NIST GCR 16-917-39

# Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery

By
*Applied Technology Council*

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Community Resilience

NIST
National Institute of
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U.S. Department of Commerce

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Cover image – Emergency generators en route to Montgomery, Alabama following April 2011 tornadoes (Photo credit: FEMA). Drinking water distribution following Hurricane Sandy, November 2012 (Photo credit: FEMA)

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# Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery

Prepared for
*U.S. Department of Commerce*
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U.S. Department of Commerce
*Penny Pritzker, Secretary*

National Institute of Standards and Technology
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# NIST GCR 16-917-39

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# Preface

In September 2014, the Applied Technology Council (ATC) commenced a task order project under National Institute of Standards and Technology (NIST) Contract SB1341-13-CQ-0009 to assess current societal expectations of acceptable lifeline performance levels and restoration timeframes that are informed by the phases of response and recovery, distinguishing those that are hazard independent and those that are specific for seismic (including tsunami), wind (including hurricane and tornado), flood, snow/ice, and wildfire hazard events.

The project included consideration of the social institutions and societal needs that should drive lifeline system performance levels and recovery timeframes and the assessment of current system guidelines/standards and performance criteria so that deficits could be identified and potentially addressed through better awareness and definition of community requirements and goals as part of the overall NIST Community Resilience Planning process.

The starting point for the project was an initial effort by the ATC-appointed Project Technical Committee to summarize key guidelines, standards, and current performance criteria, and to identify critical social considerations and system interdependencies. Those and subsequent efforts helped identify and form a set of overarching considerations and recommendations, which were then refined through several rounds of review by an ATC-appointed Project Review Panel.

The culminating effort was the development of this report, which contains:

- Detailed analyses of a broad range of societal considerations;
- Lifeline assessments and reviews of standards, guidelines, and performance criteria for electric power, natural gas and liquid fuel, telecommunication, transportation, water and wastewater systems;
- A review and analysis of available information on lifeline interdependency issues; and
- Findings, conclusions and recommendations that identify needed developments in lifeline codes, standards, and guidelines; needed research; modeling opportunities; and needs related to lifeline system operations and operational design.

ATC is indebted to the leadership of Laurie Johnson, who served as Project Director and Lead Editor, to Thomas D. O'Rourke, who served as Project Co-Director, and to the members of the Project Technical Committee, consisting of Stephanie Chang, Craig A. Davis, Leonardo Dueñas-Osorio, Ian Robertson, Henning Schulzrinne, and Kathleen Tierney, for their contributions in developing this report and the resulting recommendations. ATC similarly appreciates and recognizes the attentive review and input of the Project Review Panel, which consisted of Bruce Ellingwood, Timothy J. Lomax, Douglas J. Nyman, Dennis Ostrom, Jon Peha, and Kent Yu (ATC Board Representative). The affiliations of these individuals are provided in the list of Project Participants.

ATC also gratefully acknowledges Therese P. McAllister (NIST Technical Point of Contact), and Steven L. McCabe (Contracting Officer's Representative) for their input and guidance throughout the project development process. ATC staff members Veronica Cedillos provided project management support and Amber Houchen and Carrie Perna prepared draft and print-ready versions of this report.

Christopher Rojahn (Project Manager)
ATC Director Emeritus

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# Executive Summary

*Resilience* involves the ability of people and communities to adapt to changing conditions and withstand and rapidly recover from disruptions (Executive Office of the President, 2011). At the community level, this concept is complex and multi-dimensional, relying on contributions from social science, engineering, earth sciences, economics, and other disciplines to improve the ways communities prepare for, resist, respond to, and recover from disruptions caused by either natural hazards or manmade causes. Resilience is intended to reduce the impact of hazards by restoring a community to normal function in a specified timeframe, and in turn, reducing the duration and cost of recovery. This requires planning for recovery and restoration prior to hazard events.

Disasters can substantially reduce a community's resilience by interfering with the operation of infrastructure, such as electric power, natural gas and liquid fuel, telecommunication, transportation, and water and wastewater systems (herein collectively referred to as "lifelines"). Lifelines are often distributed over large geographic regions and have numerous interdependent levels of operation, making them especially exposed to the impacts of earthquakes, hurricanes, and other hazards that affect broad areas. As a result, lifelines can experience distress and malfunction at many locations which, in turn, can impede response and recovery. Lifeline system failures and disruptions can displace people, obstruct the social and economic institutions that comprise communities, and in the worst cases lead to death and long-term negative societal consequences.

