can be put into practice. The reported results should be used as feedback for decision makers and the planning process as described in Volume 1 Sec. 3.1. The modifications identified in Step A10 are to be described in the CWSC and CWD pre-earthquake mitigation plans, prioritized, budgeted, and implemented. The results should be used to update emergency management and emergency operations plans, continuity plans, asset management plans, seismic mitigation programs, and capital investment strategies and plans. Additionally, the results may be used to improve and update comprehensive or master plans, state and local hazard mitigation plans, recovery plans, and resilience plans. The final list of improvements and the basic service recovery time objectives presented in Tables 3-4a and 3-4b are presented to the public so that they are aware of what water system improvements are taking place and the anticipated durations at which basic services may be disrupted during similar future earthquakes.

4. WASTEWATER SYSTEM EXAMPLE

4.1. Introduction

4.1.1. Purpose of Example

This chapter presents an application of the proposed assets framework presented in Volume 1, published as NIST SP 1310 [NIST, 2024], Ch. 4 to a fictional wastewater system providing services to the Centerville community described in Ch. 2. The chapter also identifies how the proposed organizational actions framework presented in Volume 1 Ch. 5 supports the assets framework to achieve functional recovery.

Section 4.1 presents preliminary information and an overview of the wastewater system. Section 4.2 establishes the basic service recovery time objectives. Sections 4.3 through 4.13 are coordinated with the steps introduced in Volume 1 Ch. 4 for the assets framework to illustrate the application for each individual step. As part of this process, some portions of the steps are developed for general use to any wastewater system while illustrating how the framework steps are implemented specifically for the example fictional Centerville wastewater system.

4.1.2. Wastewater System Overview

The purpose of a wastewater system is to provide safe and reliable wastewater removal for the community. Wastewater systems provide collection and disposal for domestic, commercial, and industrial buildings and facilities, including critical services, emergency operations and shelter centers, and other lifeline systems.

In general, a wastewater system consists of four main subsystems and the components presented in Table 4-1. Table 4-1 provides a relatively comprehensive list of potential components that may make up each subsystem within any wastewater system, including those combining stormwater. The following notes apply to Table 4-1:

- Pump stations and treatment systems have their site-specific subsystems made up of mechanical, electrical, and civil-engineered subsystems and components.
- Instrumentation and monitoring are integrated into all subsystems. Supervisory Control and Data Acquisition (SCADA) systems are used to monitor and operate wastewater systems.
- Buildings and facilities, including central headquarters, operation and maintenance yards, pump station housings, treatment and disinfection system housings, and other components are also a part of the systems.

Table 4-1. Major Wastewater Subsystems and Typical Components [from NIST, 2016]

Subsystems	Description	Typical Facilities / Components
Collection subsystem	Networks for collecting wastewater from domestic, business, industrial, and other customers.	All piping, manholes, pumping stations, force mains, and other components that are not defined as part of another system and form a network from customer connections to points in the conveyance system, including service connections and laterals. Specific storm drainage facilities: laterals, drains, catch basins, channels, curb and gutter, and streets.
Conveyance subsystem	Systems for conveying raw sewage or stormwater. Raw water conveyance systems, sometimes referred to as trunk line or interceptor line systems, convey sewage and stormwater from, or within, service areas to points of treatment.	Pipelines, force mains, tunnels, interceptors, pumping stations (influent and satellite), manholes, drop and riser shafts, surge chambers, gates and valves, storage tanks, and chambers. Specific storm drainage facilities: catch basins, drains, culverts, channels, curb and gutter, and streets.
Treatment \subsystem	Systems for treating and disinfecting sewage and stormwater to make it safe for disposal or recycling/ reclaiming water.	Treatment plants, screens, grit chambers, sedimentation basins and tanks, bio-treatment, clarifiers, filtration systems, galleries, ponds and lagoons, chlorine or other chemical disinfectant facilities, chlorination stations, pump stations not related to conveyance and discharge systems, digesters, solids processing.
Disposal subsystem	Systems for discharging or disposing of treated sewage and stormwater or for dispersing treated water for use by customers or long-term storage. In some cases, these systems may also discharge untreated or partially treated sewage or stormwater.	Outfalls (ocean, sea, lake), river and creek outlets, levees, diffusers, gates and valves, flaps, disposal pumping stations, weirs, channels, recharge basins (for reuse), septic systems, and leach fields. Transmission lines to customers or storage locations that provide an interface with water systems where recycled water is used from wastewater treatment plants and stormwater collection sources).

4.1.3. Centerville Wastewater System

Consistent with the summary description of the Centerville wastewater system in Sec. 2.4.2, the system operates separately from the stormwater collection system and consists of the same four main wastewater subsystems outlined in Table 4-1 but with a subset of the components. Table 4-2 outlines the subsystems and lists the components of the Centerville wastewater system. The Centerville wastewater system aims to represent realistic conditions but is intentionally simplified to illustrate how the proposed framework in Volume 1 may be implemented.

The main features and important characteristics of the Centerville wastewater system example are as follows.

Collection subsystem:

- 11 main collection areas from service zones Z1 to Z11, plus other local service connections to one hospital, two fire stations, and three schools.

- There are approximately 418.4 km (260 miles) of sewer mains.
- The property service connections, sewer laterals, and main sewer lines follow the surface street grid in each of the zones Z1 to Z11.

Conveyance subsystem:

- Approximately 56.3 km (35 miles) of buried trunk lines.
- All trunk lines, with one exception, run by gravity and are designed for a depth ratio of 0.6 to 0.7.
- Close to the Rock River, one pump station (known as the Rock River Wastewater Pump Station, RR-WPS) followed by a force trunk is used to move sewage from the west side of the river to the east.
- The wastewater from the fire station between zones Z7 and Z6 is pumped via a force main to the trunk line running south on Jenkins Ave. The pump station is called the North Fire Station Wastewater Pump Station (NFS-WPS).
- A pump station at Rock River.

Treatment subsystem:

- The treatment plant is located in the light industry zone Z11.
- The treatment plant is fed by one trunk line which collects all the sewage from the entire city.

Disposal Subsystem:

- The outfall system extends into the Rock River from the treatment plant.

Equipment in the pumping stations is seismically anchored while only some of the equipment in the treatment plant is seismically anchored.

The Centerville wastewater subsystems include collection, conveyance, treatment, and disposal systems as described in Table 4-2. This wastewater system is a municipal utility owned and operated by the Centerville Department of Sanitation (CDS) that treats the wastewater and disposes it into the Rock River. Other agencies may obtain and treat the wastewater to sufficient quality for reuse, which could be an extension of the wastewater system through additional reclaimed water treatment and conveyance subsystems that are owned and operated by other agencies. This example does not include any reclaimed treatment or conveyance subsystems.

4.1.4. Wastewater System Basic Service Categories

Table 4-3 describes four Basic Service Categories (BSCs) identified for this wastewater system. The system or portion of the system meeting the service description in Table 4-3 for each category is considered to have the BSCs provided to the customer after an earthquake. The wastewater system normally provides many additional levels of service (e.g., IPWEA, 2015; LGAM, 2019) daily, in addition to those presented in Table 4-3. If services are lost due to damage caused by an earthquake, the primary objective is to restore the BSCs given in Table 4-3.

Table 4-2. Centerville Wastewater Subsystems and Components

Subsystems	Description	Typical Facilities / Components
Collection subsystem	Networks for collecting wastewater from domestic, business, industrial, and other customers.	Property service connections, sewer laterals, main pipelines, and manholes transferring sewage from Z1 to Z11 to points in the conveyance system. Laterals and mains include 418.4 km (260 miles) of PVC pipelines ranging from 15.24 cm to 30.48 cm (6 in to 12 in) in diameter
Conveyance subsystem	Systems for conveying raw sewage water. Raw sewage water conveyance systems, sometimes referred to as trunk line or interceptor line systems, convey sewage from, or within, service areas to points of treatment.	Approximately 56.3 km (35 miles) of buried concrete trunk lines with diameters ranging from 0.61 m to 1.83 m (2 ft to 6 ft), Rock River wastewater pumping station, Rock River force main, and the 1.83 m (6 ft) interceptor sewer to the Centerville treatment plant.
Treatment subsystem	Systems for treating and disinfecting sewage water to make it safe for disposal or recycling water.	Centerville treatment plant
Disposal subsystem	Systems for discharging or disposing of treated sewage or for dispersing treated water for use by customers or long-term storage. In some cases, these systems may also discharge untreated or partially treated sewage.	Outfalls to Rock River

Table 4-3. Wastewater System Basic Service Categories (modified from Davis, 2014b; NIST 2016)

Basic Service Category	Description of Service
Wastewater Collection/Removal	The system can collect and remove wastewater at the customer service connections but may not collect the quantity without sewage overflow (rationing needed), the system may not be able to treat collected wastewater to meet quality standards or properly dispose of wastewater at pre-event volumes, or meet pre-event functionality (inhibiting system performance reliability).
Quality	Wastewater is treated to pre-event effluent quality using available processes and meets public health standards (including discharge permit conditions).
Quantity	Wastewater flow capacity from customer service connections meets pre-event conditions (water rationing removed).
Disposal	The entire wastewater volume can be disposed of, protecting the environment, and meeting discharge permit conditions (including containment within the pipe network).

Identification of BSCs for wastewater systems considers how an earthquake may cause sufficient damage to the network to result in complete loss of wastewater from some or all customers. For wastewater removed through the infrastructure networks, wastewater collection is the first step in service restoration from the customer's service connection and is a prerequisite for meeting the quality, quantity, and disposal services. The quality, quantity, and disposal service restorations may be accomplished in any order and possibly along with wastewater collection restoration but cannot be restored in advance of wastewater collection. Wastewater quality, quantity, and disposal services may be lost even if wastewater collection services are maintained.

Quality basic service is achieved when the minimum regulatory requirements are met, even if before an event the minimum requirements were exceeded. The goal for meeting the quality BSC definition can simply be to report when pre-event minimum conditions are re-established. This will allow communities to know when it is safe to engage in activities that produce wastewater (i.e., wastewater can be safely transferred to the infrastructure networks). This should be communicated to the public by the wastewater utility in agreement with public health officials.

Quantity is limited by the capacity of the wastewater system. Capacity is designed to meet domestic, commercial, and industrial demands. Capacity and hydraulic grade are considered simultaneously. In terms of BSCs, the system may be able to collect wastewater but not meet its design capacity, user demands, or pre-event amounts. Once the system is restored sufficiently (i.e., average flow capacity), or ideally to meet its pre-event amounts for a customer (i.e., peak flow capacity), it then meets the wastewater quantity basic service. The goal is to restore flow meeting pre-event conditions, or as near as possible, for all customers. Special attention should be dedicated to infiltration and inflow, which will reduce the effective volume of sewage that can be handled by the wastewater system. The restoration process may take into consideration different priorities in meeting peak demands and lower-level quantity demands; in some cases, meeting lower-level demands in advance of peak may allow more customers to receive the basic services sooner.

In a properly working system, the disposal service is interlinked with the collection service because the amount of water collected into the system must equal the amount of water disposed out of the system.

Quality, quantity, and disposal are the services provided by almost all the wastewater systems in the country, and resilient systems do not require these three services to be restored at the same time (i.e., quality does not necessarily have to be inhibited if the disposal service cannot be met – it depends on how the components and system are designed and constructed). Further, resilient wastewater systems can collect wastewater from at least some users in advance of meeting the quality, quantity, and disposal services. The collection allows users to continue some important activities like flushing toilets and cooking in advance of full wastewater service recovery and these interim uses improve community resilience.

Davis [2014b, 2021] and NIST [2016] provide additional information about wastewater system basic service categories.

The Centerville wastewater system has the same BSCs as presented in Table 4-3.

4.2. Identify System Performance and Recovery Time Objectives

The system-level performance objectives include all the criteria necessary to accomplish normal operations (i.e., operating flow rate, wastewater quality) and provide the services to each customer. A system-level seismic performance objective could be specified using parameters such as a maximum number of service losses and/or a recovery rate, a total number of damaged locations, post-earthquake inflow, and infiltration (e.g., from pipe joint separation), or other parameters, all of which are conditioned on the seismic event associated with the performance objective. However, there are no existing guidelines for how to establish these types of parameters for a system-level performance objective. FEMA P-2234 [2024] proposes future work to investigate the usefulness of preparing system-level performance criteria in terms of the number of customer service losses and recovery rate. Further research is needed to identify how to develop system-level seismic performance objectives for wastewater systems.

Since there are no existing guidelines for establishing system-level seismic performance objectives, none are specified in this wastewater system example. Instead, the system-level performance is identified as an outcome of the system layout and the performance of the individual components making up the built networks. The system-level performance is identified through the assessment process in Step A11.

FEMA P-2234 provides a framework for identifying target system-level recovery time objectives based on the earthquake event scenario size and available user adaptations. Unlike the water system example in Ch. 3, FEMA P-2234 does not complete an assessment for wastewater systems. As a result, there are no published recommended target basic service recovery times for wastewater systems readily available for use. As a result, Table 4-4 presents estimated plausible target wastewater system recovery time objectives for the BSCs given in Table 4-3 for the Level II earthquake event scenario described in Ch. 2. This is one of several recommended sets of earthquake event scenarios and associated service recovery time objectives a wastewater system should investigate as defined in Volume 1 Sec. 2-5 and FEMA P-2234. Only one earthquake event scenario and associated service recovery objectives is selected for this example.

Table 4-4. Target Wastewater System BSC Recovery Times for a Level II Earthquake Event Assuming User Adaptations are Applied

BSC	Service Description	Target Recovery Time
Collection	Restore to all Customers	15 days
	Restore to 100 % of all Critical A Users	3 days
	Restore to 100 % of all Critical B Users	7 days
Quality	Maintain disinfection for 100 % of flow	0 days
	Restore full treatment capacity	7 days
Quantity	Restore to all users under dry-weather conditions	7 days
	Restore average wet weather day demand to all customers	20 days
	Restore to pre-event peak wet weather capacity	45 days
Disposal	Restore to all customers	45 days

The quality, quantity, and disposal BSCs are closely tied for wastewater systems. Compliance with discharge permits is not optional and violating any of the permit conditions must be reported, with consequences to be accounted for. An essential goal of a wastewater system is to ensure that all wastewater that flows into the collection network is conveyed to and through the treatment plant and the outfall in all types of weather conditions (i.e., water in = water out). To achieve this all the subsystems in Table 4-2 must be able to handle the quantity flows described in Table 4-4 for the different times after the earthquake. Wet weather can increase the quantity of wastewater. Customers having discharges into the wastewater system that cannot be accommodated by any of the subsystems post-earthquake under any weather condition may need to reduce some of their activities causing the releases.

In an earthquake, it is possible for the treatment process to be disrupted, removing the ability to fully treat all the flow. However, as indicated in Table 4-4, for a Level II earthquake event all the wastewater is expected to flow to the treatment plant and at least be disinfected at all times (e.g., super chlorinated or other method) before disposal. Additionally, after 7 days the objective in Table 4-4 is to treat and dispose of all normal wastewater flows under dry weather conditions. In larger earthquakes (see Volume 1 Table 2-3) it may be more difficult for some wastewater systems to meet the water in = water out goal after the event, which may result in practical limitations preventing the quality, quantity, and discharge target basic service recovery times from being the same under any weather conditions.

The target service recovery time objectives in Table 4-4 assume the following user adaptations can be implemented; these are in addition to any adaptations made to the system. As a result, the organizational actions must incorporate the needed activities to ensure these user adaptations can be implemented throughout the service area by including them in the proper plans, coordinating with the correct agencies (i.e., Volume 1 Ch. 5 Step O3), and including them in emergency exercises. The user adaptations assumed to be implemented include:

- Reducing wastewater discharge. Includes water rationing.
- Delaying wastewater discharge.
- Temporary relocation (e.g., residents going to a hotel or a friend’s or relative’s house or a medical facility).
- Using a regionally redundant facility (e.g., alternate hospital, schools, grocery store having wastewater service)
- Canceling activities
- Providing portable toilets and hand washer units
- Providing portable shower units

The component-level performance and recovery time objectives are identified in Step A4. The component-level recovery time is a function of many locally specific factors described in Volume 1 Table 4-7.

4.3. Step A1: Define System Layout and Operational Characteristics

A short description of the Centerville wastewater system is presented in Sections 2.4.2 and 4.1.3. Fig. 4-1 shows the system layout. The collection subsystem is not shown due to scale issues, except for one sewer main from the emergency shelter. The focus of this example is on the trunk lines, pump stations, and the treatment plant. The component Critical Categories described in Sec. 4.4 are depicted in Fig. 4-1.

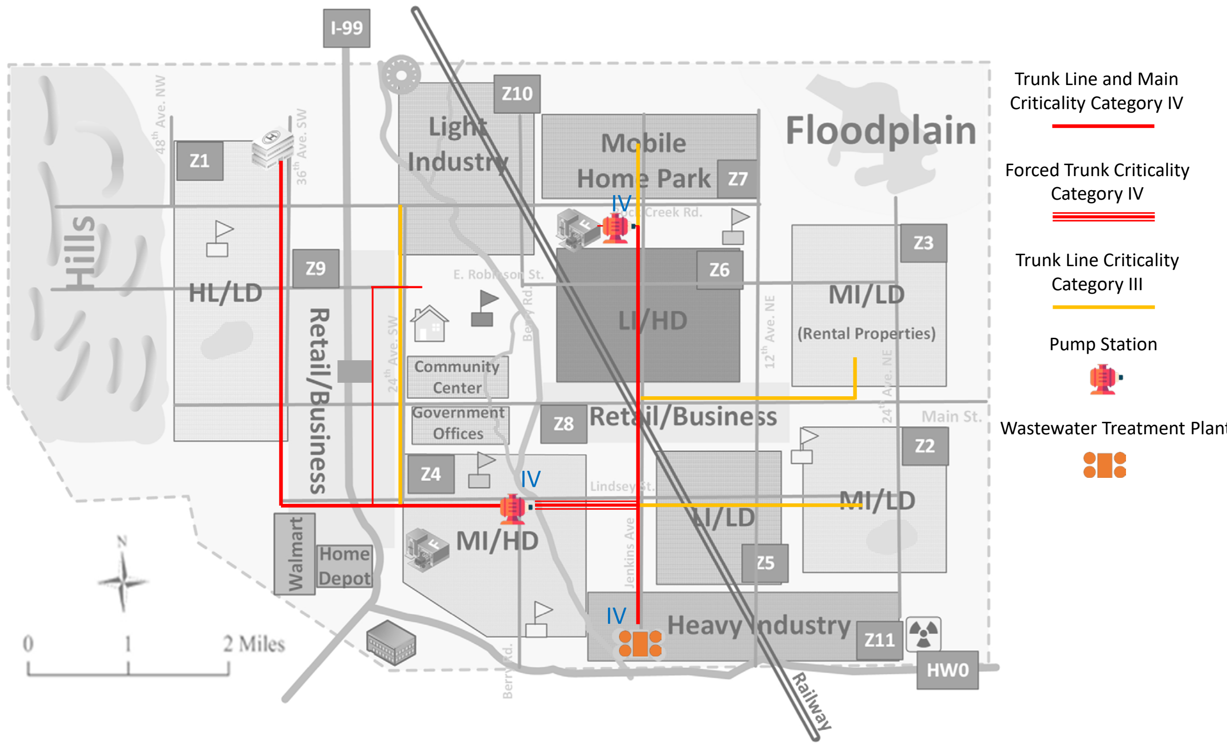

Fig. 4-1. Centerville wastewater system layout and assigned component Criticality Categories.

4.4. Step A2: Define Criticality Category and Earthquake Design Basis for System Components

The components making up the wastewater system described in Step A1 are all assigned a Criticality Category based on the importance of the customers and users the components are utilized to serve. The Criticality Categories are defined in Table 4-5 and are considered applicable to all wastewater systems. Volume 1 Table 4-2 is used to establish the recommended earthquake design basis. Fig. 4-1 shows the assigned component Criticality Categories for the Centerville wastewater system.

Criticality Categories illustrated in Fig. 4-1 are based on concepts described in Table 4-5. The trunk line that starts from the hospital in the northwest of the city and travels south parallel to 36th Ave. is categorized as Criticality Category IV. It should be noted that the hospital does not have on-site holding tanks to store sewage and liquid waste sufficient to operate essential hospital utilities and equipment. The trunk line turns near the Walmart at Lindsey St. and passes the RR-WPS pump station where it transfers to a forced trunk to meet the interceptor sewer at Jenkins Ave. The interceptor sewer transfers the entire sewage of the city to the wastewater treatment plant. All components on the path from the hospital to the wastewater treatment plant are labeled with Criticality Category IV.

The trunk line starting from the southwest of Z10 (Light Industry) follows 24th Ave. to meet the trunk line on Lindsey St. This trunk line does not collect the sewage from the Community Center and Government Offices which are used as the emergency operations facility. The latter is connected directly to the trunk sewer at Lindsey St. via a sewer main connecting the emergency shelter to the high school and the trunk line at Lindsey St. With this arrangement, the trunk line from zone Z10 to Lindsey St. is labeled as Criticality Category III.

Table 4-5. Wastewater System Component Criticality Categories (adapted from Davis [2005; 2008] and ALA [2005])

Criticality Category	Description
I	Components, in the event of failure, present a very low hazard to human life, no damage to property, and little to no effects on user's ability to perform their post-earthquake activities or functions. These components are not needed for post-earthquake system performance, response, or recovery. They typically serve small localized non-critical drain connections (yard or pool drains, etc.).
II	All components not identified in Criticality Categories I, III, and IV. These typically are normal and ordinary components not used for pumping, conveyance, or treatment. This includes commercial, some non-commercial, and industrial buildings not needed for essential emergency response or initial recovery and include.
III	Components providing wastewater services that represent a substantial hazard or mass disruption to human life in the event of failure, including significant levels of property damage. An extended operational outage of these components may result in significant social or economic impacts and cause significant effects on users' ability to perform their activities or functions. Operational disruption of these components causes long delays in post-earthquake system response or recovery. These components are needed to provide for collection, pumping, and conveyance from Critical B Customers/Users. Buildings and structures necessary for interacting with customers and users like customer service offices.
IV	Components providing wastewater services to essential facilities for post-earthquake response, public health, and safety. These components are intended to remain operable during and following an earthquake. These also include all components in the wastewater collection chain, including mechanical and electrical equipment, for Critical A Customers/Users. Additionally, this category includes components, if damaged, that may result in secondary disasters potentially impacting life safety or public health, impeding emergency response and operations, impeding evacuation routes, or disruption to other lifeline infrastructure systems. Buildings and structures necessary for performing essential and support functions by the lifeline infrastructure system organization, and facilities containing hazardous chemicals.

The pump station after Rock River (RR-WPS) feeds to a forced trunk to carry the sewer uphill and into the trunk line on Jenkins Ave. These are Criticality Category IV components. Once the forced trunk meets the trunk line on Jenkins Ave., it feeds the interceptor to the wastewater treatment plant and is labeled as Criticality Category IV.

The sewer main from the emergency shelter to the trunk line at Lindsey St. is labeled as Criticality Category IV.

On the east side of the city, the trunk lines connecting zones Z7, Z3, Z2, and Z5 to the trunk line on Jenkins Ave. are labeled as Criticality Category III. These trunk lines provide service to single- and multi-family residential zones.

The sewage from the fire station on the north side of the city, alongside the wastewater from zone Z10 east of Rock River, is carried by a forced sewer main to the trunk line on Jenkins Ave. NFS-WPS pump station provides the required head and draws power from the fire station. The forced main and NFS-WPS are labeled Criticality Category IV. The trunk line on Jenkins Ave. from the forced main to the treatment plant is labeled Criticality Category IV due to continuity.

Figure 4-1 does not include all the sewer mains within the system to simplify the diagram. Each zone has a network of sewer mains that collect sewage from the customers and convey it to the trunk lines shown in Fig. 4-1. Appendix A describes how a resilient sewer main network is created using the principles described in Table 4-5. Some zones consist entirely of the same Critical Customer type (e.g., all residential and schools having Critical Customer B types) resulting in the zone being entirely made up of sewer mains with the same Criticality Category (e.g., Criticality Category III). Other zones are made up of multiple Critical Customers (e.g., Critical Customers A, B, and C) resulting in sewer mains within the zone being a mix of Criticality Categories (e.g., Criticality Category II, III, and IV sewer mains). The Criticality Categories for the collection network within each zone can be defined similar to as described in Appendix A.

Table 2-3 defines the intensity measures for each earthquake hazard in Centerville for each component Criticality Category.

4.5. Step A3: Check Multiple Use, Continuity, and Redundancy

Per the discussion provided in Volume 1 Sec. 4.5.1, components that service multiple users shall be classified using the highest Criticality Category based on their intended use. The wastewater system components (as shown in Fig. 4-1) are assigned the highest Criticality Category for the customers and users to whom they provide service. The description presented in Step A2 in Sec. 4.4, and also in Appendix A, articulates the logic behind this assertion. In particular, the trunk line transferring sewage from the hospital down 36th Ave. is labeled Criticality Category IV solely because it serves the hospital. Otherwise, it should have been labeled as Critical Category III. The extension of this line to RR-WPS, the following forced main, and the interceptor down Jenkins Ave. are subsequently labeled as Criticality Category IV. With the same logic, the trunk line on Jenkins Ave. from its intersection with the forced main (from the fire station) to the wastewater treatment plant is labeled Criticality Category IV due to continuity from the forced main carrying the wastewater from the fire station.

The are no redundancies embedded in the wastewater system design. Consequently, there is no reduction in Criticality Category designation for its components.

Appendix A provides additional examples of continuity for wastewater system components.

4.6. Step A4: Establish Component Objectives - Maximum Level of Damage and Return to Operation Time

4.6.1. Target Maximum Component Damage

Volume 1 Table 4-4 defines the component-level performance objective in terms of tolerable component damage. Table 4-6 provides guidance descriptions of the expected damage levels related to the terms identified in Volume 1 Table 4-4 for newly designed and constructed or existing components in a wastewater system. These damage descriptions follow the general descriptions given in Volume 1 Table 4-5 and can be applied to any wastewater system, including those combined with stormwater.

Hazus [FEMA, 2022] uses damage descriptions for None, Slight, Moderate, Extensive, and Complete as part of their fragility functions. Their descriptions can be correlated to the Minor, Moderate, High, and Severe descriptions above which are based on the damage descriptions by ICC [2022].

Table 4-6. Wastewater System Damage Level and Summary Descriptions

Damage Level	Summary Description
Minor	Minimal to no perceivable damage to wastewater system components. Limited to no effects on wastewater system operations; able to continue essential emergency operations and most normal operations. For facilities[a], this damage level is equivalent to the Immediate Occupancy Structural Performance Level and Operational Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the minor level buildings and structures that are a part of the wastewater system have minimal to no damage to their structural and essential nonstructural components. Buildings are safe to occupy and able to continue essential emergency operations. Injuries to building occupants are minimal in number and minor in nature. Nonstructural systems, including mechanical and electrical equipment, needed for normal building use and emergency functions are fully operational but may require adjustments for external utilities (e.g., water, wastewater, power, communications), which may need to be provided by alternative emergency services. Damage to building contents is minimal in extent and minor in cost. Minimal hazardous materials are released into the environment. Pumping, treatment, and disposal facilities remain operable and may require some minor repairs. There is little to no damage to mechanical and electrical equipment. Tanks, dams, levees, and reservoirs have minor damage that may warrant investigation due to safety precautions but do not result in safety concerns or any significant limitations to the operations of the wastewater system. Trunk lines and their appurtenances have minor to no perceivable damage and transmission operations are not affected. Wastewater collection pipelines and appurtenances have minor damage, resulting in very few leaks and breaks that are easy to repair without impacting many customers. Tunnels and channels have minor to no damage requiring little to no repair (e.g., minor concrete cracking). Changes to the hydraulic grade are insignificant and transmission operations are not affected.

[a] Buildings and facilities that are part of the wastewater system.

Table 4-6. Wastewater System Damage Level and Summary Descriptions (continued)

Damage Level	Summary Description
Moderate	Damage is repairable. There may be some delay in re-occupying buildings[1]. Essential emergency functions are fully operational. Emergency systems remain fully operational. For facilities[a], this damage level is equivalent to the Damage Control Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the moderate level, for buildings that are a part of the wastewater system, structural damage is repairable, and some delay in re-occupying buildings is expected. Nonstructural systems needed for building use and essential emergency functions are fully operational, although some cleanup and repair may be required. Adjustments for external utilities (e.g., water, wastewater, power, communications) may be needed by alternative emergency services. Emergency systems remain fully operational. Injuries to building occupants may be locally significant but are generally moderate in number and in nature; the likelihood of a single life loss is low and the likelihood of multiple life loss is very low **[**ICC, 2022**]**. Some hazardous materials are released to the environment, but the risk to the community is minimal. Pumping, treatment, and disposal facilities may be damaged requiring temporary removal from operation for limited repairs, but not on an emergency basis (i.e., can remain operable following the earthquake, but a temporary shutdown may be warranted within days to weeks after the event). Similarly, there is limited damage to mechanical and electrical equipment, but not to the extent that wastewater system operations are seriously impacted (e.g., some equipment may require repairs but can be undertaken without serious disruption to operations). Tanks, dams, levees, and reservoirs may have some damage that may warrant immediate investigation due to safety precautions and some repairs but have limited to insignificant impacts on operations. Trunk lines and appurtenances may have minor leaks that require shutdown and repairs, but no serious structural damage, breaks, or significant flooding from the pipelines. Critical and essential mainlines will behave similarly to trunk lines. Wastewater collection pipeline networks may have several leaks and breaks, potentially locally impacting services provided to customers. Tunnels and channels have moderate to minor damage requiring little to some limited repair (e.g., concrete patching), but no serious structural defects requiring immediate shutdown. Possible changes to the hydraulic grade are minimal and transmission operations are not affected.

[a] Buildings and facilities that are part of the wastewater system.

Table 4-6. Wastewater System Damage Level and Summary Descriptions (continued)

Damage Level	Summary Description
High	Significant damage is expected. Structural damage to components may be repairable. For facilities[a], this damaging level is equivalent to the Life-Safety Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the high level, for buildings that are a part of the wastewater system, significant damage to building structural elements, but no large falling debris, is expected. Repair of the structural damage is possible, but significant delays in re-occupancy can be expected. Nonstructural systems needed for normal building use are significantly damaged and inoperable. Emergency systems may be significantly damaged but remain operational. Injuries to building occupants may be locally significant with a high risk to life but are generally moderate in number and nature. The likelihood of a single life loss is moderate, and the likelihood of multiple life loss is low [ICC, 2022]. Hazardous materials are released to the environment and localized relocation is required [ICC, 2022]. Pumping, treatment, and disinfection facilities may be significantly damaged removing them from operation until repairs are completed. Similarly, damage to mechanical and electrical equipment may require extensive repairs or replacement. Tanks, dams, and reservoirs may show observable and significant damage warranting immediate investigation and potential removal from use due to safety precautions but do not pose a threat of a catastrophic release of wastewater. Trunk lines and appurtenances may have significant structural damage, but either retain their pressure boundaries or have limited leakage, requiring them to be shut down for repairs. Critical and essential mainlines will behave structurally similar to trunk lines but may be drained due to other distribution pipe damages. Wastewater collection pipeline networks may have many leaks and breaks, potentially locally impacting services provided to customers. Tunnels and channels can have serious damage requiring them to be removed from use for repair. Changes to the hydraulic grade are significant and transmission operations are affected.
Severe	Substantial damage is expected. Repair may not be technically feasible. For facilities[a], this damaging level is equivalent to the Collapse Prevention Structural Performance Level and Hazard Reduced Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the severe level, for buildings that are a part of the wastewater system, substantial building structural damage is expected, and repair may not be technically feasible, though all significant structural components are intended to continue carrying gravity load demands. Partial or total collapse is possible [ASCE, 2023]. The building is not safe for re-occupancy because re-occupancy or aftershocks could cause collapse. Nonstructural systems for normal building use may be inoperable, and emergency systems may be substantially damaged and inoperable. Injuries to building occupants may be high in number and significant in nature. Significant hazards to life may exist. The likelihood of life loss is high. Large amounts of hazardous materials may be released into the environment and relocation beyond the immediate vicinity is required [ICC, 2022]. Tanks, dams, levees, and reservoirs have signs of severe distress and may be leaking or even releasing large volumes of water; they require immediate drainage of any retained water to ensure the safety of downstream properties. Trunk lines and appurtenances have ruptured requiring immediate shutdown for repairs and releasing significant amounts of wastewater onto the ground surface and/or resulting in backup and flooding of properties. Pumping facilities are severely damaged, and unlikely operable; required repairs are extensive and may not be feasible. Mechanical and electrical equipment is not usable. Distribution pipeline networks have a great number of leaks and breaks, impacting services provided to a large number of customers. Tunnels and channels can have substantial damage where repairs may not be feasible, requiring complete reconstruction. Changes to the hydraulic grade are severe resulting in halting some transmission operations.

[a] Buildings and facilities that are part of the wastewater system.

4.6.2. Target Return to Operation Time

The target time increments for returning components to operation within the Centerville wastewater system are identified in Volume 1 Table 4-6.

To aid the preliminary design in Step A6, each physical component should have a potential repair time estimated and then added to any expected or assumed time increment after the earthquake to initiate work plus lead times as described in Volume 1 Sec. 4.6.2. In Step A7, the resulting estimated time is compared to Volume 1 Table 4-6. For example, consider a trunk line buried deeply (e.g., 6 m to 9 m) below a very narrow and busy street and all repairs must be made external to the pipeline due to internal access constraints. If the trunk line experiences moderate damage in an earthquake, it may take a week or more to repair. This time increment is longer than what is identified for a Criticality Category III component experiencing a 975-year return period earthquake hazard per Volume 1 Table 4-6. As a result, a Criticality Category III pipeline having these specific site conditions may need to be designed to a higher-level standard.

The repair time increment objectives therefore represent another type of acceptance criterion for newly designed and constructed or the retrofit of existing components in a wastewater system. The repair time increment objectives may be taken strictly during component design or incorporated into a broader system-level analysis in Step A9. Following a system analysis, if the basic service recovery times are shown to be met, even if the component recovery time increment exceeds the target duration in Volume 1 Table 4-5, then the component design may be deemed acceptable.

Due to simplifications, recovery time increments for all components in the Centerville example are not prepared, and the preliminary designs in Step A6 conform with Volume 1 Table 4-6. Wastewater systems are recommended to consider specific component conditions when applying the framework.

4.7. Step A5: Identify Dependent Services

The wastewater system is dependent upon services from other lifeline infrastructure systems identified in Table 4-7. These dependencies are identified for the Centerville example. Additional dependencies may be identified for wastewater systems in general.

Table 4-7. Wastewater System Component Dependencies

Component/Activity	Dependent upon services from System
Pumping station	Electric power
Treatment plant	Electric power, chemical/transportation, cogeneration, solids treatment (digester gas)
Collection subsystem	Water
Emergency generators	Liquid fuels
Vehicles (damage inspection and repair)	Transportation Gas fuels Liquid fuels

4.8. Step A6: Develop Preliminary Design

This example starts with evaluating the hypothetical existing Centerville wastewater system. The design and construction of the existing wastewater system were accomplished without the component- and system-level consideration for functional recovery. Accordingly, the existing wastewater system is treated as a preliminary design for the purpose of investigating performance in the context of functional recovery in this example.

4.9. Step A7: Assess Component Performance and Repair Time, Compare with Target Objectives

An investigation of the as-built trunk line drawings for the Centerville wastewater collection system reveals that they are not expected to be damaged for the design-level transient ground motions. The buried trunks are not expected to be subjected to excessive permanent ground deformations. In locations where lateral spreading is anticipated to occur, most of the trunk lines are buried deeper than the expected depth of movement. In addition, the design can handle small ground movements up to several cm of horizontal and vertical displacements without damage.

The anchorage of the mechanical equipment in the treatment plant (e.g., pumps, tanks, content), and in pumping stations (e.g., pumps), are not designed according to recent ASCE 7 [ASCE, 2022] requirements. The few available as-built drawings, supported by sporadic site visits, have validated this deficiency. The Centerville hospital does not have on-site holding tanks to store sewage and liquid waste sufficient to operate essential hospital utilities and equipment for three days.

Volume 1 Table 4-4 identifies the target maximum level of component damages based on Criticality Categories. Accordingly, the Criticality Category IV trunk lines should not experience more than moderate damage; Criticality Category III trunk lines are not to exceed moderate to high damage. Using Table 4-6 identifies how both requirements are met according to the trunk line as-built drawings. However, the wastewater collection system does not have any redundancies to reroute sewage in case of minor leaks.

The lack of on-site holding tanks to store hospital sewage and the precarious nature of equipment anchorage in the pump stations and the treatment plant are major deficiencies. According to Volume 1 Table 4-4, moderate damage is tolerable for equipment in the treatment plant and pump stations (all Criticality Category IV), but the damage is highly likely to be at high or severe levels when subjected to the design level earthquake intensities (i.e., 2,475 years average return period).

Volume 1 Table 4-6 provides input about target time increments for repairing components thereby returning them to operation. The trunk lines should be repaired and be operable within a few days (i.e., around 1 to 3 days). These requirements are expected to be met, and possibly exceeded, by the Centerville wastewater trunk lines. However, the issue of equipment anchorage and lengthy repair time of potentially weeks would jeopardize the return to operation time constraint of a few days necessary to meet the basic service recovery times in Table 4-4 for the pump stations and the treatment plant. Consequently, path ‘No’ is followed in Volume 1 Fig. 4-1a for the equipment.

4.9.1. Design Revision

The equipment anchorage in RR-WPS and NFS-WPS pump stations and the treatment plant have identified deficiencies leading to nonconforming damage and repair time constraints detailed in Volume 1 Tables 4-4 and 4-6, respectively. These deficiencies led to following the path 'No' in Volume 1 Fig. 4-1a back to Step A4, Establish Asset Objectives - Maximum Level of Damage and Return to Operation Time. There are no changes to the component performance objective, which leads to following the path on the flowchart to Step A6, Develop Preliminary Design. This triggers the rehabilitation of the equipment anchorage at the pump stations and the treatment plant to bring them up to the current ASCE-7 [ASCE, 2022] design levels.

With the suggested design revision, the revised preliminary design of the Centerville wastewater pump stations and treatment plant would meet the target maximum damage and return to operation time for returning components to operation outlined in Volume 1 Tables 4-4 and 4-6. Consequently, path 'Yes' is followed in Volume 1 Fig. 4-1a, which allows a system-level evaluation to be performed using Volume 1 Fig. 4-1b.

4.10. Step A8: Identify Recovery Time Factors

The recovery time factors described in Volume 1 Sec. 4.10 are reviewed. They are all applicable to the Centerville wastewater system and will be assessed as part of Step A9. No additional dependencies to those listed in Table 4-7 were identified.

4.11. Step A9: Assess System Performance and Recovery Time

The Centerville wastewater system is evaluated using the earthquake event scenario outlined in Sec. 2.7. This assessment incorporates the recovery time factors identified in Step A8 and determines how long it will take to recover the basic services so that they can be compared with the objectives in Table 4-4.

The five damage locations, identified as D1 to D5 in Table 4-8, are illustrated in Fig. 4-2. The extent of damage is limited given the updates in the wastewater treatment system described in Sec. 4.9.1. This assessment assumes the previously identified design improvements are incorporated into the network. However, the damage experienced is mainly due to a lack of efficient design of the existing infrastructure. This assessment is streamlined to illustrate how to implement the framework and is limited only to portions of the conveyance and treatment system. Actual systems may experience more or less damage than described in this assessment. The effects of the earthquake hazards on the Centerville wastewater system are described in the following subsections. The descriptions identify the damage number in Fig. 4-2 and Table 4-8 in brackets [**Dx**].

Table 4-8. Summary of Expected Damage to Wastewater System

No	Component	Damage	Repair Time	Repair Description
D1	Trunk line elbow at 36th St. and Lindsey Ave.	Leak	3 days	Replace bend
D2	Sewer main emergency shelter	Pull-out of pipe joints due to liquefaction	1 month	Clearing debris, and repair of washrooms
D3	RR-WPS pump station	Pumps unusable, electrical node down	1 day	Add pumps with liquid fuel and fuel tanks
D4	Wastewater treatment plant	Disinfection and other chemical depleted due to damage to the off-ramp on HW0 not allowing delivery trucks to pass	Unknown	Temporary repair of the off-ramp
D5	Wastewater treatment plant	Mechanical damage in one of the primary clarifiers	7 days	Repair of mechanical equipment

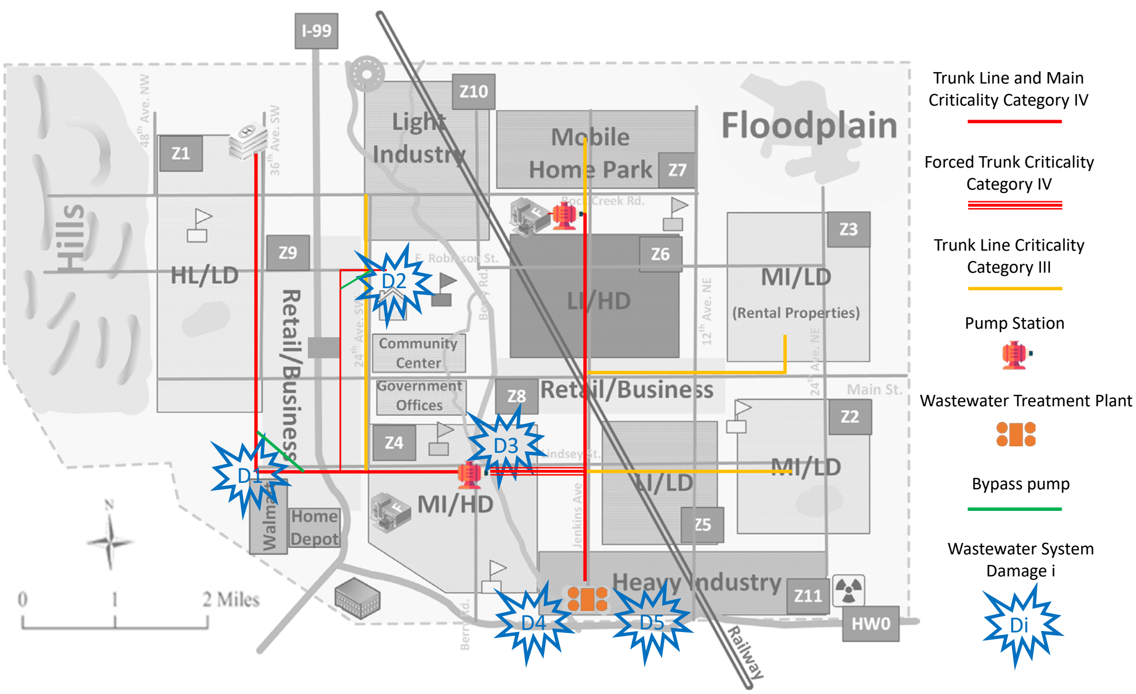

Fig. 4-2 Centerville wastewater system damage locations.