This study of lifeline system performance was undertaken to better understand societal needs during recovery. The study was conducted as part of the National Institute of Standards and Technology (NIST) Community Resilience Program, a multi-year, multi-faceted program responding to the call for action laid out in *The President's 2013 Climate Action Plan* (Executive Office of the President, 2013b). The assessment described herein is intended to inform the *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (NIST, 2015). The *Guide* defines a six-step voluntary process for engaging stakeholders and representatives to define key social and economic needs and community functions; develop an inventory of the community's building stock and infrastructure systems; establish performance goals for buildings and infrastructure to serve key social and economic needs over a range of different hazard types; identify and evaluate gaps between the desired and anticipated performance of buildings and infrastructure; and set priorities and define strategies to reduce risks and improve the resilience of buildings and infrastructure systems in their community. The *Guide* recommends that communities identify and plan for the prevailing hazard types (e.g., wind, earthquake, inundation, fire, snow or rain, and technological or human-caused) that may have a significant effect on their built environment. It also recommends consideration of a range of hazard levels defined as: Routine (occurs frequently and is below the design level); Design (often based on codes and standards); and Extreme (above the design level and sometimes referred to as the maximum considered event).

The primary purpose of this study was to *assess current societal expectations of acceptable lifeline performance levels and restoration timeframes that are informed by the phases of response and recovery, distinguishing those that are hazard independent and those that are specific for seismic (including tsunami), wind (including hurricane and tornado), flood, snow/ice, and wildfire hazard events.* An additional goal of the study was to identify gaps between the desired and anticipated performance of lifeline systems to enable communities and lifeline system operators to set priorities and define strategies to reduce risks and improve lifeline resilience. In addition, this study was intended to provide a technical foundation for first-generation systems-based models that can be used to analyze community resilience and account for interdependencies among lifeline systems and the social and economic functions that they support.

This work included a series of assessments of electric power, natural gas and liquid fuels, telecommunications, transportation, water and wastewater systems, and more broadly examined the societal considerations and interdependencies associated with the performance of these systems. Each lifeline assessment summarizes current codes, standards, guidelines, manuals and performance requirements as well as societal considerations and critical infrastructure interdependencies. Each assessment also describes system performance, summarizes disaster lessons, discusses key gaps and deficits between expected lifeline system performance and the performance required to support societal needs, and makes recommendations for improvements.

## Findings

The findings address the current state of lifeline codes, standards, guidelines, and performance requirements; overarching societal considerations; critical interdependencies; disaster lessons (short- intermediate- and long-term recovery); key gaps and deficits; and future trends and considerations.

### *A. Current State of Lifeline Codes, Standards, Guidelines, and Performance Requirements*

The study provides a survey of the many codes, standards, guidelines, and manuals of practice that govern the design, construction and performance of lifeline systems and system components. While these instruments can serve as approximate indicators of societal expectations with respect to lifeline system performance, there are critical gaps. In particular, the great majority of lifeline system performance standards relate to normal day-to-day lifeline system operations and do not cover their performance during hazard events. Thus, they offer little guidance for communities wishing to understand how lifeline systems are likely to perform during and after a hazard event.

Other issues of interest with respect to lifeline codes and standards include: the gaps in codes and standards for some lifeline systems and system components; lack of consistency in the performance requirements for lifeline systems and system components; uneven treatment of hazards and hazard levels; emphasis on component-level instead of system-wide performance or interdependent function; emphasis on engineering and operational concerns relative to societal concerns; and the need for consistent standards development processes across lifeline systems.

### *B. Overarching Societal Considerations*

Empirical data and research literature on societal expectations for lifeline system performance are scarce. Without such data, inferences have to be made about those expectations. Gauging societal expectations across the United States is challenging given the diversity of social and economic demographics and vulnerabilities, variations in hazard exposures and levels of vulnerability, and the physical vulnerability of different lifeline systems. Societal expectations and tolerances for lifeline service disruptions are also dynamic and likely to be shaped by both risk perception and risk communication that are in turn influenced by prior experience with disasters and lifeline outages, understanding of the risks, redundancy and dependency on lost services, and available information about disruptions.