4.11.1. Earthquake Effects on the Centerville Wastewater System and Loss of Services

4.11.1.1 Damage

The trunk line at the intersection of 36th Ave. and Lindsey St. is damaged at the elbow connection [**D1**]. This damage is due to a vulnerable pipe connection and the relatively large ground strains. This damage results in loss of service to Centerville Hospital, zone Z1, and zone Z9. The trunk line on 36th Ave. is Criticality Category IV because it provides service to the Centerville Hospital.

The wastewater collection sewer main running from the emergency shelter is damaged from the pull-out of the pipe segments [**D2**] due to liquefaction-induced permanent ground movements. The damage is local but extensive. The damage results in loss of service to the emergency shelter. The sewer mains were not reviewed along with the trunk line as-builts as described in Step A7.

[**D3**] is the damage to the electrical power node at the location RR-WPS pump station. The damage is not directly to the pump station, rather, it is damage to a portion of the line connecting to the electric power distribution grid to which the wastewater system is dependent. This line is part of the wastewater pumping station system and not part of the electric power network (i.e., it is on the customer side of the connection to the electric power network). However, due to its location, the problem is difficult to identify. This damage results in compounding the same loss of services as from [**D1**] with additional loss of service to Walmart, Home Depot, Southside Fire Station, zone Z9, and the high school. All loss of services are from Criticality Category IV components with an unknown time for permanent repair, but a system adaptation is completed within one day.

Due to seismic shaking, the off-ramp on HW0 is damaged [**D4**] and would not allow delivery trucks carrying important chemicals for the wastewater treatment plant to pass. This is another damage related to the dependency of the wastewater system on another infrastructure system. At the time of the earthquake the treatment plant has enough chemical storage to last seven days; after which the plant will need to shut down.

The mechanical apparatus in one of the primary clarifiers of the treatment plant is damaged [**D5**]. The envisioned repair time is 7 days. Because the treatment plant has two primary clarifiers with reduced flow there is no loss in wastewater quality service.

4.11.1.2 Dependencies

In addition to the dependencies identified in Sec. 4.11.1.1, damage to the water system described in Ch. 3 led to a reduction in activities generating wastewater. This reduction was enforced through water rationing, requiring nonessential customers to cut their water usage by 75 % of normal levels (see Sec. 3.11.1). As a result, the amount of wastewater generated decreased proportionally. The road network was significantly affected by the damage, which in turn impacted the ability of the wastewater system field groups to carry out inspections, initiate repairs, and restore normal operations. In summary, the damage to the water and wastewater system, as well as the road network, had a significant impact on wastewater generation.

4.11.1.3 Service Losses

The earthquake damage to the wastewater system described in the Sec. resulted in losses in the collection basic service to the Centerville Hospital, emergency shelter, Walmart, Home Depot, Southside Fire Station, high school, and all of zones Z1and Z9.

4.11.2 Response and Service Restoration

To ensure the functionality of the hospital, the discontinuity in the trunk line from the hospital to the treatment plant due to damages [**D1**] and [**D3**] must be remedied. The solution employed to resolve damage [**D1**] (i.e., elbow at 36th St. and Lindsey Ave.) is to place bulkheads inside the pipeline on each side of the bend and use a bypass pump. This solution is accomplished within 3.5 days after the seismic event. The damage was not immediately observable, but once identified crews were able to set up the bulkheads and pumps in a relatively rapid manner. In the meantime, the sewage collection service was hampered on the west side of Centerville requiring the deployment of numerous portable toilets around the area. [**D1**] and [**D3**] also severely hampers sanitation and operations at the hospital, preventing many healthcare activities. After initiating the temporary bypass pumping, the construction crews proceed to fix the trunk line elbow, which takes at least 7 days given the size and location. The sewage collection service was resumed once the temporary bypass pumping was initiated at 3.5 days.

Damage [**D3**] is to the RR-WPS pump station; the electric pumps (two pumps, trunk line, and auxiliary) in RR-WPS are unusable due to damage to the electrical power node. Due to its location, it takes extra time and effort to identify the problem and who is responsible for making repairs. As a result, a decision is made to deploy portable emergency diesel generators as the most practical solution to bring the pump station back to operation. This system adaptation is accomplished within 1 day when the sewage collection services upstream of this pumping station were resumed, except for those inhibited by [**D1**].

Damage [**D2**] essentially makes the emergency shelter unusable. Portable toilets are deployed; however, the emergency shelter has severe limitations in supporting the community and requires people to move to the other possible emergency shelters resulting in overcrowding at those locations. The extent of the damage requires at least a month to repair the pipeline. As an alternative, a system adaptation is pursued to install a temporary sump outside the shelter and pump using a temporary bypass line around the damaged sewer main. This effort takes over 3 days to complete the resumption of the sewage collection basic service. As a result, the emergency shelter operates with severe limitations and is required to address sanitation concerns for more than three days until the temporary sewer bypass line is installed. After which the overcrowding at other emergency shelters is relieved by making full use of this location.

The storage capacity of the chemical tanks at the wastewater treatment plant can manage the plant's full operation for up to three weeks. However, at the time of the seismic event, the available chemical storage is adequate for seven days of full operation. While this amount is adequate to maintain functionality immediately after the event, it is important to devise solutions for the continued operation of the plant. Given [**D4**], damage to the off-ramp on HW0 does not allow important chemical delivery trucks to pass through their normal route. The CDS works with the transportation department to use a detour and safely reroute the trucks on surface streets to deliver the needed chemicals. The detour is accomplished within four days and allows for chemical replenishment before they are used up.

The availability of the second clarifier and the 75 % reduction in water usage due to damages to the water system provide a safe cushion for the treatment plant to manage the plant's operation (for [**D5**]) until the primary clarifier is repaired within 7 days.

The recovery times given in Table 4-9 identify the basic services and when complete operability is reached.

Table 4-9. Wastewater System Basic Service Restorations

Service Zone	Collection		Quality		Quantity		Disposal	
	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.
Z1	3.5 d	U-BPP & D-PEDG	0 h	R-CDT	3.5 d	U-BPP & D-PEDG	0 h	U-SC
Z2	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z3	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z4	3.5 d	U-BPP & D-PEDG	0 h	R-CDT	3.5 d	U-BPP & D-PEDG	0 h	U-SC
Z5	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z6	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z7	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z8	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z9	3.5 d	U-BPP & D-PEDG	0 h	R-CDT	3.5 d	U-BPP & D-PEDG	0 h	U-SC
Z10SW	1d	D-PEDG	0 h	R-CDT	1d	D-PEDG	0 h	U-SC
Z10NE	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Z11	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Community Center & Government Offices	1d	D-PT & M-OES	0 h	R-CDT	1d	D-PT & M-OES	0 h	U-SC
Hospital	3.5 d	U-BPP & D-PEDG	0 h	R-CDT	3.5 d	U-BPP & D-PEDG	0 h	U-SC
Northern Fire Station	1d	-	0 h	R-CDT	1d	-	0 h	U-SC
Southern Fire Station	1 d	D-PEDG	0 h	R-CDT	1 d	D-PEDG	0 h	U-SC

RC = Recreational Center (Emergency Shelter); U-BPP = Use Bypass Pump; D-PT = Deploy Portable Toilets; D-PEDG = Deploy Portable Emergency Diesel Generators; M-OES = Move to Other Emergency Shelters; R-CDT = Reroute Chemical Delivery Trucks; U-SC = Use Second Clarifier

Table 4-9. Wastewater System Basic Service Restorations (continued)

Service Zone	Collection		Quality		Quantity		Disposal	
	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.
Home Depot/ Walmart	1 d	D-PEDG	0 h	R-CDT	1 d	D-PEDG	0 h	U-SC
Wastewater Treatment Plant	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
High School	0 h	D-PEDG	0 h	R-CDT	0 h	D-PEDG	0 h	U-SC
Northern Middle School	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Southern Middle School	1 d	D-PEDG	0 h	R-CDT	1 d	D-PEDG	0 h	U-SC
Eastern Elementary School	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Western Elementary School	3.5 d	U-BPP & D-PEDG	0 h	R-CDT	3.5 d	U-BPP & D-PEDG	0 h	U-SC
Center Elementary School	0 h	-	0 h	R-CDT	0 h	-	0 h	U-SC
Southern Elementary School	1 d	D-PEDG	0 h	R-CDT	1 d	D-PEDG	0 h	U-SC

RC = Recreational Center (Emergency Shelter); U-BPP = Use Bypass Pump; D-PT = Deploy Portable Toilets; D-PEDG = Deploy Portable Emergency Diesel Generators; M-OES = Move to Other Emergency Shelters; R-CDT = Reroute Chemical Delivery Trucks; U-SC = Use Second Clarifier

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4.12 Step A10: Compare System Assessment Results with Target Objectives

4.12.1 Comparing Assessed and Target Recovery Times

Except for the sewage collection services for Critical A Customers, the basic service recovery times outlined in Table 4-9 are less than the target recovery times suggested in Table 4-4 with a reasonable margin. Table 4-10 shows this comparison. Even though most of the basic service recovery times are less than the target values, the descriptions for repairs outlined in Table 4-9 are mainly temporary/ad-hoc solutions. Further, an alternative to the solutions presented for [**D1**], [**D2**], and [**D3**] were to pump raw sewage directly into the Rock River, which poses environmental and public health problems and does not meet the wastewater quality service. As a result, path ‘No’ is followed in Volume 1 Fig. 4-1b and it is important to modify component designs and/or response actions to ensure the basic service recovery times can be met for various future earthquake events (i.e., the scenario in Ch. 2 and other expected scenarios described in Volume 1 Sec. 2.5).

Table 4-10. Comparison of Basic Service Recovery Times with Target Recovery Times in Table 4-4

BSC	Service Description	Target Recovery Time	Is Target met?
Collection	Restore to 100 % of all Users	15 days	Yes
	Restore to 100 % of all Critical A Users	3 days	No
	Restore to 100 % of all Critical B Users	7 days	Yes
Quality	Maintain disinfection for 100 % of flow	0 days	Yes
	Restore full treatment capacity	7 days	Yes
Quantity	Restore to all users under dry-weather conditions	7 days	Yes
	Restore average wet weather day demand to all customers	20 days	Yes
	Restore to pre-event peak wet weather capacity	45 days	Yes
Disposal	Restore to all customers	45 days	Yes

4.12.2 Making System Modifications and Framework Iterations

Since not all the target service recovery time objectives were met, Volume 1 Fig. 4-1b shows the next part of the process is to revise the system recovery time factors in Step A8 and/or the performance and service recovery time objectives in Table 4-4. It is most important to focus on how to first modify the recovery time factors to identify cost-effective ways to improve the system performance and recovery before attempting to change (i.e., lengthen) the service recovery time objectives. The service recovery time objectives target societal needs for the wastewater system services so extending these durations results in potentially not meeting the needs of the community. Therefore, this example will proceed with investigating how to modify the system assets and organizational actions while maintaining the target service recovery time objectives in Table 4-4.

Reviewing the assessment identifies several needed modifications to the Centerville wastewater system. In addition to those previously identified in Step A7 in Sec. 4.9, seismic improvements include, but are not limited to:

- Installing on-site tanks at Centerville Hospital sufficient to hold wastewater to operate essential hospital functions for 72 hours. This alternative solution is mandatory for all hospitals in California after the year 2030 according to the California Office of Statewide Health Planning and Development §727.0 Emergency Sanitary Drainage [IAPMO, 2021].
- Maintaining portable emergency generators for system use or adding backup diesel pumps and fuel storage sufficient to run for three days at RR-WPS and NFS-WPS pump stations (D3-S3).

All components should be designed to meet the Criticality Categories shown in Fig. 4-1. Additionally, some organizational actions may be modified to improve performance and service recovery times. The above-listed outline focuses on how asset improvements will aid in meeting the recovery time objectives, but these are costly and time-consuming. Some are required to meet the objectives, while some organizational activities must be modified to meet the objectives. This example identifies how coordinating with other dependent systems like the transportation and electric power departments helps to improve the services needed by the CDS. Additional example modifications of organizational actions are summarized in Ch. 3 Sec. 3.12.2 for the water system example that are also applicable to this wastewater system example.

It is beyond the scope of this example to provide detailed guidance on how to modify the assets and organizational actions to meet the performance objectives. The main point is to show that once the comparison of recovery time objectives is made, and if system modifications are needed, the process is iterated to identify which changes may be made to portions of the assets and organization. These are then designed in accordance with the framework and another assessment and comparison made. The process is continued until the performance and recovery time objectives are met. If in special cases, after investigating all options for modifying the assets and organizational actions, some objectives cannot be met for cost or logistical reasons, they may be revisited, coordinated with the community and all critical customers, and modified if appropriate as described in Volume 1 Chs. 3, 4, and 5.

4.13 Step A11: Report System Assessment Results

The system assessment results are documented and filed in a safe place for future reference and use. An important aspect of reporting is to ensure all the appropriate findings can be put into practice. The reported results should be used as feedback for decision makers and the planning process as described in Volume 1 Sec. 3.1. The modifications identified in Steps A7 and A10 are to be described in the CDS pre-earthquake mitigation plan, prioritized, budgeted, and implemented. The results should be used to update emergency management and emergency operations plans, continuity plans, asset management plans, seismic mitigation programs, and capital investment strategies and plans. Additionally, the results may be used to improve and update comprehensive or master plans, state and local hazard mitigation plans, recovery plans, and resilience plans. The final list of improvements and the basic service recovery time objectives presented in Table 4-4 are presented to the public so that they are aware of what wastewater system improvements are taking place and the anticipated durations at which basic services may be disrupted during similar future earthquakes.

5. ELECTRIC POWER SYSTEM EXAMPLE

5.1. Introduction

5.1.1. Purpose of Example

This chapter presents an application of the proposed assets framework presented in Volume 1, published as NIST SP 1310 [NIST, 2024], Ch. 4 to a fictional electric power system providing services to the Centerville community described in Ch. 2. It also identifies how the proposed organizational actions framework presented in Volume 1 Ch. 5 supports the assets framework to achieve functional recovery.

This Sec. 5.1 presents preliminary information and an overview of the electric power system. Sec. 5.2 establishes the basic service recovery time objectives. Secs. 5.3 through 5.13 are coordinated with the steps introduced in Volume 1 Ch. 4 for the assets framework to illustrate the application for each individual step. As part of this process, some portions of the steps are developed for general use to any electric power system while illustrating how the framework steps are implemented specifically for the example fictional Centerville electric power system.

5.1.2. Electric Power System Overview

The purpose of an electric power system is to provide affordable, safe, and reliable power to communities in which all users receive the same service quality and reliability. Affordability, safety, and reliability are primary goals for developing existing electric power systems. Although these goals persist today, resilient power supply is an added operational objective that communities expect from electric power systems. An electric power grid, or electric power system as it is also called in this chapter, provides alternating current (ac) power supply for domestic, commercial, and industrial uses, including for critical services, emergency operations and shelter centers, and other lifeline systems. Only in extremely limited cases is direct current power supply provided to customers.

An electric power system consists of the three subsystems made up of specialized facilities and components identified in Table 5-1 and covers everything from generation to delivery regardless of who owns and operates the subsystems. These three subsystems are also represented in Fig. 5-1 and described in Table 5-1. Each of the subsystems could be government-owned or privately-owned either in public listed companies or in cooperatives. Each of the three subsystems could be owned and operated by a single or different organization, although most commonly the subsystems are separately owned and operated by different organizations due to regulatory requirements in many states. The following notes apply to Table 5-1:

- Generation, converter stations, and receiving stations have their own site-specific subsystems made up of mechanical, electrical, and civil engineered subsystems and components.

- Instrumentation and monitoring are integrated into all subsystems. Supervisory control and data acquisition (SCADA) systems are used to monitor and operate power systems.
- Buildings and facilities, including central headquarters, operation and maintenance yards, and other components are also a part of the systems.

Table 5-1. Major Electric Power Subsystems and Typical Components

Subsystems	Description	Typical Facilities / Components
Generation systems	Systems generating electric power.	Generation comes from energy conversion of other energy sources to create electric power by use of turbines or internal combustion engines or in the case of solar systems, PV cells. Common sources of energy include water reservoirs, natural gas, coal, nuclear fission, solar radiation, and wind.
Transmission systems	Systems for transmitting bulk power from source generation to a distribution area.	Transmission towers and conductors, cables, converter stations, receiving stations, substations, transformers, circuit breakers, switches, sensors, actuators, and other associated mechanical and electrical equipment.
Distribution systems	Networks for distributing power to domestic, commercial, business, industrial, and other customers.	Substations, cables, poles, power lines, vaults, transformers, service lines not included as part of the generation or transmission subsystems. Includes service lines and meters.

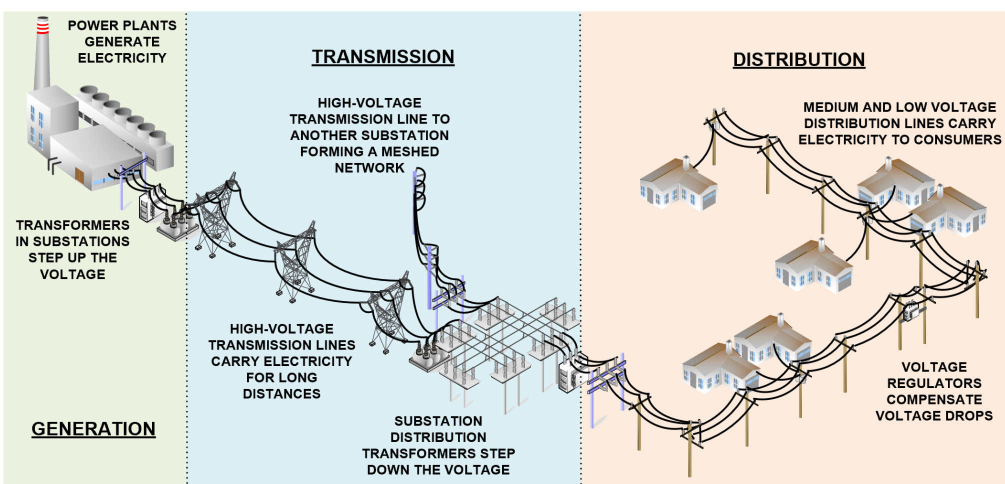

Fig. 5-1. Simplified representation of the three subsystems forming an electric power system.

Electric power generation involves conversion from different types of energy into electricity. Most commonly, turbines convert potential energy in water reservoirs, nuclear energy, kinetic energy in the wind, heat in geothermal source or chemical energy in fuels such as coal, natural gas, or fuel oil, into electricity. Electrical energy can also be converted from the sun's electromagnetic radiation in photovoltaic (PV) modules, although the amount of PV-generated electricity is still much less than that generated by other means. Electric power can also be generated locally from these same sources but on a much smaller scale. The most common sources of locally-generated electricity are from PV sources or from fuels, such as diesel or natural gas, using internal combustion engines or microturbines for energy conversion. Still, the vast majority of the generated electricity originates in turbine-based conversion processes occurring in power stations or plants that are located at some distance from the electricity consumption centers. Compared to the number of electricity users, i.e., loads, power stations are much fewer but with more electric power capacity. Moreover, a main control action is for system operators to determine power dispatch levels at power stations. This configuration introduces a resilience vulnerability in power grids even when there is usually some power generation capacity margin because power grids are mostly centralized systems with relatively long paths between generation and consumption.