Using terminology from vulnerability science and resilience research, different segments of the population and sectors of the economy are differentially *exposed* and differentially *sensitive* to lifeline service disruptions. They are also different in their *adaptive capacities* when disruptions occur. The growing reliance on telecommunications and electric power systems can lead to performance expectations that exceed system capabilities. A gap between expectations and service capability makes the community more vulnerable when hazard-related disruptions occur.

Human health and safety, the functionality of health-care systems, and economic well-being are priority issues that this study has used in assessing and characterizing societal expectations for lifeline performance. Emphasis is also given to the short-term recovery phase (measured in days) following a major hazard event or other lifeline disruption since it is within this timeframe that societal impacts, such as deaths, injuries, and business interruption losses, are generally most acute. Also, practically speaking, the study found more data on short-term than on long-term disruptions.

### C. Lifeline Interdependencies

The study also investigated the interactions between lifeline systems during normal operations and system restoration after hazard-related events. Dependent and interdependent relationships among lifeline systems have evolved over time. Although they provide efficiency and other benefits during normal operations, they also introduce unique and largely unknown behaviors in hazard-related events and system disruptions.

There is a growing body of research on system modeling pertaining to lifeline system interdependencies that can be leveraged to improve resilience across lifeline systems. However, the vast majority of lifeline interdependency studies and tools tend to focus on the technical aspects of systems and the impacts of hazards on them. More emphasis on risk reduction, system restoration, and societal impacts are needed.

There is also a lack of unified performance and restoration goals across multiple and interdependent systems. Rigorous and readily implementable theories and methods for the study of lifeline system interdependencies are similarly lacking.

The assessments provided in this report reveal a number of critical dependencies and interdependencies across lifeline systems. Virtually every lifeline system depends on electric power and telecommunications for system control and monitoring. All lifeline systems also depend on fuel and transportation, particularly for service restoration and system repairs. Fuel is a critical contingency for power when outages occur. Water is critical for cooling in the generation processes for electric power. Water also helps with pollution control, and supports other infrastructure, such as natural gas and liquid fuel systems.

The colocation of multiple lifelines also increases the likelihood that failure in one system can damage and interrupt others. Because information is typically not shared among different lifeline operators, many areas of colocation are unknown. It is also important to recognize that some interdependencies are increasing with time, such as the expanding role that telecommunications play in monitoring and remote control of electric power, gas and liquid fuel, transportation and water systems.

### D. Disaster Lessons

In general, there is a substantial body of literature on the social and economic impacts of lifeline service disruptions, spanning studies on actual events—both hazard and non-hazard related—and scenario-based and probabilistic loss projections. The lifeline assessments found great variability in both the quantity and quality of data available for lifeline systems, hazard types and severity, and across the various phases of disaster-related response and recovery. Most studies of disaster related impacts on lifeline systems are event-specific; systematic, multi-event studies are generally rare. Also, in general, there is more information and a more complete understanding of the societal impacts and restoration patterns of short-term rather than longer-term disruptions.

In terms of recovery timeframes, disaster experiences show that most lifeline system outages generally last from hours to weeks (short- to intermediate-term recovery). In the most severe cases, outages can last for months or years. The long-term outages are associated with the most destructive events when critical and/or multiple components of lifeline systems that are time consuming to replace, such as buildings, bridges, piping, and essential equipment, must be reconstructed or replaced to restore system operability.

### *E. Key Gaps and Deficits: Codes, Standards, Performance Requirements, and Societal Considerations*

Overall, this assessment found uneven study and treatment of societal considerations in the codes and standards governing lifeline systems performance for different hazards. As previously noted, lifeline codes, standards, guidelines and manuals of practice are largely associated with the performance and safe operation of components rather than system response and levels of service. And even less common are efforts to consider interoperability issues across various lifeline systems (upstream and downstream interdependencies). In a few instances, system owners or operators have established system-level performance objectives or targets for a limited number of hazards. Most guidance does not address the range of hazard types considered in this study, particularly the low-probability/high-consequence events. In general, more is known about the lifeline impacts and performance objectives for earthquakes and wind-related hazard than for other hazards.

Strategies to enhance resilience will invariably require difficult investment decisions in the face of limited resources. To make rational decisions, lifeline owners and operators need to consider the tradeoff between risk reduction and financial investment. Quantitative uncertainty and risk analysis therefore need to be an integral part of performance requirements and criteria. In addition, risk communication needs to be an essential part of the overall dialogue, including public messaging.