Electric power transmission includes the components used to carry electric power from the power stations to the usually distant consumption centers. The most characteristic components of the electric power transmission subsystem are the high-voltage transmission lines. Almost all these high voltage transmission lines are overhead and operate with ac. Underground transmission lines are often found in urban areas and they span much shorter distances than overhead lines. Transmission lines begin and end at substations where additional critical components of the electric power grids are located. These components include transformers, switchgear and monitoring, actuation, and communications equipment. Transformers are used to step-up or step-down ac voltages and represent the interface among the three power subsystems. Step-up transformers are placed at the interface between power generation and transmission subsystems and step-down transformers are placed at the interface between transmission and distribution subsystems. Switchgear includes circuit breakers, disconnect switches, and other equipment used to open or close electric circuits either due to operational needs or for protection in case there is a fault. Monitoring, actuation, and communication equipment include a variety of devices, such as sensors and relays, that are connected to a SCADA platform via a dedicated communication network to monitor the condition of the grid, e.g., measure transmission line power flow and bus voltages and frequencies, and to transmit control commands. Other important power grid equipment that contributes to a stable operation with the required power quality, such as voltage regulators or devices for reactive power compensation, are also found in substations. Additionally, there are some cases in which power is transmitted using high-voltage direct current (HVDC) lines. Direct current conversion is also used for interconnecting two of the three main transmission grids in the U.S.: the Eastern Interconnect, the Western Interconnect, and the electric grid in Texas known as the Electric Reliability Council of Texas (ERCOT). Use of HVDC systems requires electronic equipment usually located in large rooms at substations. Although the power transmission subsystems have some resilience vulnerabilities due to the long paths often observed in lines, transmission lines and some critical components in substations, such as some high-power transformers, they are engineered with some redundancy. Moreover, transmission lines in the U.S. grids form meshes with some geographic path diversity that mitigate the negative effects of a very limited number of failures in the system.

The third subsystem is the one used to distribute and ultimately deliver electric power to the users. Electric power distribution lines originate in substations where transformers step-down the voltage as power from the transmission lines is divided among various power distribution circuits. As Fig. 5-2 represents, these circuits typically pass through at least two more step-down voltage transformation stages, one at a distribution substation and the last one at a distribution transformer which usually serves a few customers and are either mounted on poles or on the ground on concrete pads. The lines used to connect the step-down transformer at a distribution substation to the distribution transformers are called feeders (the part of the line at the output of the distribution substation) and laterals (the part of the distribution circuit derived from a feeder and connected to various distribution transformers). As in the transmission subsystem, other components of the distribution subsystem include voltage regulators, circuit breakers, fuse sectionalizers, and capacitors for reactive power compensation. Power distribution lines can be installed either overhead or underground, in this latter case, usually in urban areas, typically in a radial architecture. The radial architecture makes power distribution circuits to be the most vulnerable subsystem in power grids because any one single damage along the power distribution path would make the circuit experience a loss of service. That is, commonly the power distribution portion of an electric power system lacks redundancy, which limits the technological options for recovery to customer-based solutions, such as microgrids or backup power generators, or adding redundant power distribution lines. Redundant distribution lines may not be sufficient because a complete redundant circuit may require the use of separate distribution substations, which although it is a technically feasible solution, it is likely impractical due to its very high cost especially considering the uncertainty on whether an earthquake will happen within the planning and design horizon. The distribution sub-system may also include medium-voltage lines operating below what is usually considered the lowest voltage of transmission subsystems, which is 69 kV, to connect relatively distant substations or to connect relatively large electric power consumers.

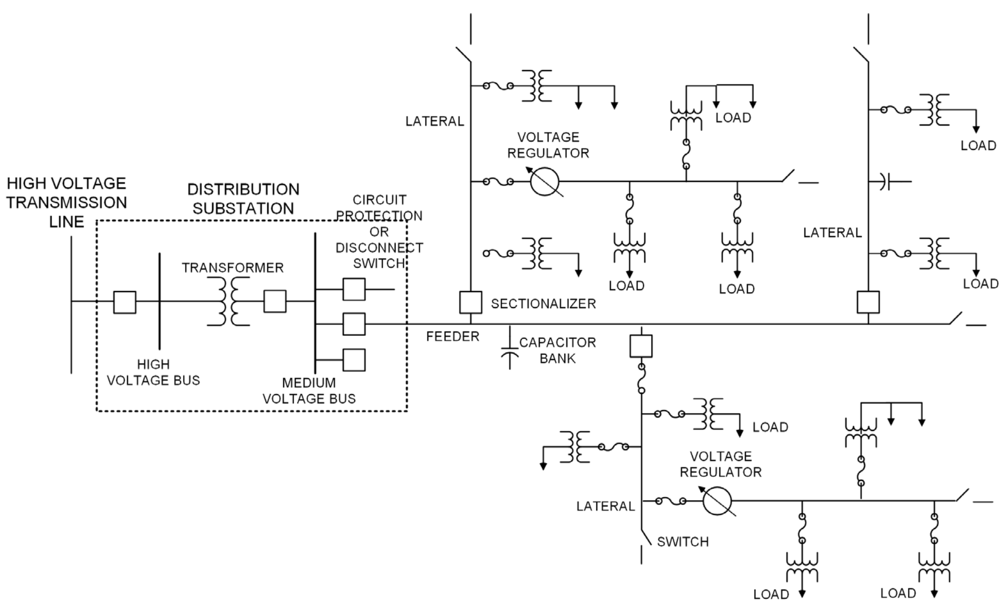

Fig. 5-2. Representation of part of a typical electric power distribution subsystem. Electric power flows from left to right.

Technology changes may likely affect how power grid components are considered in the future. Energy storage is one of these technologies. One important differentiating characteristic of existing electric power systems when compared to the other infrastructure systems discussed in this document is that the energy storage capacity extremely limited and is mostly found in turbine rotor inertia that are able to maintain frequency within the specified range for at most a few seconds. Most stored energy in existing power systems is found, instead, in chemical energy in fuels or potential energy in water reservoirs and, thus, it is not directly coupled to the power grid state variables because a process is needed to convert the stored energy into electricity. Some very limited directly coupled energy storage is found in customer-owned systems, such as batteries used to provide a few hours of power backup. However, in addition to representing a small percentage of the total energy found in a power system, this energy storage is decoupled from the rest of the grid, and it is only usable by its private owner at the facility where the batteries and load are located. Often, these energy storage systems are coupled with generators as part of backup power systems. In the past decade, the concept of local energy storage and power generators has been expanded into self-contained and independently controlled power systems called microgrids that are equipped with their own local power sources and energy storage devices. Microgrids are intended to be able to operate when connected to a grid or by themselves in what is called islanding mode. That is, microgrids are different from backup power generation in the sense that the latter operate only in case of a power outage whereas the former are intended to operate by powering its loads even when microgrids are connected to an operating electric power grid. As such, microgrids are permanently installed systems with their local power generation sources as the primary means for powering nearby-located loads. Examples of sources used in microgrids include PV modules, fuel cells, microturbines, and internal combustion engines. Microgrids are almost always also equipped with energy storage devices, usually batteries, although other technologies are utilized such as ultracapacitors, flywheels, and compressed air. Still, power ratings of microgrids are orders of magnitude lower compared to that of conventional electric grids. For example, microgrid power can rarely exceed 10 MW, with the largest microgrid claimed to be the one at The University of Texas at Austin with a total load of 60 MW compared to a peak demand for ERCOT of 75,000 MW. At a grid scale level microgrids may not represent a significant portion of the system capacity. However, at a local level, within a city, microgrids could be relevant from a resilience perspective. Use of PV modules either at residential or local level have gained increased penetration in the U.S. power grid. Yet, it is important to note from a resilience perspective that these systems are usually of the grid-connected type and, thus, can only produce a power output when connected to an operating grid.

Another electric power-related technology gaining increasing relevance is electric vehicles (EVs). Because of the energy stored in their batteries, it has been proposed to use that energy as a backup source of electricity for homes during long power outages that often follow a disruptive event. However, using the stored energy in batteries for that purpose reduces the ability for people to move using the EVs to obtain food, water, and other supplies and also to reach operating charging stations to recharge the EV batteries. Thus, electric power resilience is a significant challenge for increased adoption of EVs.

5.1.3. Centerville Electric Power System

Consistent with the summary description of the Centerville electric power system in Sec. 2.4.3, the Centerville electric power system consists of the same three main electric power subsystems presented in Table 5-1, but with a subset of components. Table 5-2 presents the subsystems and components making up the Centerville electric power system. The Centerville electric power system aims to represent realistic conditions but is intentionally simplified to illustrate how the proposed framework in Volume 1 may be implemented.

The Centerville electric power distribution system is owned and operated by the Centerville Electric Power Department (CEPD), a municipal utility. The CEPD owns and operates one power generation plant and other generation plants in the region are owned and operated by a privately owned company named the Regional Power Generation Corporation (RPGC). The transmission lines are owned by a conglomerate named the Power Transmission Agency (PTA). The main features, important characteristics, and the subsystem owners and operators for the Centerville electric power system example are as follows.

Generation Subsystem (CEPD and RPGC):

- 200 MW natural gas power plant in Centerville owned by CEPD
- Transmission Substation owned by CEPD
- 500 MW coal fired power plant southwest of Centerville owned by RPGC
- Other generation plants feeding the transmission grid far from Centerville owned by RPGC

Transmission (PTA) and Subtransmission (CEPD) Subsystems:

- Two 69 kV regional transmission lines (PTA)
- Other transmission lines around Centerville (PTA)
- One substation in Centerville (PTA)
- One line to a distribution substation in Centerville (PTA)

Distribution Subsystem (CEPD):

- Subtransmission system in Centerville (CEPD):
    - Two subtransmission lines
    - One subtransmission station
- Four distribution substations
- Overhead distribution lines
- Two buried lines
- Transformers and other equipment
- Service drops and meters for every customer connection

5.1.4. Electric Power System Basic Service Categories

Table 5-3 describes three Basic Service Categories (BSCs) identified for electric power systems. The system or portion of system meeting the service description in Table 5-3 for each category is considered to have the BSCs provided to the customer after an earthquake. The electric power system normally provides many additional levels of service (e.g., IPWEA, 2015; LGAM, 2019) on a daily basis, in addition to those presented in Table 5-3. If services are lost due to damage caused by an earthquake, the primary objective is to restore the BSCs given in Table 5-3.

All electric power systems are designed and operated to ensure proper quality and quantity of power in a stable system to provide their services.

Table 5-2. Centerville Electric Power Subsystems and Components

Subsystems	Description	Facilities / Components
Generation systems	Systems generating electric power.	200 MW natural gas power plant in Centerville owned by CEPD and the associated transmission substations.
Transmission systems	Systems for transmitting bulk power from source generation to a distribution area.	Two 69 kV regional transmission lines (PTA), one main substation in Centerville (PTA), and one line to a distribution substation in Centerville (PTA).
Distribution systems	Networks for distributing power to domestic, commercial, business, industrial, and other customers.	The subtransmission system in Centerville (CEPD), four distribution substations, overhead distribution lines, two buried cable lines, seven electric power distribution zones, transformers and other equipment, service drops and meters for every customer connection.

Table 5-3. Electric Power System Basic Service Categories (expanded from Davis [2021])

Basic Service Category	Description of Service
Power Delivery	The system is able to distribute power to customer service connections, but power delivered may not meet pre-event quality, pre-event quantities (requires power rationing), or pre-event functionality (inhibiting system performance).
Quality	The power quality at service connections meets pre-event standards, i.e., voltages and frequency are within pre-specified ranges.
Quantity	Power to customer service connections meets pre-event demand volumes (power rationing removed).

The concept for addressing BSCs for electric power systems considers how an earthquake may cause sufficient damage to the network to result in complete loss of electric power delivery to some or all customers. For electric power delivered through the infrastructure networks, power delivery is the first step in service restoration to the customer's service connection and is a prerequisite for meeting the quantity and quality services. IEEE Standard 1366 [IEEE, 2022] defines a forced outage as "the state of a component when it is not available to perform its intended function due to an unplanned event directly associated with that component." It is worth noting that IEEE Standard defines electric power distribution reliability indexes under normal operating conditions and excludes from its statistics what are defined as "major event days. Although the quantity and quality basic services may be lost even if power delivery services are maintained, in practical terms, power delivery and quality are coupled concepts. For example, if one of the three phases making an electric service into an area is lost, customers served by one of the other two phases will likely experience voltage levels significantly lower than the minimum specified level to the extent that these other phases experience a loss of service also (i.e., the voltage level delivered to the customer is too low for practical purposes to run equipment). Thus, as further explained at the end of this section, power delivery services are tightly coupled to their quality of delivery requirements so power delivery restoration many times implies that power quality is also restored within minimum acceptable quality levels. Still, it is possible to have situations where power delivery is restored and power quality conditions may deviate from normal expected standards, for example, by exhibiting lower than normal voltage levels or higher harmonic content and still power equipment. These conditions could be observed in "weak" power distribution circuits, such as long rural feeders.

The quantity of power delivered to customers depends on the network operating at a stable point. The network is at a stable operating point when generated power (i.e., supply) equals consumed power (i.e., demand) by the load plus losses. When supply exceeds demand, then power generation units need to reduce their output power or need to be taken offline to avoid blackouts due to increasing operating frequency beyond the specified range. Blackouts cut the delivery of electric power supply to large groups of customers. Thus, if blackouts occur faster than power generation reduction, then the excess generated energy will increase, which, in turn, will exacerbate the power imbalance problem and could lead to a potential large cascading outage. When supply is less than demand, then power generation output needs to be increased to avoid system frequency dropping below specified limits. If the generation ramp-up is not sufficiently fast or there is insufficient power generation or transmission capacity to quickly balance supply and demand, then load needs to be shed by disconnecting distribution circuits. Milder supply-demand imbalances caused by insufficient power generation capacity leading to consumption exceeding power generation can be mitigated by customers rationing their use of electricity through demand/response programs. In the absence of adequate rationing, circuits may be shut down resulting in brownouts in which customers connected to these circuits lose power. Then, while the power generation shortages persist, limited supply can be rotated periodically to different circuits within the distribution grid temporarily delivering power to different customers. Thus, the quantity basic service can be reduced from normal either by continuous rationing or through periodic temporary loss of power. Blackouts and brownouts result in loss of delivery service to customers. Quantity is restored when brownouts and blackouts are no longer expected as a consequence of the event.

IEEE defines power quality in its standards 1100-1999 [IEEE, 1999] and 1159-1995 [IEEE, 1995] as "the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment." This definition tends to be more applicable from a customer perspective, for example, in order to ensure that equipment at a customer premises does not affect the operation of other equipment at the same customer premises. In a practical sense, this definition implies that voltage and current amplitude, frequency, and waveforms conform to what is required for adequate load operation. Thus, power quality requirements are a function of the sensitivity of the equipment being powered from the system. From an electric power utility perspective, [Santoso, 2010] explains that the IEEE Standard 1100-2005 [IEEE, 2005] defines a power quality problem as "any problem manifested in voltage, current, or frequency deviations that results in failure or mis-operation of end-user equipment." Thus, based on the aforementioned definition of forced outage from IEEE Standard 1366 [IEEE, 2022], a load experiencing a failure or mis-operation due to power quality issues could be considered to be experiencing a forced-outage within the context of this framework. Therefore, in this context and within the perspective of electric utilities and government utility regulators, the concept of an outage, i.e., a power delivery interruption, tightly couples power delivery and quality conditions, i.e., loss of quality beyond minimum levels also implies a power delivery loss. Significant events like earthquakes damaging electric power equipment can cause power quality issues. Power quality issues such as sags, swells, over-voltages, under-voltages, harmonics, noise, and transients are defined in standards IEEE-1100 [IEEE, 2005] and IEEE-519 [IEEE, 2014]. From a functional recovery perspective, customers who can utilize electric power from the network, but at less than standard quality, may be able to undertake activities to improve their resilience and that of the community. Thus, recognizing the ability of a utility to safely provide electric power at lower-than-normal quality standards can improve the community resilience, even if some customers may not be able to utilize the power to operate some equipment. This may also require proper communications for delivering lower quality power. Moreover, in some jurisdictions, it may also require changes to regulations that may prevent or significantly limit electric utilities to still deliver power at lower-than-normal power quality levels. Therefore, it is important to distinguish the notion of power quality from the perspective of electric utilities and those from the perspective of customers. For customers, the notion of power delivery and quality is more decoupled than from the perspective of electric utilities because they can resort to restoring power delivery through what is defined in this framework as adaptation strategies, such as using power backup generators, albeit likely at lower-than-standard quality conditions. Davis [2021] also addresses electric power system basic service categories.

5.2. Identify System Performance and Recovery Time Objectives

The system-level performance includes all the objectives and criteria necessary to accomplish normal operations (i.e., operating current, voltage, quality) and provide the services to each customer. The assets framework provides for the inclusion of a system-level seismic performance objective. A system-level seismic performance objective could be specified using parameters, such as a maximum number of service losses and/or a recovery rate, a total number of damaged locations, or other parameters, all of which are conditioned on the seismic event associated with the performance objective. However, there are no existing guidelines for how to establish these types of parameters for a system-level performance objective. FEMA P-2234 [2024] proposes future work to investigate the usefulness of preparing system-level performance criteria in terms of a number of customer service losses and recovery rate. Further research is needed to identify how to develop system-level seismic performance objectives for electric power systems.

Since there are no existing guidelines for how to establish system-level seismic performance objectives, none are specified in this electric power system example. Instead, the system-level performance is identified as an outcome of the system layout including redundancy and isolation capabilities and the performance of the individual components making up the built networks. The system-level performance is identified through the assessment process in Step A11 as the level of performance for the earthquake event defined in Ch. 2 necessary to achieve the target service recovery times defined in Table 5-4a in combination with all the recovery time factors.

FEMA P-2234 provides a framework for identifying target system-level recovery time objectives based on the earthquake event scenario size and available user adaptations. Unlike for the water system example in Ch. 3, FEMA P-2234 does not complete an assessment for electric power systems. As a result, there are no published recommended target basic service recovery times for electric power systems readily available for use. The FEMA P-2234 framework is unable to be fully implemented as part of this project because of scope and time constraints. As a result, Table 5-4a presents estimated plausible target electric power system recovery time objectives for the BSCs given in Table 5-3 for the Level II earthquake event scenario described in Ch. 2. This is one of several recommended sets of earthquake event scenarios and associated service recovery time objectives an electric power system should investigate as defined in Volume 1 Sec. 2.5 and FEMA P-2234. Only one earthquake event scenario and associated service recovery objectives is selected for this example.

Because of the aforementioned coupling between service delivery and quality conditions, this framework does not distinguish between delivery and minimum quality restoration times from the perspective of electric utility actions. That is, from an electric utility perspective power delivery is restored with at least the minimum required power quality levels. Thus, different recovery times for quality and power delivery implies customers using their own electric power generation resources, such as backup diesel generators until the network is able to return the pre-event quality level needed by customers that exceeds the minimum.

The target basic service recovery times in Table 5-4a apply to end users and are therefore intended for use by the CEPD. As described in Volume 1 Secs. 2.3.6.2 and 3.2 coordination with the PTA and RPGC is necessary to identify service recovery time targets for the transmission and generation subsystems. Using Step O3 in the organizational actions framework in Volume 1 Ch. 5, the three organizations along with the regional power dispatch and regional systems operator coordinate to identify the target service recovery times in Table 5-4b for the PTA and RPGC. Because the RPGC and PTA generate and transmit power over a wide area and provide to many different cities, the objectives in Table 5-4b are standard for all power distribution agencies they serve.

Table 5-4a. Target Electric Power BSC Recovery Times for a Level II Earthquake Event Assuming User Adaptations are Applied where Basic Services are Applicable to Distribution of Electric Power to end Customers and Users

BSC	Service Description	Target Recovery Time
Delivery	Restore to 100 % of all Critical A Users	1/2 day
	Restore to all customers	10 days
Quality	Restore to high-power commercial, industrial, and institutional users	5 days
	Restore to industry having sensitive equipment	5 days
	Restore to all customers	10 days
Quantity	Restore to 100 % of all Critical A Users	1/2 day
	Restore to 50 % of all customers	7 days
	Restore to 100 % of all Critical B Users	10 days
	Restore to all customers	15 days

Table 5-4b. Target Electric Power System BSC Recovery Times for a Level II Earthquake Event Assuming User Adaptations are Applied where Basic Services are Applicable to Electric Power Transmission provided to the Power Transmission Agency and the Regional Power Generation Corporation

BSC	Service Description	Target Recovery Time
Delivery	Restore to CEPD	1 day
Quality	Restore to CEPD	1 day
Quantity	Restore energy demand to CEPD	4 days
	Restore to pre-event normal demand (rationing removed)	10 days

The target service recovery time objectives in Tables 5-4a and 5-4b assume the following user adaptations are able to be implemented; these are in addition to any adaptations made to the system. As a result, it is essential that the organizational actions incorporate the needed activities to ensure these user adaptations can be implemented throughout the service area by including them in the proper plans, coordinating with the correct agencies who can ensure they can be implemented (i.e., Volume 1 Ch. 5 Step O3), and including them in emergency exercises. The user adaptations assumed to be implemented include:

- Reducing consumption. Includes rationing power which may be implemented system wide
- Delaying consumption
- Temporary relocation (e.g., residents going to hotel or a friend’s or relative’s house or a medical facility)
- Using a regionally redundant facility (e.g., alternate hospital, schools, grocery store having water service)
- Canceling activities

- Portable generators
- Backup generators (some customers may need to meet the basic quality service)
- Flashlights and candles for light
- Cloths and blankets for warmth
- Campfires, stoves, and fireplaces for heat and light

The component-level performance and recovery time objectives are identified in Step A4. The component-level recovery time is a function of many locally specific factors described in Volume 1 Table 4-7.

5.3. Step A1: Define System Layout and Operational Characteristics

The Centerville electric power system is described in Sec. 2.4.3 and the major components making up the generation, transmission, and distribution subsystems are outlined in Sec. 5.1.3. Figures 2-6 and 2-7 show the electric power system major components and connectivity. Figure 5-3 shows the electric power system in Centerville, including components from all three of the described subsystems, used as an example to demonstrate the framework application. For simplicity, low voltage circuits and drops to customers are not represented in this figure. Figure 5-4 shows the electric power grid for portions of the generation and transmission subsystems in the region around Centerville.

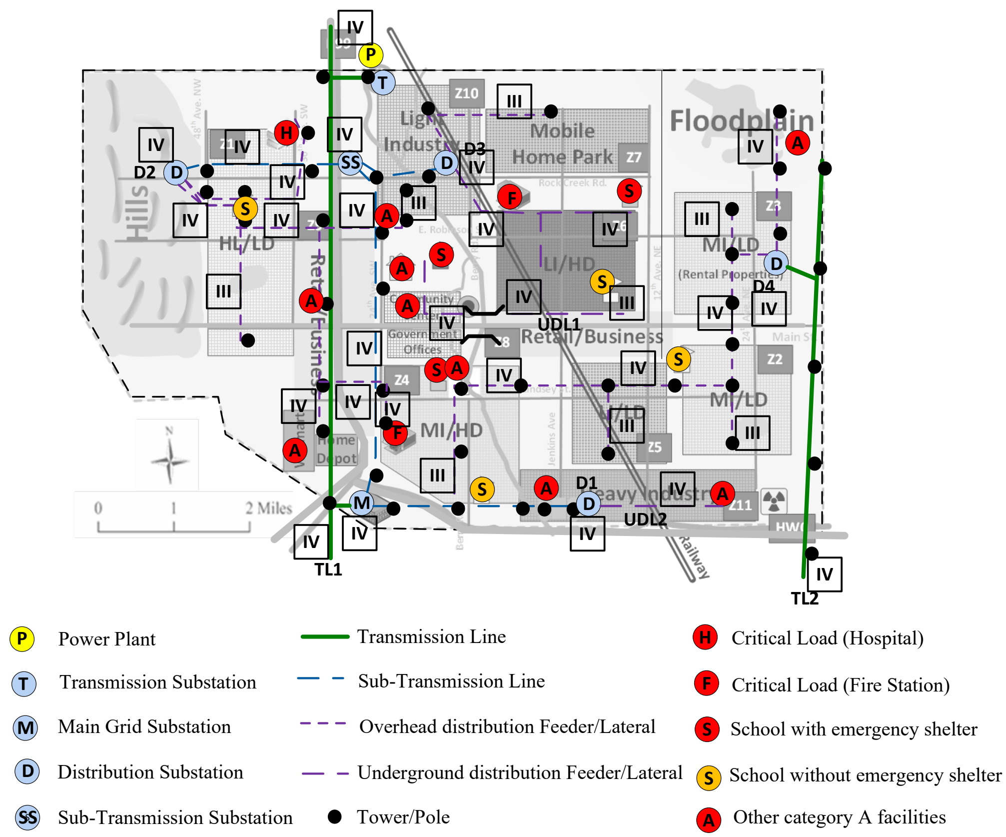

Fig. 5-3. Centerville electric power grid and assigned Criticality Categories.

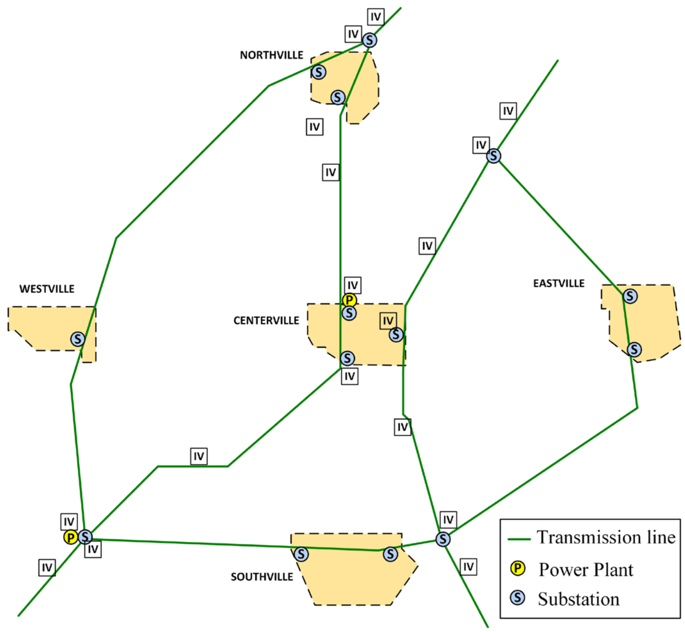

Fig. 5-4. Electric power grid in region around Centerville. Criticality Categories are only indicated from Centerville's perspective.

5.4. Step A2: Define Criticality Category and Earthquake Design Basis for System Components

The components making up the electric power system described in Step A1 are all assigned a Criticality Category based on the importance of the customers and users the components are utilized to serve. The Criticality Categories are defined in Table 5-5 and are considered applicable to all electric power systems. Volume 1 Table 4-2 is used to establish the recommended earthquake design basis.

Table 5-5. Electric Power System Component Criticality Categories (adapted from Davis [2005; 2008] and ALA [2005])

Criticality Category	Description
I	Components, in the event of failure, present very low hazard to human life, no damage to property, and little to no effects on user's ability to perform their activities or functions. Not needed for post-earthquake system performance, response, or recovery.
II	All components not identified in Criticality Categories I, III, and IV. These typically are normal and ordinary components providing services for commercial, some non-commercial, and industrial buildings not needed for essential emergency response or initial recovery.
III	Components providing electric power services that represent a substantial hazard or mass disruption to human life in the event of failure, including significant levels of property damage. An extended operational disruption for these components may result in significant social or economic impacts and cause significant effects on users' ability to perform their activities or functions. Operational disruption of these components causes long delays in post-earthquake system response or recovery. Operational condition affects local or regional loads to services for Critical B Customers/Users. Buildings and structures necessary for interacting with customers and users like customer service offices.
IV	Components needed to provide electric power services to essential facilities for post-earthquake response, public health, and safety. Components providing services that have a direct effect on human life in the event of failure. Total to almost total levels of property damage. Failure of these components results in critical social or economic impacts. Practical impossibility for users to perform their activities or functions. These components are intended to remain functional during and following an earthquake. Operational condition affects local or regional loads to services for Critical A Customers/Users. Buildings and structures necessary for performing essential and support functions by the lifeline infrastructure system organization, and facilities containing hazardous chemicals.

At this point, it is important to emphasize that existing electric power systems are the technological outcome of a design process carried out more than 100 years ago in which the provision of electricity with different service characteristics, such as selective load criticality, was not a design goal. Resilience and functional recovery were not design objectives. Thus, present electric grids are inherently designed for a provision of equal service characteristics to all users. As a result, existing electric power systems may not be able to easily modify their networks or their operations in short periods of time (e.g., 1 to 5 years) in order to accommodate different criticality levels. Thus, some solutions may demand high capital investments, which could generate financial stress onto the community in order to fund modifications. However, it is important to realize that designs intended to improve functional recovery imply a capital investment for an event that is not certain to occur with a probability of occurrence dependent on the time horizon considered. Longer time horizons not only allow to scale the capital investments more gradually over time, but it also allows for the possibility of coordinating functional recovery improvements with the necessary maintenance replacements of components, thus, further reducing the financial impact of implementing designs for improved infrastructure resilience. Still, existing electric grids have an inherent practical limitation in how much improvement can be achieved in order to provide a resilient electric power delivery service in which there is a possibility of selectively serving different service characteristics depending on the load criticality. Fortunately, there are modern technologies that provide alternatives for addressing these limitations. For example, in some cases the solution for loads with higher critical levels may necessarily rely on adaptation strategies implemented by the users or within the system, unless local or state regulations further limit such solutions by, for example, preventing electric distribution utilities to own and deploy distributed generation or electric energy storage in their grids, in which case the solution may require changes in the regulatory environment. Most commonly these strategies are the use of backup diesel, natural gas, or propane generators. It is envisioned that in the future, microgrids will increasingly represent a customer-centric technology used for such selective power delivery service based on load criticality, as demonstrated by the microgrid that was envisioned for such purpose and was operating in the city of Sendai during the 2011 Great Tohoku Region earthquake and tsunami [Marnay, 2015]. Alternatively, if initial choices for restoration objectives imply an investment that neither the electric utility, its users, or the community can afford, this framework provides a method for readjusting the restoration time objectives based on coordinated agreements among all stakeholders.

Various criteria can be considered to define the component Criticality Category in Table 5-5, based on Volume 1 Table 4-1. A starting point for identifying such criteria is to consider the definition of critical load in IEEE Standard 1100-2005 that indicates that these loads are "devices and equipment whose failure to operate satisfactorily jeopardizes the health or safety of personnel, and/or results in loss of function, financial loss, or damage to property deemed critical by the user." As explained above, IEEE Standard 1100-2005 presents a user-centric perspective. As a result, some of its definitions may not fully represent the electric utilities perspective. For example, based on this definition, communication network equipment, such as wireless communications base stations or central offices, should be considered critical loads because communication network operators consider their loss to be critical. However, it is practically impossible for electric utilities to fully recognize such criticality because there are so many loads receiving electricity from a distribution utility that it results in considering most power distribution feeders as serving a critical load. Since all loads connected to the same feeder receive electric power provision services with roughly the same reliability and resilience, recall that a fundamental characteristic of power grids design is that all users receive a service with the same characteristics, then most loads are expected to be connected to a circuit identified as critical. Still, the definition of critical load identifies the following criteria for criticality: health and safety, damage to property and relative importance that the loss of service has. From a user perspective, the latter relates to the effects of service disruption in terms of load functionality or financial impact. This latter criterion can be extended from the perspective of electric utilities into the potential extent of the outage in terms of number of affected customers. This framework identifies loss of service from a community perspective, not by each individual user perspective, but in terms of the relative importance of the customer to the community during a disaster. Thus, this framework is intended to assist in identifying enhancements needed to meet the service recovery time objectives and incorporates the potential use of adaptations that are more suitable to provide targeted improvements to particular users and avoid impacting the electric power system planning, design, and operation under normal or common operating conditions (i.e., in the absence of a major earthquake,) by potentially creating substantial financial burdens for an event that is uncertain to occur.

It is important to recognize that facilities, such as power plants, usually have more than one power generation (or units) so criticality may differ when considering the entire facility or each power generation unit independently of the others. Because of power generation margins present in power grids, considering the criticality of a facility in isolation may likely differ when considering other facilities. That is, failure of a single power plant may have little to no effect to an entire power grid. However, such failure could be more impactful if other power plants also fail, removing redundancies (see Volume 1 Sec. 4.5.3), or if damage to transmission lines limit the power transfer capacity into the region neighboring the damaged power plant, removing continuity (see Volume 1 Sec. 4.5.1).

The power distribution grid of Centerville serves a variety of loads including residential, retail, and industrial areas. Additionally, there are various critical facilities, such as two fire stations and a hospital, also served by Centerville’s power distribution grid. Although not shown in Fig. 5-3, Centerville’s power distribution grid loads also include other lifelines, including pumps for water distribution networks. Some of the components of these lifelines depend on receiving electric power for their operation, which in normal conditions is provided by an electric power grid but during emergency operations after an earthquake could be provided through adaptation strategies, such as backup generators.

Figs. 5-3 and 5-4 show the circuit Criticality Category resulting from the loads they serve based on Table 5-5. Load criticality was assigned based on Table 2-2. The basic principle for determining component criticality is to examine load criticality starting at the end of each circuit and move “upstream” the power delivery path. Thus, circuit criticality at its end is the same as the load it serves at that point. The criticality is maintained as the examination proceeds upstream until reaching a more critical load at which point the criticality of the circuit also increases to match the more critical load. The criticality of an individual component is, then, the same as that of the circuit segment where the component is located. This analysis leads to having most, if not all, transmission and generation-level components being identified as Criticality Category IV. Because of the relatively large number of critical loads in Centerville, and limited line redundancy, most components have a Criticality Category IV, although it is possible to observe some circuits end in segments identified with Criticality Category III.

Table 2-3 defines the intensity measures for each earthquake hazard in Centerville for each component Criticality Category.

5.5. Step A3: Check Multiple Use, Continuity, and Redundancy

In electric power grids, it is common to observe multiple use along any given circuit with the criticality of the circuit at a given point determined by the most critical load downstream of such point. Multiple use can also be found in substations where components, such as transformers, can serve circuits of different categories. An example of this situation can be found in distribution substation D3 that serves a Criticality Category III circuit to its north and a Criticality Category IV circuit to its south. In this case, then the substation D3 is assigned a Criticality Category of IV matching the served circuit with the highest criticality. Under the criteria set forth in Table 5-5 and Volume 1 Ch. 4, all transmission and generation-level components in Centerville are designated as Criticality Category IV components.

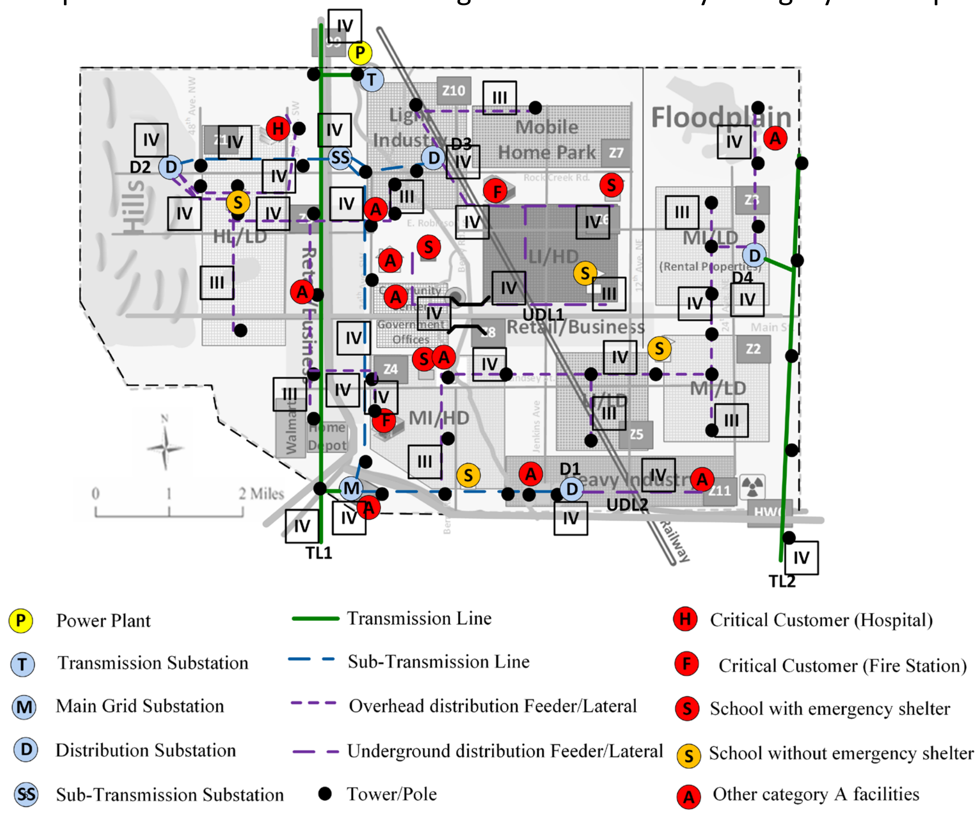

Fig. 5-5. Electric power grid components assigned Criticality Categories.

A required practice in electric circuits is to place circuit breakers at the beginning of each circuit in order to protect the system against short circuits. Hence, disconnection capabilities for each electric power distribution circuit are naturally observed as a basic design characteristic. Because of the radial architecture of electric power distribution circuits, a disconnect device located at the beginning of the circuit is sufficient to provide disconnection capabilities. Circuit architecture at the transmission level does not commonly follow a radial configuration. Hence, circuit breakers are located at each end of every transmission line in order to provide full disconnection capability.

In terms of redundancy, as described above, the electric power distribution subsystem usually lacks redundancy. This is exemplified by Fig. 5-6, which shows the service area of each distribution substation. Lack of overlapping areas indicates that there is no redundancy at this power distribution level of the grid. Additionally, it is uncommon to observe redundancy for power distribution components, such as having more than the minimum necessary transformers in distribution substations.

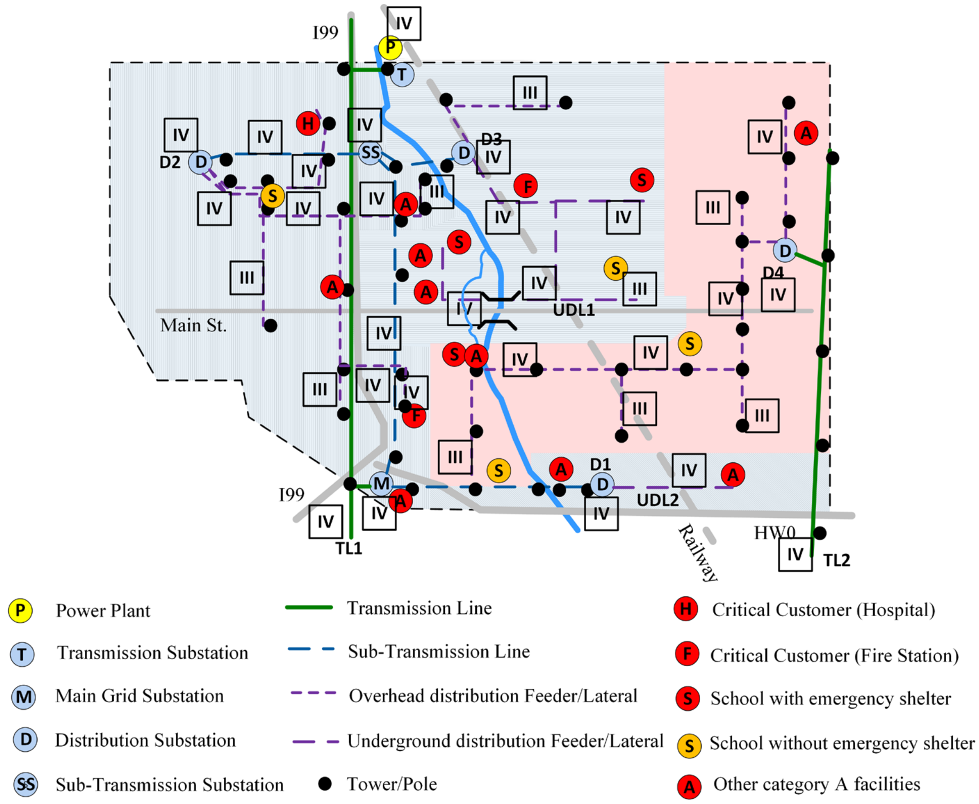

Fig. 5-6. Service area for each transmission line and each distribution substation in Centerville. Component Criticality Categories are identified.

Fig. 5-6 also distinguishes which of the two transmission lines serve the distribution substations. As shown, distribution substations D1, D2 and D3 are powered by transmission line TL1, while distribution substation D4 is powered by transmission line TL2. Lack of overlapping zones also indicates lack of redundancy in terms of how transmission lines power distribution substations. That is, substation D4 could not be powered from transmission line TL1 in case transmission line TL2 is disconnected both north and south of substation D4. However, a better understanding of the redundancy of transmission and generation subsystems requires examining the regional power grid infrastructure and beyond. Fig. 5-4 shows that TL1 and TL2 are connected with a transmission line running east-west through Southville. That is, TL1 and TL2 end up being connected at the substation of the power station located southwest in Fig. 5-4. This connection is critical as it provides some flexibility in how to power TL1 and TL2 and also provides a way in which the power plant in Centerville can energize TL2. However, it is also important to note that the TL1 and TL2 capacity of about 90 MW is just short of the 100 MW peak power consumption of Centerville but each of them are enough to transmit the 70 MW of average power consumed by Centerville. Additionally, it is assumed that transmission-level components in substations, specifically transformers, have an *N*+1 redundancy as it is common practice in many power grids. However, this redundancy may not be observed when evaluating the location of the considered components. For example, it is common practice that large transformers are *N*+1 redundant but that the redundant transformer is collocated with the nominal operating transformers in which case all transformers could be damaged in an earthquake with significant intensity at the substation where those transformers are located. Transmission lines may also be redundant, although in their case, it is more common to have redundant lines running on different paths, which would reduce the probability of simultaneous damage. In terms of power sources for Centerville, the town can receive power from both power stations in the region immediately neighboring Centerville and shown in Fig. 5-4 and also from other power stations beyond this region through two transmission lines on the north and two transmission lines on the south. Evidently, ability to power the region in Fig. 5-4 is dependent on the power consumption of all five towns, and the capacity of both power plants and the four transmission lines into this region. It is also assumed that the regional power generation dispatch center and regional system operations facility are backed up by another similar facility located away from the zone in Fig. 5-4 and connected through a private communication network with all necessary components of Centerville's and the region's power grid.