Also, there is little information on societal expectations of system performance during routine, design, and extreme hazard events for most lifeline systems. Some potential "proxies" and informants for societal expectations of lifeline performance and recovery timeframes are available, including outage reporting thresholds and criteria, post-event reviews of utility performance, regulatory changes made following disruptions, societal and economic losses, and state and local energy assurance plans. Societal expectations may also be indirectly reflected in industry practices for service restoration following outages.

Currently there is a lack of systematic research or accepted methods for quantifying or even bounding the gap between the disaster capabilities of lifeline systems and the societal expectations of their performance. The study identified some important examples for how the gap between prescriptive performance and societal expectations can be filled, which include: community planning programs and stakeholder engagement in risk reduction planning and practices, as well as high quality system design, detailed risk assessments coupled with appropriate emergency planning, system monitoring, well-communicated emergency response procedures, and robust contingency planning and design.

### *F. Future Considerations and Trends*

This study identifies a number of considerations outside its scope as well as important trends that are likely to shape future lifeline system design and performance and societal expectations. As has been noted previously, societal expectations for lifeline system performance are changing, with decreasing societal tolerance for outages in general and lower thresholds for outage durations. Increasing interdependencies among lifeline systems, urbanization and the growing inventory of aging and deteriorating infrastructure increase the risk of system damage and disruption in future hazard-related events as well as the potential for cascading effects.

Future work both in research and applications related to community resilience needs to consider the following issues:

- Increasing social vulnerabilities due to an aging population, urbanization, and policies that are increasingly enabling disabled persons to remain in their homes where they are especially vulnerable to the loss of lifeline services;
- Economic vulnerabilities caused by the ongoing shift from a manufacturing to an information economy, growth of "cloud" based information technology, rising use of "just-in-time" strategies in inventory control and maintenance, and data storage, e-commerce and the expansion of the financial service sector, increases in telecommuting; and cost-cutting and efficiency measures in business and inventory management;
- Increasing vulnerabilities to distant lifeline disruptions caused by the continued rise of globalization, supply chains, and the interdependencies inherent in modern manufacturing and finance;
- Dependency of all lifeline systems on electric power and telecommunications for system control and monitoring;

- Increasing availability of renewable and distributed energy resources, grid modernization, decentralized power management, energy storage, and changes in the traditional structure of the electric power industry;
- Increasing physical and social vulnerability caused by the effects of climate change; and
- Lifeline system performance issues caused by theft of essential equipment (e.g., copper wire used in telecommunication systems), cyber-attacks, and other security threats.

Finally, the study cautions that unanticipated societal impacts will likely present themselves in future hazard events due to existing lifeline system vulnerabilities that remain poorly understood, absence of guidance on hazard resilient construction and installation practices, unknown and unfavorable states of repair, issues with system functional capacity, and ongoing changes in technology.

## Recommendations

Recommendations resulting from this study are organized to identify the needs associated with: (a) codes, standards, and guidelines; (b) research; (c) modeling; and (d) systems operations. These needs target lifeline operators, practitioners, regulators, and researchers concerned about societal considerations in hazard-related system performance and potentially involved in lifelines standards and code development related activities. The following set of overarching recommendations was derived from the individual assessments of the study team. They were then discussed and prioritized with the review panel. All recommendations shown below were deemed high priority. Additional recommendations are provided in Chapters 2 through 8.

### *A. Codes, Standards, and Guidelines*

This study reveals critical gaps in the codes, standards, and guidelines that govern the design, construction, and performance of various lifeline systems and system components. Ten recommendations are offered to address needs related to lifeline codes, standards, and guidelines. The priority rankings reflect organizational and framework needs, available information, new knowledge needs, guidelines and standards development needs, and scoping breadth, with recommendations that pertain to broad issues and improving community resilience considered higher priorities than recommendations for specific lifelines.

A1. Identify or establish an organization and process for advocating, harmonizing and unifying the consensus procedures for lifeline guidelines and standards development.

A2. Develop more consistent terminology for lifeline standards.

A3. Develop an up-to-date and complete suite of codes, standards, and guidelines for all lifeline systems to reflect the current state of practice, knowledge, and performance requirements.

A4. Develop a methodology to combine component-based design criteria into system level performance targets.

A5. Develop lifeline system performance requirements that relate to community resilience and better reflect societal considerations.

A6. Develop consensus-based guidelines and standards for the design of new lifelines and the retrofit of existing lifelines that reflect community resilience performance requirements and societal considerations.