5.6. Step A4: Establish Component Objectives - Maximum Level of Damage and Return to Operation Time

5.6.1. Target Maximum Component Damage

Volume 1 Table 4-4 defines the component-level performance objectives in terms of tolerable component damage. Table 5-6 provides guidance descriptions of the expected damage level related to the terms identified in Volume 1 Table 4-4 for newly designed and constructed or existing components in an electric power system. These damage descriptions follow the general descriptions given in Volume 1 Table 4-5 and can be applied to any electric power system.

Table 5-6. Electric Power System Damage Level and Summary Descriptions

Damage Level	Summary Description
Minor	Minimal to no perceivable damage to electric power system components. Limited to no effects on electric power system operations; able to continue essential emergency operations and most normal operations**.** For facilities[a], this damage level is equivalent to the Immediate Occupancy Structural Performance Level and Operational Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the minor impact level buildings and structures that are a part of the electric power system have minimal to no damage to their structural and essential nonstructural components. Buildings are safe to occupy and able to continue essential emergency operations. Injuries to building occupants are minimal in number and minor in nature. Nonstructural systems, including mechanical and electrical equipment, needed for normal building use and emergency functions are fully operational, but may require adjustments for external utilities (e.g., water, wastewater, communications), which may need to be provided from alternative emergency services. Damage to building contents is minimal in extent and minor in cost. Minimal hazardous materials are released to the environment**.** Power stations and substations remain operable and may require some minor repairs**.** There is little to no damage to mechanical and electrical equipment**.** Transformers, storage tanks, reservoirs, and other key components have minor damage which may warrant investigation due to safety precautions, but do not result in safety concerns or any significant limitations to operations. Circuit breakers, relays and other protections may be triggered but when they are reset after inspection, they did are not triggered again and operations are not limited**.** Transmission and substransmission lines and associated components along their paths, such as reactive power compensation components, have minor to no perceivable damage and transmission operations are not affected**.** Electric power distribution feeders and laterals, and transformers and other components in distribution circuits, such as voltage regulators, have minor damage, resulting in very few faults or service affecting issues which are easy to repair and impact a small number of customers. Ancillary equipment, including those used for sensing and control, have minor damage and do not affect operations.

[a] Buildings and facilities that are part of the electric power system.

Table 5-6. Electric Power System Damage Level and Summary Descriptions (continued)

Damage Level	Summary Description
Moderate	Damage is repairable. There may be some delay in re-occupying buildings[1]. Essential emergency functions are fully operational. Emergency systems remain fully operational**.** For facilities[a], this damage level is equivalent to the Damage Control Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the moderate level, for buildings that are a part of the electric power system, structural damage is repairable, and some delay in re-occupying buildings is expected. Nonstructural systems needed for building use and essential emergency functions are fully operational, although some cleanup and repair may be required. Emergency systems remain fully operational. Injuries to building occupants may be locally significant but are generally moderate in number and in nature; the likelihood of a single life loss is low and the likelihood of multiple life loss is very low [ICC, 2022]. Some hazardous materials are released to the environment, but the risk to the community is minimal. Power stations and substations may be damaged requiring temporary removal from operation for limited repairs, but not on an emergency basis (i.e., can remain operable following the earthquake, but a temporary shutdown may be warranted within days to weeks after the event)**.** Similarly, there is limited damage to mechanical and electrical equipment, but not to the extent electric power grids system operations are seriously impacted (e.g., some equipment may require repairs but can be undertaken without serious disruption to operations)**.** Transformers, storage tanks, reservoirs and other key components may have some damage which may warrant immediate investigation due to safety precautions and some repairs but have limited to insignificant impacts to operations. Circuit breakers, relays and other protections may be triggered but although they can be reset after inspection they may require some repairs or recalibration that have limited to insignificant impacts to operations. Transmission and substransmission lines and associated components along their paths, such as reactive power compensation components, may have minor damage which require line disconnection and repairs, but no serious damage or line interruptions occur. Electric power distribution circuits may be interrupted, potentially locally impacting services provided to customers**.** Ancillary equipment, including those used for sensing and control, have moderate to minor damage requiring little to some limited repair, but no serious damage requiring immediate removal from service.

[a] Buildings and facilities that are part of the electric power system.

Table 5-6. Electric Power System Damage Level and Summary Descriptions (continued)

Damage Level	Summary Description
High	Significant damage is expected. Structural damage to components may be repairable**.** For facilities[a], this damaging level is equivalent to the Life-Safety Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the high impact level, there is significant damage to structural elements of buildings that are necessary for the electric power system to deliver its service, but no large falling debris, is expected. Repair of the structural damage is possible, but significant delays in re-occupancy can be expected. Nonstructural systems needed for normal building use are significantly damaged and inoperable. Emergency systems may be significantly damaged but remain operational. Injuries to building occupants may be locally significant with a high risk to life but are generally moderate in number and nature. The likelihood of a single life loss is moderate, and the likelihood of multiple life loss is low [ICC, 2022]. Hazardous materials are released to the environment and localized relocation is required [ICC, 2022]. Power stations and substations may be significantly damaged resulting in removing them from operation until repairs are completed**.** Similarly, damage to mechanical and electrical equipment may require extensive repairs or replacement**.** Transformers, storage tanks, reservoirs and other key components may show observable and significant damage warranting immediate investigation and potential removal from use due to safety precautions, but do not pose a threat of a catastrophic failure or explosion. Circuit breakers, relays and other protections are triggered and show damage, also requiring their removal of service but do not pose a threat for catastrophic failure or explosion**.** Transmission and sub-transmission lines and associated components along their paths, such as reactive power compensation components, may have significant damage in one or more segments, requiring them to be shut down for repairs**.** Electric power distribution feeders and laterals, and transformers and other components in distribution circuits, such as voltage regulators, have many failure points locally impacting services provided to customers**.** Ancillary equipment, including those used for sensing and control, can have serious damage requiring them to be removed from use for repair.

[a] Buildings and facilities that are part of the electric power system.

Table 5-6. Electric Power System Damage Level and Summary Descriptions (continued)

Damage Level	Summary Description
Severe	Substantial damage is expected. Repair may not be technically feasible**.** For facilities[a], this damaging level is equivalent to the Collapse Prevention Structural Performance Level and Hazard Reduced Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023]. At the severe impact level, for buildings that are a part of the electric power system, substantial building structural damage is expected, and repair may not be technically feasible, though all significant structural components are intended to continue carrying gravity load demands. Partial or total collapse is possible [ASCE, 2023). The building is not safe for re-occupancy because re-occupancy or aftershocks could cause collapse. Nonstructural systems for normal building use may be inoperable, and emergency systems may be substantially damaged and inoperable. Injuries to building occupants may be high in number and significant in nature. Significant hazards to life may exist. The likelihood of life loss is high. Significant amounts of hazardous materials may be released to the environment and relocation beyond the immediate vicinity is required [ICC, 2022]. Power stations and substations may be significantly damaged resulting in removing them from operation until significant repairs or rebuilding is completed. Similarly, damage to mechanical and electrical equipment may require extensive repairs or replacement**.** Transformers, storage tanks, reservoirs, circuit breakers and other key components have clearly observable damage without the need of inspections that results in the certain need for replacement of the entire component or for repairs. Transmission and sub-transmission lines and associated components along their paths, such as reactive power compensation components, show damage and circuit interruptions in multiple locations forcing the removal of lines from service until extensive repairs are completed**.** Electric power distribution feeders and laterals, and transformers and other components in distribution circuits, such as voltage regulators, have extensive damage in many segments, impacting services provided to a vast majority of customers**.** Ancillary equipment, including those used for sensing and control, have damage beyond repair requiring them to be removed from use and completely replaced.

[a] Buildings and facilities that are part of the electric power system.

5.6.2. Target Return to Operation Time

The target time increments for returning components to operation within the Centerville electric power system are identified in Volume 1 Table 4-6.

To aid the preliminary design in Step A6, each physical component should have a potential repair time estimated and then added to any expected or assumed time increment after the earthquake to initiate work plus lead times as described in Volume 1 Sec. 4.6.2. In Step A7, the resulting estimated time is compared to Volume 1 Table 4-6. For example, consider a buried cable (e.g., 4ft to 6ft) below a very narrow and busy street. If the cable experiences moderate damage in an earthquake, it may take a week or more to make the repair. This time increment is longer than what is identified for a Criticality Category III component experiencing a 975-year return period earthquake hazard per Volume 1 Table 4-6. As a result, a Criticality Category III cable having these specific site conditions may need to be designed to a higher-level standard.

The repair time increment objectives therefore represent another type of acceptance criterion for newly designed and constructed components or the retrofit of existing components in an electric power system. The repair time increment objectives may be taken strictly during component design or incorporated into a broader system-level analysis in Step A9. Following a system analysis, if the basic service recovery times are shown to be met, even if the component recovery time increment exceeds the target duration in Volume 1 Table 4-6, then the component design may be deemed acceptable.

Due to simplifications, recovery time increments for all components in the Centerville example are not prepared, and the preliminary design in Step A6 conforms with Volume 1 Table 4-6. Electric power systems are recommended to consider specific component conditions when applying the framework.

5.7. Step A5: Identify Dependent Services

The electric power system is dependent upon services from other lifeline infrastructure systems identified in Table 5-7. These dependencies are identified for the Centerville example. Additional dependencies may be identified for electric power systems in general.

In general, negative impacts from dependencies on resilience can be mitigated with local buffers. Buffers for water, natural gas, and fuel are realized in practice with local storage tanks that are distributed using tanker trucks and transportation networks. The autonomy of a buffer for power plant fuels can vary greatly. Locally stored fuels for nuclear power plants could last for years, whereas coal storage could last at most for a few days. In many cases, natural gas is not stored locally in power stations. Backup fuel storage for generators can also vary greatly but rarely exceed a few days. Additionally, fuel for operations vehicles is stored in tanks commonly located in operations and maintenance yards. These normally provide enough supply for refueling vehicles for up to a few days. No significant buffers exist for dependencies on communication system services.

Additionally, it is important to realize that the potential effects of dependencies are related mostly to administration and management but are also observed to a lesser degree for other activities and are affected by organizational processes and interactions among different teams and organizations. Thus, although the focus of Table 5-7 is on services provided by infrastructure systems, other dependencies could be identified when considering services provided by humans to humans, which can be evaluated based on the discussion presented in Volume 1 Ch. 5 and that, in particular, relates to Steps O3 in Volume 1 Fig. 5.1a. One example of such dependencies observed in power grids is the need to coordinate restoration activities among grid operators in charge of generation, transmission, and distribution subsystems because it is possible to find, particularly in de-regulated power grid environments, that the three subsystems in which power grids are divided are operated by different organizations. Thus, dependencies based on the need for information and, in some cases, resources, are established among operators of the three subsystems, because of the need to coordinate restoration activities among personnel from the different organizations. Dependencies among these organizations are further exemplified in Sec. 5.11.8 through the need for coordinating restoration activities.

Table 5-7. Electric Power System Component Dependencies

Component/Activity	Dependent upon services from System
Generation	Water Natural gas Transportation
Backup generators (conditional dependencies)	Liquid fuels or natural gas Transportation
Vehicles (damage inspection and repair)	Transportation Gas Fuels Liquid fuels
Administration	Communications
Loads	Water Natural gas Wastewater Transportation

5.8. Step A6: Develop Preliminary Design

Centerville's power grid is based on an existing hypothetical system which has already been constructed, but not designed for functional recovery. Hence, since power systems across the country have not been designed for functional recovery, this example will utilize the existing designed and constructed system that has not been modified for functional recovery to carry out the remainder of the framework; this will realistically represent the situation that will be found when applying this framework.

To carry through with the framework, this example identifies the underground distribution line UDL1 running from substation D3 to Main Street and the community center area by crossing the river using the Main Street bridge. Like a typical underground cable, after 25 years of operation, the cable needs to undergo a preventive replacement to avoid unscheduled outages caused by the cable failing as a result of aging. This cable serves a relatively old area of Centerville, so its load of 13 MW and other design aspects have not changed significantly from the time when it was originally installed using a direct burial method protected only by a weak cement backfill except along the Main Street bridge where the cable runs inside a PVC pipe secured to one side of the bridge. The cable is an XLPE AG 4/0 copper conductor rated for 35 kV.

As shown in Fig. 5-5, this feeder serves multiple loads for Critical Customer A types and, thus, it is a Criticality Category IV component. Parts of its path, such as those segments crossing the Rock River are subject to soil liquefaction and permanent ground deformation, for which the direct burial method makes it vulnerable to damage under the earthquake scenario considered. Because Centerville is not considered to be at a higher risk of other hazards, particularly severe storms, the design process results in replacing the underground feeder by an overhead circuit that is much less vulnerable to earthquake effects such as permanent ground deformations and soil liquefaction. The poles supporting the overhead line can be located outside of the potential liquefaction-induced lateral spreading zones. An overhead line is, thus, found to meet the seismic demands for the UDL1 circuit.

Although UDL1 has no functional dependencies, it has a physical dependency as it uses the Main Street bridge to cross the Rock River. However, because the Rock River is sufficiently narrow, an overhead crossing is feasible, thus, reducing the seismic risks associated with depending on the bridge to cross the river. The main drawback of using an overhead line instead of the existing underground cable is poor aesthetics. Yet, the City Council approves the overhead line as it considers that the high criticality of this electrical circuit and the longer-than-needed repair times for underground cables (i.e., longer times than those in Table 5-4a and Volume 1 Table 4-6), which includes finding the damage points in a sequential process and digging at each point of failure, outweighs concerns about aesthetics. The new overhead feeder is not expected to be damaged. As a result, this design does not incorporate repair time, or any direct or indirect costs associated with putting this circuit back into service.

5.9. Step A7: Assess Component Performance and Repair Time, Compare with Target Objectives

The feeder design described in the previous section based on Step A7 is not expected to be damaged for the design level transient ground motions, even when performing a series of assessments to transient motions exceeding the design level PGV. In addition, the design can handle ground movements up to several cm of horizontal and vertical displacements without damage. Volume 1 Table 4-4 indicates that the newly designed overhead feeder should not sustain more than moderate damage, which according to Step A4 Table 5-6 implies that electric power distribution circuits may be interrupted, potentially locally impacting services provided to customers. The default acceptance criteria in Volume 1 Table 4-6 suggests that the main line should be repairable within few hours to days. These criteria are identified based solely on the design criteria of Volume 1 Table 4-2 and the component Criticality Category (i.e., this is independent of any intensity measures associated with an earthquake event scenario). As a result, the newly designed overhead feeder is expected to meet or exceed the target performance and recovery time criteria and path 'Yes' is followed in Volume 1 Fig. 4-1a. This allows a system-level evaluation to be performed using Volume 1 Fig. 4-1b.

5.10. Step A8: Identify Recovery Time Factors

The recovery time factors described in Volume 1 Sec. 4-10 were reviewed. They are all applicable to the Centerville electric power system and will be assessed as part of Step A9. No additional dependencies to those listed in Table 5-7 were identified, except for those above-mentioned items related to human-provided services and organizational processes, which are not discussed in detail here for being out of the scope of this example.

5.11. Step A9: Assess System Performance and Recovery Time

The Centerville electric power system assessment uses the earthquake event scenario described in Sec. 2.7 to evaluate expected basic service disruptions and recovery times using metrics that allow the results to be compared with the information provided in Tables 5-4a and 5-4b. The assessment covers all the subsystems in Table 5-2 and how they interact regardless of who owns or operates them. Hence, the assessment includes both assets that are found within the limits of Centerville and power generation and transmission components that belong to the regional power grid infrastructure shown in Fig. 5-4 as their performance affects electric power supply to Centerville. As indicated, recovery time assessment involves coordinating activities of the different organizations managing each one of the three power grid subsystems. Thus, the recovery time assessment needs to take into account the effect of organizational processes as described, in particular, Step O6 shown in Volume 1 Fig. 5-1a. Another example of organizational processes affecting recovery time is found in the impact of restoration crew training activities preparing for potential future earthquakes in reducing recovery time if/when these events happen. These examples show the critical importance that organizational processes have during service restoration activities and, thus, identifies the need to integrate the recovery time assessment influenced by organizational processes as described in Volume 1 Ch. 5.

5.11.1. Effects of the Earthquake Hazards on the Centerville Electric Power System

The scenario earthquake event and hazards are described in Sec. 2.7.1. This assessment is streamlined for the purpose of illustrating how to implement the framework. Actual systems may experience more or less damage than described in this assessment. Figures 5-7 and 5-8 show the general extent and severity of damage to electric power infrastructure. Descriptions of the impacted components are found in Table 5-8, which identifies each damage location as [**I*x***] as found in Figures 5-7 and 5-8, where *x* indicates a number to distinguish all impacted components. Damages to other lifeline infrastructures providing serves to power grid facilities are not indicated in the table or figures but they are discussed in the following subsections.

Figure 5-7 shows that there are two main areas with significant damage to power system components, based on the corresponding fragility curves. One of these areas is near the earthquake epicenter southwest of Centerville where the power plant and substation are damaged near the earthquake epicenter; these damages are indicated as [**I2**] and [**I3**] in Fig. 5-7, and, thus, affects service to Centerville from the south via the transmission line TL1. The other area of more significant damage to power system components is along the Rock River and other water bodies in Centerville. Based on the fragility curves, damage is observed on the power supply to Centerville from the north via both TL1 and the Centerville Power Station [**I16**] and its substation [**I17**], and from the south via TL2 as some spans of this transmission line are affected due to proximity to the Rock River south of Centerville [**I5**]. Thus, the only remaining path to power Centerville is via TL2 from the north, which is, nevertheless, compromised by moderate damage to substation D4 [**I11**]. Additional description of the damage to electric power generation, transmission, and distribution is given in the following subsections. Notice also that other damage suffered to the transmission system affects neighboring cities, with the most critical case observed in Westville which had its power supply compromised due to the damage ([**I3**], [**I6**], [**I7**], and [**I8**]) suffered by the transmission line serving this town both on the north and south. Restoring services to this town will affect resource availability to Centerville and, thus, will impact Centerville power supply restoration.

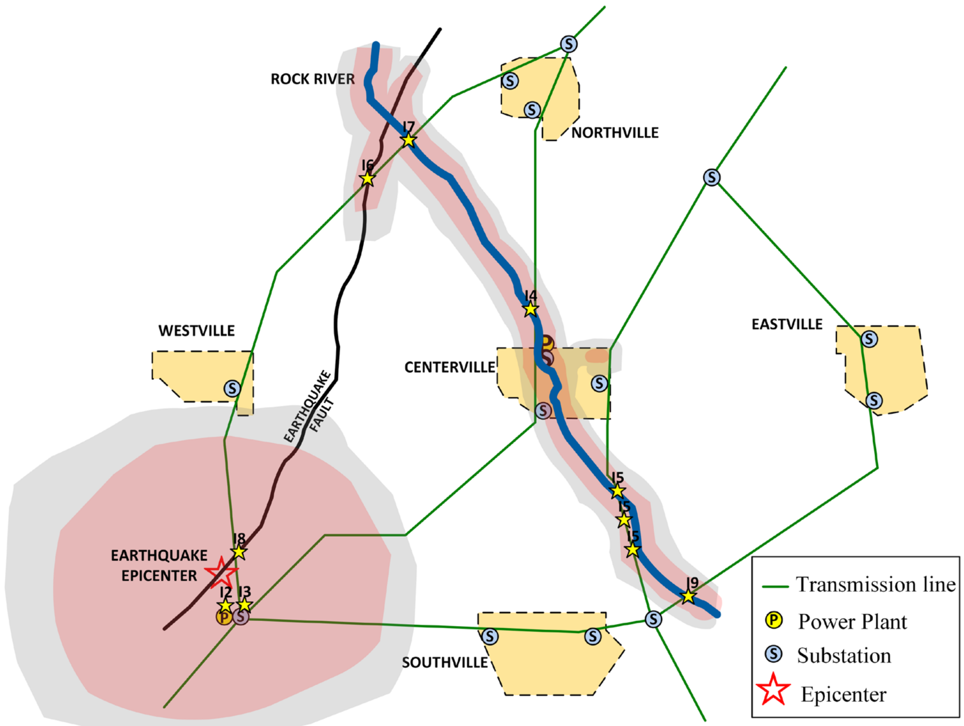

Fig. 5-7. General extent and severity of damage to power grid components at a regional level. Shaded areas represent in a qualitative way ground motion and permanent ground deformation decreasing from the epicenter, the river and Centerville's flood plain. Yellow star identifies a damage location.

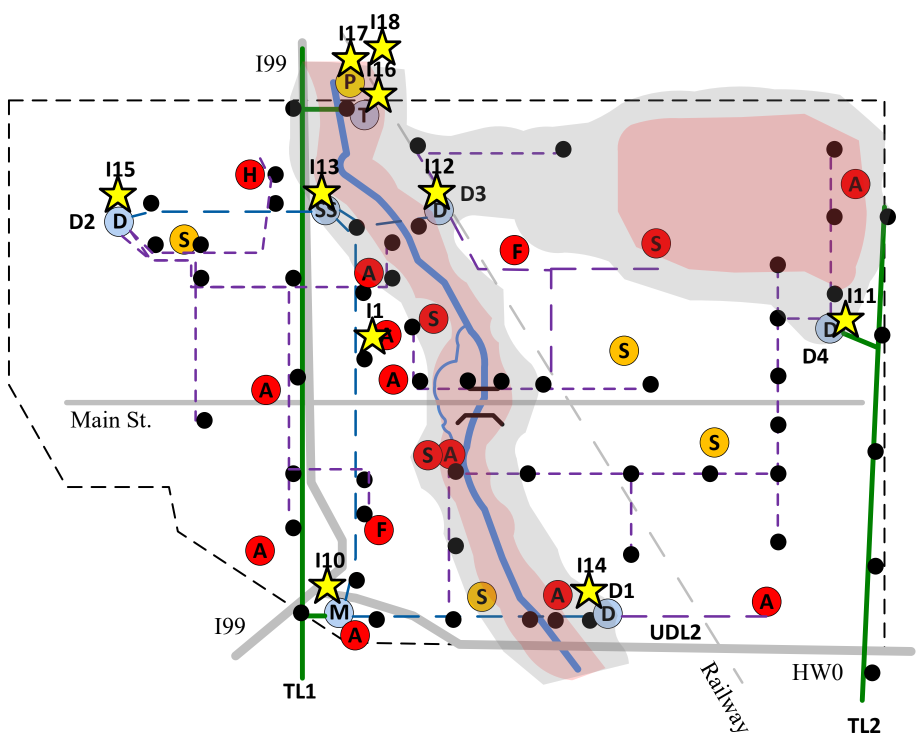

Fig. 5-8. General extent and severity of damage to power grid components in Centerville caused by the earthquake. Shaded areas represent in a qualitative way ground motion and permanent ground deformation decreasing from the river and Centerville's flood plain. Yellow star identifies a damage location. See also legend in Fig. 5-6.

Additionally, the CEPD headquarter offices collocated with the Water Department headquarters building are highly damaged from shaking and lateral spreading [**I1**] and is unusable until repaired. The operations and maintenance yard buildings and structures collocated with the power station had moderate damage [**I18**], particularly to the warehouse building used to store spare parts and, thus, this damage also impact operations.

Table 5-8. Summary of Expected Damage to Electric Power System

No.	Component	Damage	Repair Time[1]	Repair Description
I1	HQ Building	Moderate building structural damage	2 years	Repair structural and nonstructural
I2	Power Station SW of Centerville	Damage to electric equipment, such as the electrical generators and turbines, boilers and coal conveyor belts, and building structure	8 months; 1.5 year	8 months to repair the generator and turbine and have some limited operational capability 1.5 years to repair the building structure
I3	Substation of the power station SW of Centerville	Damage to transformers, circuit breakers and other critical components	4 months	Replacement of damaged bushings in transformers and circuit breakers
I4	Transmission line TL1 Rock River crossing north of Centerville	Two towers collapsed due to foundation failures.	4 days	Installation of three temporary towers replacing the damaged ones.
I5	Transmission line TL2 Rock River crossing south of Centerville	Six towers collapsed due to foundation failures	14 days	Installation of temporary towers replacing damaged ones
I6	Westville-Northville line crossing over earthquake fault	Two towers with bended braces	4 days	Replacement of damaged braces
I7	Westville-Northville line crossing over Rock River	Two towers collapsed due to foundation failures	5 days	Replacement of fallen towers with temporary ones
I8	Transmission line south of Westville crossing over earthquake fault	Two towers with bended braces	4 days	Replacement of damaged braces
I9	Southville-Eastville line Rock River crossing east of Eastville	Two towers collapsed due to foundation failures	7 days	Replacement of fallen towers with temporary ones
I10	Substation M	Tripped relays and minor damage to control building and other non essential controllers	12 hours	Inspect damage and reset relays

Table 5-8. Summary of Expected Damage to Electric Power System (continued)

No.	Component	Damage	Repair Time[1]	Repair Description
I11	Substation D4	One transformer with damage and one circuit breaker with damaged bushings	3 days	Deployment of a mobile substation
I12	Substation D3	One transformer with damage and two circuit breakers with damaged bushings	3 days	Deployment of a mobile substation
I13	Substation SS	Damaged bushings at a voltage regulator and damaged sensing equipment	3 days	Bypass damaged voltage regulators and replacement of damaged sensing equipment
I14	Substation D1	Tripped relays and damaged capacitor bank	12 hours	Reset relays and isolate damaged capacitor bank
I15	Substation D2	Tripped relays	6 hours	Reset relays
I16	Centerville's Power Station	Minor structural damage to buildings and moderate damage to ancillary equipment and battery bank	2 months	Replacement of damaged ancillary equipment
I17	Substation of Centerville's power station	Damage to transformers, support structures and towers due to liquefaction.	3 months	Replacement or repair of damaged components
I18	Maintenance yard and buildings	Moderate damage warehouse	2 days	Clear debris to access spare parts and installation of container serving as office.

5.11.1.1 Lifelines for Power Stations (Natural Gas and Water Networks)

Two lifelines are of particular interest to ensure operations of both power stations shown in Fig. 5-7: water and natural gas networks. CEPD's power station in Centerville is fueled by natural gas. The water and natural gas networks are affected by the earthquake. The details of how the water supply for the Centerville Power Station is interrupted due to water system damage (e.g., see damages [**D16**] and [**D17**] and also Table 3-8) are described in Ch. 3. Description of how water supply to the power station southwest of Centerville is affected, is not detailed here because the focus is on the Centerville Water Department and the Centerville Water Supply Company, which are not serving that power station. However, multiple breaks and the proximity of that power station to the earthquake epicenter results in several weeks of service interruption.

Although natural gas networks are out of the scope of this report, it is necessary in order to provide a complete assessment of the CEPD to include some general assumptions about the natural gas networks serving the power station in Fig. 5-5. Based on the characteristics of the earthquake and the location of Centerville's power station in a vulnerable zone (Rock River bank where liquefaction occurred) the natural gas network serving this facility experienced significant damage that resulted in the inability to provide natural gas to this power plant for several weeks. Since the Centerville Power Station lacks any natural gas storage facility, even when the damage in the power plant [**I16**] and its associated substation [**I17**] is repaired, power generation will not resume until natural gas service is restored.

5.11.1.2 Electric Power Generation

The power station southwest of Centerville [**I2**] experienced severe shaking due to its proximity to the epicenter resulting in damage to the building, including the stack, and most of the equipment, like the generators and turbine, boilers, and coal transport system such as conveyor belts. The collocated substation [**I3**] also experienced significant damage to components including transformers and circuit breakers. Both facilities require extensive repairs to be put back into service.

The Centerville Power Station [**I16**] also suffered damage but not as significant as the coal power station. The damaged equipment includes ancillary components, like two pumps that are part of the cooling system. The battery bank was also damaged. Soil liquefaction and differential ground movement caused damage to one transformer and various support structures and towers in the substation collocated with the power station [**I17**].

5.11.1.3 Electric Power Transmission

Because electricity in the Centerville region is transmitted with overhead lines, significant damage that would have happened if the lines were underground was avoided. Still, some transmission lines experienced localized damage. In particular, the line running north from the substation collocated with the power station southwest of Centerville and passing Westville before reaching Northville had two spans [**I6**] [**I8**] affected when the line crossed the earthquake fault. Two towers at each of these two points had bent braces due to the excessive torques caused by fault surface rupture. Still, these towers remained in operation although repairs to the bent braces needed to be completed promptly to avoid additional stresses from aftershocks or storms that could cause the towers to fail and collapse. However, due to damage at the substation next to the power station southwest of Centerville, this transmission line cannot be energized from the south until repairs at the substation are completed. Additionally, this line cannot be energized from the north because of more serious damage to a span crossing the Rock River. At this river crossing [**I7**] soil liquefaction caused the foundation of the towers at each bank of the river to fail. Fortunately, adequate design practices prevented other towers from being brought down in a domino cascading fashion. Similar damage of transmission line towers collapsing due to foundations failing because of soil liquefaction is observed in transmission lines TL1 [**I4**] and TL2 [**I5**], and the transmission line running from Southville to Eastville [**I9**]. This damage prevents power delivery to Centerville from the north using TL1 and from the south using TL2 until repairs are completed. Additionally, transmission line TL1 cannot be energized from the south due to the damage experienced by the substation [**I17**] collocated with the power station southwest of Centerville.

5.11.1.4 Electric Power Distribution

Since most of the electric power distribution in Centerville uses overhead lines, damage to distribution lines is minimal even to the few paths that are buried because they are not running in areas affected by liquefaction. Damage to substation D1 [**I14**], D2 [**I15**] and M [**I10**] is minor or non-existent; in some cases just requiring resetting tripped relays. Although substations D3 [**I12**], D4 [**I11**] and SS [**I13**] experience more damage as indicated in Table 5-8 because of their location in areas with some liquefaction, this damage is not as significant as that observed in the substations described in the previous subsection.

5.11.1.5 Other Dependencies

Because of the improvements described in Step A6 to the underground line using the Main Street bridge to cross the Rock River, failure of this bridge does not have an impact on the electric power grid. No other bridges or cases of shared infrastructure components are observed in the Centerville power grid so there is no impact due to other dependencies except from those described in Sec. 5.11.1.1.

5.11.1.6 Service Losses

Electric power supply from the CEPD is completely interrupted in all of Centerville after the earthquake. The only customers who are able to utilize electric power, such as the hospital, are those who maintain their own onsite emergency diesel generators. Power outages also affected neighboring cities, especially Westville which also experinces a complete loss of electrical services.

5.11.2. Response and Service Restoration

Immediately after the earthquake, the CEPD utility crews start to assess damage. However, completion of tasks were hindered by damaged and obstructed roads, and the aftershocks. Also, damage to the headquarter building affected operations in various ways. One important impact is how the regional dispatch center, which is in the building, stops operating. Thus, within the first few hours after the earthquake, operations of the dispatch center are transferred to the backup facility located outside of the affected region. Restoration activities are also affected by damage to the headquarters building. Since the alternative facility is the O&M building and yard collocated with Centerville’s power station, which also suffered damage, temporary offices are set within the first week after the earthquake in containers equipped as offices that are placed in open areas of the O&M yard.

Damage to both power stations in the region and to the natural gas network used to fuel Centerville’s power station are severe enough to prevent their operation for at least a few months after the earthquake. Thus, the only option for restoring power in Centerville, besides some local solutions through system adaptation measures using diesel generators, is to rely on transmission lines carrying power from generating stations that are located outside of the affected area and, thus, remain operational. Because damage to transmission lines serving Centerville is more severe in the south, restoration efforts initially focus on restoring service through the lines from the north. However, as Fig. 5-7 shows, there are only two transmission lines coming from the northeast serving the entire region except Southville. Thus, even when additional transmission capacity becomes available once the Southville-Eastville line crossing over the Rock River [**I9**] is repaired a week after the earthquake, available capacity remains constrained leading to the need to implement electric power usage rationing in the entire city at 50 % of normal by implementing rotating scheduled power outages to power distribution circuits.

Of the two transmission lines serving Centerville, transmission line TL2 does not suffer damage from the north and, thus, is able to remain operational once the section south of the substation D4 is isolated to prevent damage south of Centerville [**I5**] affecting its operation. However, damage to substation D4 [**I11**] negates the possibility of powering loads in Centerville using transmission line TL2. Electric power delivery service to the entire east and southeast of Centerville is restored 3 days after the earthquake thanks to the use of a mobile substation deployed to substation D4. The following day, repairs to transmission line TL1 north of Centerville [**I4**] are completed, thus restoring electric power delivery to the rest of Centerville as repairs to all connected substations to this line had been completed at least provisionally by the previous day. Quality services are assumed to be restored along with the delivery service. As indicated, once electrical delivery service is restored in Centerville, power usage is rationed to 50 % of normal, except to Critical A Customers because they keep critical loads powered from locally installed generators as described below. Rationing at this level remains in place for 10 more days until repairs to transmission line TL2 south of Centerville [**I5**] are completed, thus allowing power to flow directly from the transmission line powering the region from the southeast without passing through Eastville. Once the repairs to TL2 are completed, power usage to the east and southeast of Centerville (indicated as zones E and SE, respectively, in Fig. 5-9) is rationed at 75 % of normal. Power rationing for the rest of Centerville, served by TL1 remains at 50 % of normal due to the damage suffered at the substation southwest of Centerville [**I3**]. To alleviate this situation and considering the extent of the damage in the substation, a temporary transmission line running parallel to HW0 is installed connecting TL1 and TL2. This line is completed 30 days after the earthquake at which time power rationing to all of Centerville becomes 75 % of normal. Power rationing for non-critical loads is lifted 4 months after the earthquake, once repairs at the substation southwest of Centerville are completed. As a result, power quantity is recovered throughout Centerville 4 months after the earthquake.

After the earthquake Critical A Customers experienced loss of electrical service. In particular, all schools serving as emergency shelters, the recreational center and the chemical storage facility on Centerville’s southeast corner experienced a complete outage. Service to these facilities was restored by deploying mobile generators within 36 hours after the earthquake. The mobile generators were deployed by the CEPD and for safety reasons they were connected to the main service circuit breaker panel. Other Critical A and B Customers, such as the hospital, fire stations, the community center and government offices, and the transportation department, avoided loss of power thanks to the permanent diesel backup power generators located in their facilities. Not all of the water and wastewater facilities have permanent backup generators, so service restoration to these facilities follow the same strategy as the other Critical A Customers. Use of generators, whether they are permanent or mobile, are limited to the critical loads (i.e., noncritical power usage is rationed) within these facilities to curtail fuel consumption and, thus, reduce logistical needs related to refueling operations. Such usage restriction is lifted once the delivery power service from the electric grid is restored in the zones where these loads are located (i.e., at 3 or 4 days depending on the location in Centerville). Once the power delivery service is restored, the Critical A Customers no longer are required to ration power and the portable generators are redeployed. Due to their importance for the community, electricity rationing to Critical B Customers is removed once power is restored to the zones where these customers are located due to the redeployment of mobile generators that become available as power service restoration starts.

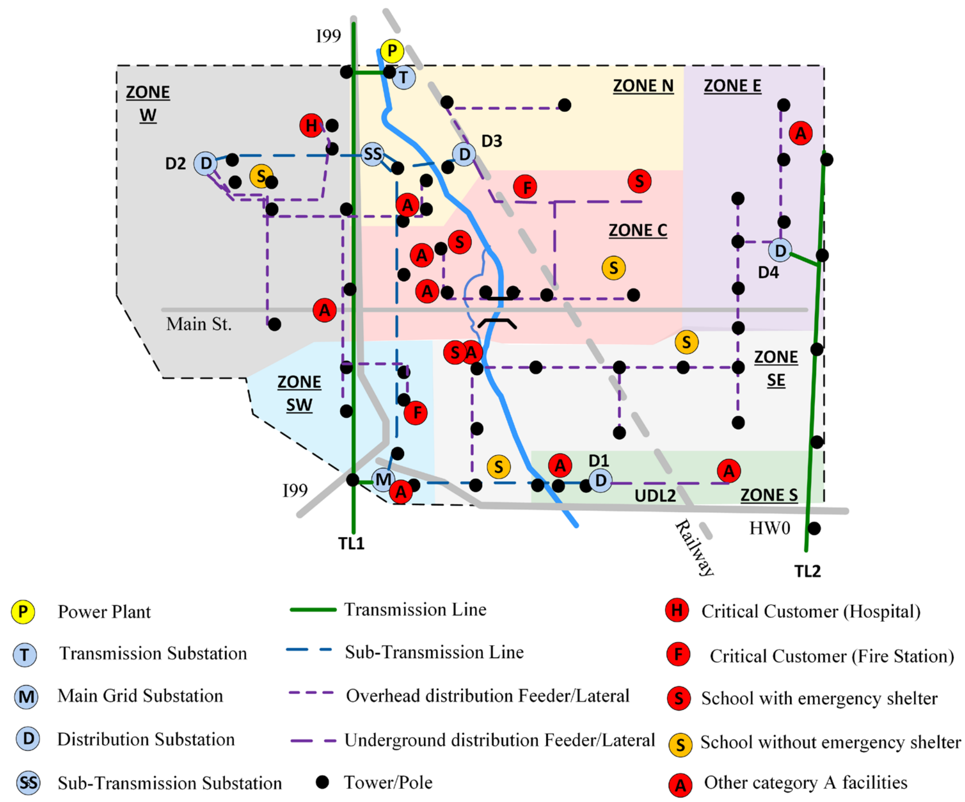

Fig. 5-9. Electric power provision for geographical zones in Centerville.

The recovery times given in Table 5-9 identify only the basic services and when complete operability is reached. Many of the facilities were temporarily repaired to allow them to be put back into operation. Like for other infrastructure systems discussed in earlier chapters, much more effort and time are necessary to reach full functionality for the system, which is important and should also be assessed, but it is beyond the scope of this example looking only at functional recovery.

Table 5-9. Electric Power System Basic Service Restorations

Service Zone	Delivery		Quality		Quantity	
	Dur.	**Descr.**	**Dur.**	**Descr.**	**Dur.**	**Descr.**
N	4 d	Repair I4	4 d	Repair I4	4 m	Repair I3, I5, I9
W	4 d	Repair I4	4 d	Repair I4	4 m	Repair I3, I5, I9
SW	4 d	Repair I4	4 d	Repair I4	4 m	Repair I3, I5, I9
C	4 d	Repair I4	4 d	Repair I4	4 m	Repair I3, I5, I9
E	3 d	Repair I11	3 d	Repair I11	4 m	Repair I3, I5, I9
SE	3 d	Repair I11	3 d	Repair I11	4 m	Repair I3, I5, I9
S	4 d	Repair I4	4 d	Repair I4	4 m	Repair I3, I5, I9

Table 5-9. Electric Power System Basic Service Restorations (continued)

Service Zone	Delivery		Quality		Quantity	
	Dur.	Descr.	Dur.	Descr.	Dur.	Descr.
Community Center & Government Offices	0 h	N/A	0 h	N/A	4 d	Repair I4
Hospital	0 h	N/A	0 h	N/A	4 d	Repair I4
Northern Fire Station	0 h	N/A	0 h	N/A	4 d	Repair I4
Southern Fire Station	0 h	N/A	0 h	N/A	4 d	Repair I4
Home Depot / Walmart	4 d	Repair I4	4 d	Repair I4	4 d	Deploy genset, repair I4
Water Pump West	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Water Reservoir Pump	36 h	Deploy genset	36 h	Deploy genset	3 d	Repair I11
Water Treatment Plant	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Wastewater Treatment Plant	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Wastewater Pumping Station	36 h	Deploy genset	36 h	Deploy genset	3 d	Repair I11
High School	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Northern Middle School	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Southern Middle School	36 h	Deploy genset	36 h	Deploy genset	3 d	Repair I11
Eastern Elementary School	3 d	Repair I11	3 d	Repair I11	3 d	Deploy genset, repair I11
Western Elementary School	4 d	Repair I4	4 d	Repair I4	4 d	Deploy genset, repair I4
Center Elementary School	4 d	Repair I4	4 d	Repair I4	4 d	Deploy genset, repair I4

Table 5-9. Electric Power System Basic Service Restorations (continued)

Service Zone	Delivery		Quality		Quantity	
	Dur.	**Descr.**	**Dur.**	**Descr.**	**Dur.**	**Descr.**
Southern Elementary School	3 d	Repair I11	3 d	Repair I11	3 d	Deploy genset, repair I11
Recreational Center (Emergency Shelter)[a]	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Transportation Department	12 h	Reset relays in substation M	12 h	Reset relays in substation M	4 d	Repair I4
Chemical Storage Location	36 h	Deploy genset	36 h	Deploy genset	4 d	Repair I4
Eastern Elementary School	3 d	Repair I11	3 d	Repair I11	3 d	Deploy genset, repair I11

[a] When emergency shelter is activated.

5.12. Step A10: Compare System Assessment Results with Target Objectives

5.12.1. Comparing Assessed and Target Recovery Times

Tables 5-10a and 5-10b compare the basic service recovery times given in Table 5-9 with the target recovery times given in Tables 5-4a and 5-4b. As seen in Tables 5-10a and 5-10b right columns, some of the target basic service recovery times are met and some are not. Additionally, given the uncertainty in the type of assessment undertaken in Step A9, some of the assessed recovery times may vary from those indicated and times that would meet community needs, may, in reality exceed those limits and vice-versa. In any case, path 'No' is followed in Volume 1 Fig. 4-1b and modifications are needed to the electric power system so the basic service recovery time objectives may be achieved in future earthquakes which may strike Centerville (i.e., the scenario in Ch. 2 and other expected scenarios).

Table 5-10a. Comparison of Basic Service Recovery Times from System Assessment with Target Recovery Times in Table 5-4a

BSC	Service Description	Target Recovery Time	Is Target Met?
Delivery	Restore to 100 % of all Critical A Users	1/2 day	No
	Restore to all customers	10 days	Yes
Quality	Restore to high-power commercial, industrial, and institutional users	5 days	Yes
	Restore to industry having sensitive equipment	5 days	Yes
	Restore to all customers	10 days	Yes
Quantity	Restore to 100 % of all Critical A Users	1/2 day	No
	Restore to 50 % of all customers	7 days	No
	Restore to 100 % of all Critical B Users	10 days	No
	Restore to all customers	15 days	No

Table 5-10b. Comparison of Basic Service Recovery Times from System Assessment with Target Recovery Times in Table 5-4b

BSC	Service Description	Target Recovery Time	Is Target Met?
Delivery	Restore to CEPD	1 day	No
Quality	Restore to CEPD	1 day	No
Quantity	Restore energy demand to CEPD	4 days	No
	Restore to pre-event normal demand (rationing removed)	10 days	No

5.12.2. Making System Modifications and Framework Iterations

Since not all the target service recovery time objectives were met, Volume 1 Fig. 4-1b shows the next part of the process is to revise the system recovery time factors in Step A8 and/or the performance and service recovery time objectives in Tables 5-4a and 5-4b. It is most important to focus on how to first modify the recovery time factors to identify cost-effective ways to improve the system performance and recovery before attempting to change (i.e., lengthen) the service recovery time objectives. The service recovery time objectives target societal needs for the electric power system services so extending these durations results in potentially not meeting the needs of the community. Therefore, this example will proceed with investigating how to modify the system assets and organizational actions while maintaining the target service recovery time objectives in Tables 5-4a and 5-4b.

Table 5-10a shows that two main targets are not met: delivery target for 100 % of Critical A Customers/Users and all of the quantity targets. Additionally, Table 5-10b shows the transmission delivery and quantity targets were not met. By distinguishing the criticality of specific electricity users, the presented functional recovery framework focuses on local, disaggregated analysis. As a result, prioritization of more critical users in functional recovery restoration may favor local solutions over solutions supporting centralized systems. Such an approach for improvements can be observed when attempting to meet the 1/2-day delivery objective for all Critical A Customers/Users because use of microgrids or backup generators for these loads is more economic effective than solutions based on centralized power grid designs, which could require high investments. As explained, there are still strategies to reduce the financial impact of such centralized system-based designs, for example, by considering longer time horizons that allow coordinating retrofit solutions with unavoidable and necessary maintenance required equipment replacements. Still, even when the solution for achieving both delivery targets is to equip all critical loads either with backup power generators or, in cases of interest, like the hospital, a microgrid, selections of sources for microgrids needs to be done carefully to avoid outages caused by damage to their lifelines for fueling power generators. Details of how such design can be achieved can be found in Kwasinski et al. [2024]. Additional seismic improvements should be implemented to address the missed quantity targets. These include, but are not limited to:

- Improvement of foundations in transmission line towers and other structures near the Rock River.
- Make the temporary line south of Centerville parallel to HW0 permanent.
- Build a new transmission line from the east to the southern substation in Eastville.
- Seismically upgrade (mitigate) both power stations and their collocated substations
- Seismically upgrade (mitigate) the regional dispatch center and headquarters.
- Build a new operations and maintenance facility with a warehouse and yard southeast of Centerville.

With a proper design for the new components using the appropriate Criticality Categories as shown in Fig. 5-5 it is expected that the electric power system will meet the delivery, quality, and quantity objectives. Additionally, enhancements are not necessarily dependent exclusively on equipment changes because performance and service recovery time may be improved by modifying some organizational actions. The above-listed outline focusses on how asset improvements will aid in meeting the recovery time objectives, but these are costly and time-consuming. However, modifying organizational processes will likely be less costly than asset improvements. Some asset improvements are required while at the same time some organizational activities must be modified to meet the objectives. Example modifications of organizational actions are summarized in Ch. 3 Sec. 3.12.2 for the water system example that are also applicable to this electric power system example.

It is beyond the scope of this example to provide detailed guidance on how to modify the assets and organizational actions to meet the performance objectives. The main point is to show that once the comparison of recovery time objectives is made, and if system modifications are needed, the process then iterates to identify which changes may be made to portions of the assets and organization. These are then designed in accordance with the framework and another assessment and comparison made. The process is continued until the performance and recovery time objectives are met. If in special cases, after investigating all options for modifying the assets and organizational actions, some objectives cannot be met for cost or logistical reasons, they may be revisited, coordinated with the community and all critical customers, and modified if appropriate as described in Volume 1 Chapters 3, 4, and 5.

5.13 Step A11: Report System Assessment Results

The system assessment results are documented and filed in a safe place for future reference and use. An important aspect of reporting is to ensure all the appropriate findings can be put into practice. The reported results should be used as feedback for decision makers and the planning process as described in Volume 1 Sec. 3.1. The modifications identified in Step A10 are to be described in the CEPD pre-earthquake mitigation plan, prioritized, budgeted, and implemented. The results should be used to update emergency management and emergency operations plans, continuity plans, asset management plans, seismic mitigation programs, and capital investment strategies and plans. Additionally, the results may be used to improve and update at the system and community levels the comprehensive or master plans, state and local hazard mitigation plans, recovery plans, and resilience plans. The final list of improvements and the basic service recovery time objectives presented in Tables 5-4a and 5-4b are presented to the public so that they are aware of what electric power system improvements are taking place and the anticipated durations at which basic services may be disrupted during similar future earthquakes.

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APPENDIX A. PIPELINE NETWORKS TO SUPPORT FUNCTIONAL RECOVERY

A.1 Introduction

This appendix provides example applications of water and wastewater networks useful for aiding the functional recovery of the systems. The purpose of these examples is to show how a network can be laid out to achieve the framework criteria as described in Volume 1, published as NIST SP 1310 [NIST, 2024], Ch. 4 and applied to the water and wastewater systems in Chapters 3 and 4, respectively.

A.2 Example Water Distribution Network for Functional Recovery

Every distribution grid provides fire service to the area. Pipelines providing fire service are designated as Criticality Category IV in Table 3-5. Additionally, many residential zones contain schools which are designated as Critical Customer B, or Critical Customer A if they are used as emergency shelters, resulting in the mainlines being designated as Criticality Category III or IV. Similarly, business districts may also have acute care medical or other facilities designated as Critical Customer A or B in an area otherwise populated with customers designated as Critical Customer C. Further, these same areas may also contain recreational parklands and open space that are irrigated with water provided through mainlines which may be designated as Criticality Category I. This results in distribution networks having mainlines ranging from Criticality Category I to IV. The overlying concern is how to install a water distribution network without requiring all mainlines to be designed as Criticality Category IV to meet the fire service and other Critical Customer A needs in areas mostly populated with customers of lower criticality. The simplest layout is to employ only Criticality Category IV pipelines. However, using only Criticality Category IV pipelines may not be the most cost-effective solution. This appendix provides an example to show how a water distribution grid may be laid out using the multiple-use, continuity, and redundancy concepts described in Volume 1 Sec. 4.5 to employ an assortment of mainlines potentially ranging from Criticality Category I to IV.

For continuity, all the mainlines connecting from the trunk line and feeding zones Z1 to Z11 in Fig. 3-1 are designated Criticality Category IV because they are used to provide the fire protection basic service. Figure A-1 shows the layout of a typical zone distribution grid with isolation valves, fire hydrants, and mainline criticality categories meeting the criteria to be a seismically resilient pipe network [Davis, 2018]. For simplicity, not all fire hydrants and houses are shown in Fig. A-1. Figure A-1 provides an example of how the distribution grid is laid out to meet the multiple-use, continuity, and redundancy criteria described in Volume 1 Sec. 4.5.

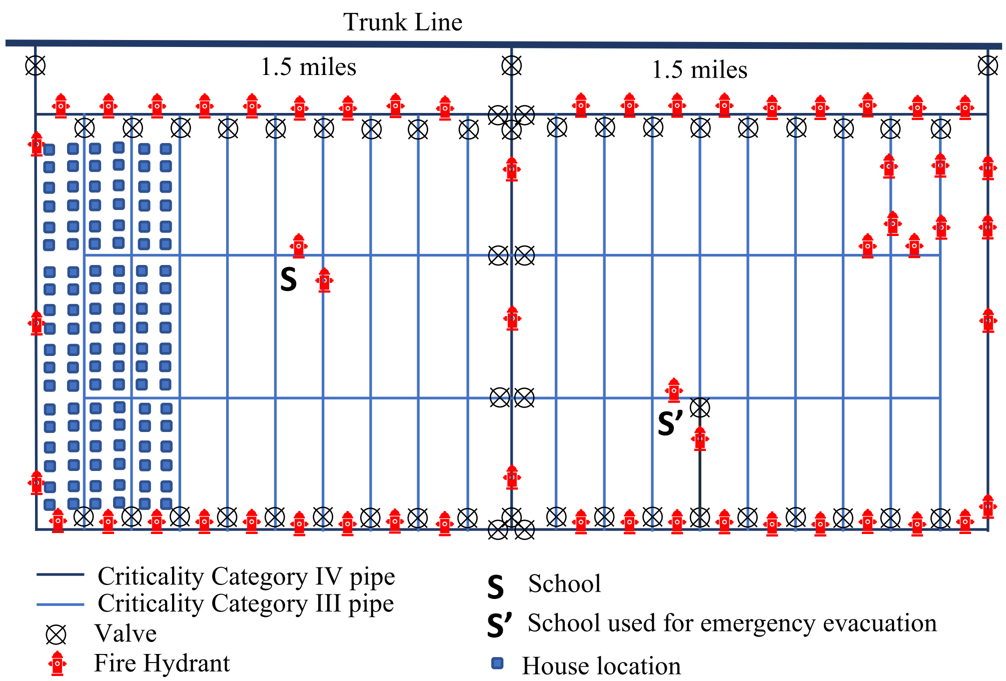

Fig. A-1. Example potable water distribution pipe grid (4.82 km by 2.78 km or 3 miles by 1.5 miles). For clarity, not all houses or fire hydrants are shown.

Figure A-1 shows a mainline connecting from a trunk line to feed a single-family residential neighborhood. This could represent zones Z1 to Z7 in Centerville (see Figures. 2-1 and 3-1). The trunk line and connecting mainline are assigned Criticality Category IV. As shown in Fig. 3-1, all trunk lines feeding to these zones have continuity with Criticality Category IV components to the Rock River water source. The pipelines are buried beneath the streets, but street locations are not shown in Fig. A-1.

The Criticality Category IV mainline creates two loops measuring 2.78 km by 2.78km (1.5 miles by 1.5 miles) each. The loops have three Criticality Category IV connections to trunk lines to provide redundancy, each equipped with an isolation valve. The grid resiliency can be improved with valved connections to other trunk lines. This appendix focuses on the distribution network within the mainline grid shown in Fig. A-1, so no further explanation is provided on the transmission subsystem. However, the concepts can be used to develop a resilient water transmission network [Davis, 2018]. The mainline loops provide redundancy for water delivery within the zone. Each branch from the T connections forming the loops has a valve that can be used to isolate a portion of the loop if there is damage. If a loop is isolated, the neighborhood can still be served by routing water through an alternate path. To aid in this delivery method, additional valves not shown in Fig. A-1 are installed to reduce the number of customers who may be removed from service during a repair. The greater the number of loops and isolating valves, the greater the redundancy and resilience of the network. The Criticality Category III mainlines described in the next paragraph also aid in adding looped redundancy to the Criticality Category IV pipelines.

Within the loops of Criticality Category IV mainlines resides a grid of Criticality Category III mainlines. The Criticality Category III mainlines have valves located at each connection to the Criticality Category IV mainlines to allow them to be isolated if they were damaged in an earthquake sufficient to create enough hydraulic losses to reduce the ability for the Criticality Category IV pipelines to operate as required. All residential customers are served by Criticality Category III or IV pipelines to meet the criterion described in Table 3-5 because residential customers are identified as Critical Customer B in Table 2-2. The Criticality Category III mainlines running left to right provide redundancy within the grid and could be assigned as Criticality Category II pipelines if they were equipped with valves at connections to the Criticality Category III pipelines; they could also be connected to the Criticality Category IV pipelines with isolation valves.

This example seismic resilient pipe network shows two schools within the neighborhood like that for zone Z4 in Centerville; one that is planned to be used as an emergency shelter during a disaster and one that is not, identified as S' and S respectively in Fig. A-1. Table 2-2 defines the school S' as a Critical User A and S as a Critical User B. In accordance with Table 3-5 school S' is to be served by a Criticality Category IV pipeline and school S may be served by a Criticality Category III pipeline, as shown in Fig. A-1. The mainline serving school S' has continuity with all other Criticality Category IV pipelines and has valves at the connections to the Criticality Category III mainlines.

All lines in Fig. A-1 are equipped with fire hydrants to provide fire services in the neighborhood. For clarity of the image, not all hydrants are shown. Table 3-4a identifies hydrants within 0.81 km (0.5 mile) of Critical A Users and multi-resident users and within 1.61 km (1 mile) of any other area requiring fire protection to have fire protection basic service restored within three days. This assumes the Centerville Fire Department maintains equipment that can be deployed and relay water to these distances (The Centerville Water and Fire Departments need to coordinate using Step O3). The double loop of Criticality Category IV mainlines of dimension 2.78 km by 2.78 km (1.5 miles by 1.5 miles) around the neighborhood is intended to help accomplish this basic service recovery target. The Critical User A school S' has water provided by the Criticality Category IV mainline equipped with fire hydrants to meet the 0.81 km (0.5 mile) distance criterion. All points within the rest of the neighborhood are within less than 1.61 km (1 mile) of a hydrant on a Criticality Category IV mainline.

All the zones in Centerville can have a seismic resilient pipe network layout like that described and shown in Fig. A-1. The grids for industrial, business, and other types of zones can be created similar to the residential zone in Fig. A-1 but using the proper Criticality Category pipelines to meet the Critical Users defined in Table 2-2. The zones having hospitals, fire stations, police stations, toxic or explosive materials, and other facilities defined as Critical User A should have Criticality Category IV mainlines branching from the main loops like those used for school S' in Fig. A-1. Networks may have grids made of Criticality Category II pipelines for Critical User C facilities. They can also include Criticality Category I pipelines (e.g., serving non-essential agriculture or recreational parks for irrigation.

Further, analysis performed as part of Step A9 can be used to show if and how the Criticality Category III mainlines in Fig. A-1 may be reduced to Criticality Category II; more easily in areas not experiencing permanent ground deformations. The main point of this framework is to create water networks that can provide the basic services within the target recovery times identified in Table 3-4a in the most cost-efficient manner possible. It is beyond the scope of this report to undertake the analyses, but to develop cost-effective networks the analyses are encouraged to identify the most efficient layout using Criticality Category I to IV pipelines. The ability to reduce mainline Criticality Categories is significantly enhanced through the looping layout shown in Fig. A-1 and explained earlier in this appendix. The looping and isolation capability using valves is valuable even for the lower-level Criticality Category mainlines connecting to the higher-level Criticality Category mains.

Fig. A-1 provides a single example water distribution grid useful to aid in functional recovery showing how the criteria provided in the assets framework can be met in multiple ways without always requiring the pipeline component design to meet the highest Criticality Category. Other layouts are possible. It is beyond the scope of this report to identify the range of possible resilient network layouts.

A.3 Example Wastewater Collection Network for Functional Recovery

Figure A-2 presents an example of a wastewater collection network useful for functional recovery showing Critical Customers/Users A, B, and C and their service connections to the pipe network. The Critical A Customer is represented by a hospital identified as the box with a '+'. Houses represent Critical B residential customers. The industrial area represents Critical C Customers. The pipe network is primarily gravity flow except for one force main coming off the lift station.

All component pipelines are defined as having Criticality Categories in accordance with Table 4-5. To ensure continuity for components providing service to multiple user types (e.g., hospital and residential), the higher Criticality Category is used in accordance with Volume 1 Sec. 4.5.1. For example, all components downstream of the hospital are defined as Criticality Category IV, even when they serve Critical Customers/Users B and C. This includes pipelines, the lift station, and the treatment plant for the example presented in Fig. A-2. Above the hospital, only residential customers exist. The pipelines serving the residential Critical B Customers above the hospital are designated Criticality Category III in accordance with Table 4-5. As seen in Fig. A-2, the pipeline starts with Criticality Category III pipe segments in the upper left of the diagram and changes to Criticality Category IV pipe segments at the hospital. On the upper right side of the diagram, an industrial area exists having Critical C Customers. These Critical C Customers are served using Criticality Category II pipelines in accordance with Table 4-5. Downstream of the industrial area are Critical B Customers from residential neighborhoods. As a result, the segments change to Criticality Category III pipelines until the line reaches the manhole where the pipe intersects with the line serving the hospital.

Analysis performed as part of Step A9 can be used to show if and how the Criticality Category III mainlines in Fig. A-2 may be reduced to Criticality Category II; more easily in areas not experiencing permanent ground deformations. The main point of this framework is to create wastewater networks that can provide the basic services within the target recovery times identified in Table 4-4 in the most cost-efficient manner possible. It is beyond the scope of this report to undertake the analyses, but to develop cost-effective networks the analyses are encouraged to identify the most efficient layout using Criticality Category I to IV pipelines. Unlike water systems shown in Fig. A-1 where the pressurized pipelines commonly make up a redundant grid, wastewater pipelines usually provide gravity flow and do not make a looped network and therefore lack redundancy. As a result, it may be more difficult to show through network analysis how wastewater Criticality Category III pipelines can be reduced to Criticality Category II. However, if the structural integrity of the pipelines can be shown to continue to perform services in a damaged state meeting the criteria in Table 4-6 at a moderate damage level as a Criticality Category II subjected to 975-year return period hazards, then potentially the Criticality Category III can be reduced to Criticality Category II.

Figure A-2 provides a single example wastewater distribution grid useful for functional recovery showing how the criteria provided in the assets framework can be met in multiple ways without always requiring the entire pipeline component design to meet the highest Criticality Category. Other layouts are possible. It is beyond the scope of this report to identify the range of possible resilient network layouts.

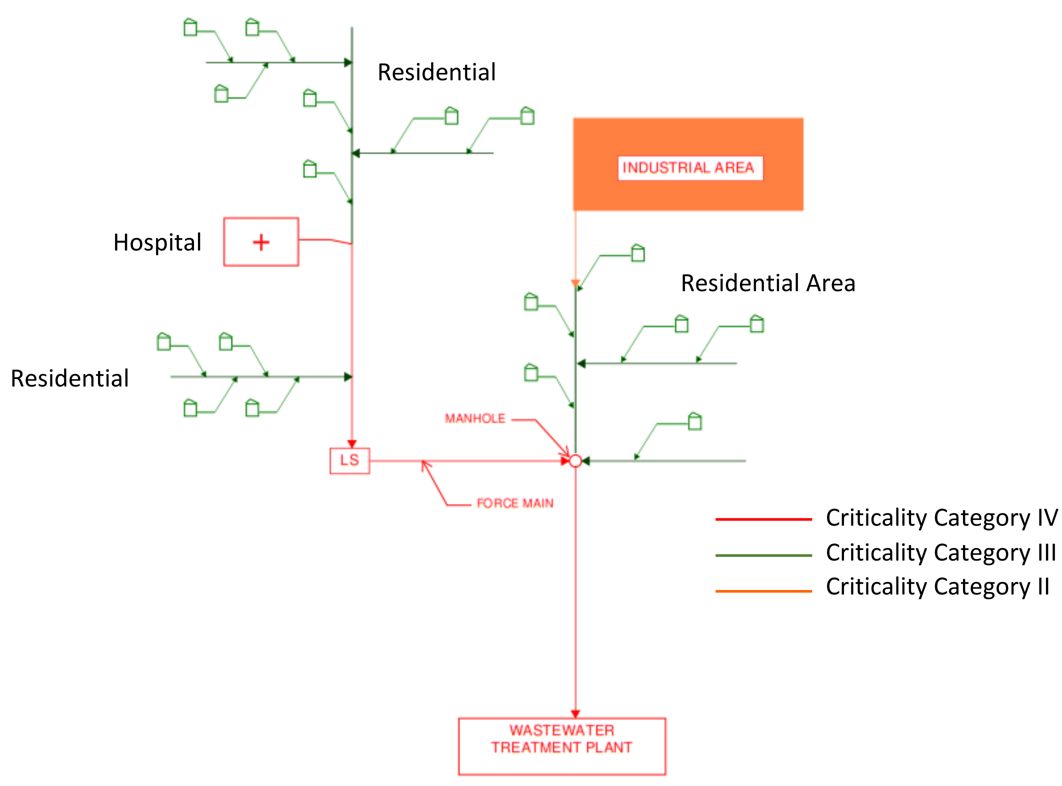

Fig. A-2. Example wastewater pipe network.