A7. Develop guidelines to inform the design, interoperability, and upkeep of lifeline system dependencies.

A8. Reduce inconsistencies in the compendium of codes and standards that guide design, construction and resilience of the built environment, such as fire codes, building codes, and lifelines codes, standards, and guidelines.

A9. Develop consistent policy and standards on accessing information and databases about critical infrastructure systems that is coordinated with Department of Homeland Security critical infrastructure activities.

A10. Provide updated guidance for evaluating gas and liquid fuel pipeline and facility response to seismic hazards, floods, coastal storms, and tsunami-related inundation.

### *B. Research*

The study has identified a number of gaps in data and knowledge necessary to improve the fundamental understanding of acceptable lifeline performance. Fifteen recommendations with respect to systematic study and research needs are offered. All are considered high priority, with those encompassing all lifelines and broader topics listed before those related to only one lifeline.

B1. Gather information on and systematically study the relationships between service disruptions, and societal impacts and expectations to better understand lifeline system performance.

B2. Develop and conduct a targeted research program to assess societal expectations associated with lifeline system performance.

B3. Systematically study and compare the array of design approaches and methods for addressing societally-based performance requirements within current codes, standards and guidelines for lifeline systems.

B4. Investigate the differential vulnerability among social groups to lifeline system outages.

B5. Systematically collect and review various "proxies" and secondary evidence for societal expectations of lifeline performance and restoration timeframes.

B6. Assess the various lifeline performance programs and practices for public safety and develop guidance on their application to other critical lifelines, including multiple, interdependent systems and collocated facilities.

B7. Conduct research on needed service restoration times, including how system operability as a performance metric supports community resilience.

B8. Study lifeline system operator organizational issues and how they affect community-scale lifeline performance and resilience planning.

B9. Enhance the understanding of infrastructure-related failures and cascading effects resulting from low-probability/high-consequence events.

B10. Develop post-event data collection protocols to assess lifeline system recovery and restoration timeframes and improve the understanding of restoration processes across individual and interdependent lifeline systems.

B11. Develop tools to identify interdependent infrastructure systems and services along with their restoration criteria.

B12. Establish procedures to quantify hazards for spatially distributed systems.

B13. Enhance the understanding of lifeline system supply sources and end-point facilities and their role in system performance, restoration, and community and regional recovery with the goal of improving databases and modeling of such sources and facilities.

B14. Perform studies on changes in water demand considering an array of hazards as well as seasonal and longer-term climate variability, like drought.

B15. Improve knowledge, databases and modeling for the impact of widespread flooding and storm damage on regional fuel supplies.

### *C. Modeling*

There is a growing body of system modeling for lifeline systems and their interdependencies that can be leveraged to improve resilience across lifeline systems, but there are also notable limitations in scope, outputs, integration, and validation that need to be addressed. Three modeling related recommendations are offered. All are considered high priority, with those encompassing all lifelines and broader topics listed before those related to only one lifeline.

C1. Aggregate the existing suite of infrastructure modeling tools and create a user-friendly interface so communities can properly assess their lifeline-related system performance and restoration risks, including uncertainty.

C2. Develop first-generation models and practical tools to analyze community resilience that account for lifeline system dependencies and interdependencies.

C3. Improve numerical modeling of water and wastewater systems, with emphasis on validation of models, developing the most effective simulation procedures, and applications in real systems.

### *D. Lifeline System Operations*

The study also identifies a number of needs related to lifeline system operations and operational design. These too must be addressed in order to improve community resilience and bridge the gap between the post-event capabilities of lifeline systems and the societal expectations of their performance and restoration. Five recommendations are offered. All are considered high priority.

D1. Develop a process for major utilities to conduct self-assessments of their preparedness for various natural hazard events, as a basis for prioritizing improvement to system robustness and post-event response.

D2. Develop guidance for lifeline service providers on how to engage and collaborate with communities, including emergency management agencies and other key community institutions, in developing resilience strategies and preparing system restoration and contingency plans.

D3. Develop guidance for local planning (e.g., for fuel delivery to emergency responders and critical infrastructure).

D4. Develop guidance for lifeline service providers to evaluate the effects of system component failures, both in isolation and in combination, and considering upstream and downstream dependencies.

D5. Design protocols for lifeline service providers, working with emergency management and other community institutions, to communicate to the public the likely impacts of different hazard events on service provision and disruption.

# Chapter 1
# Introduction

Electric power, natural gas and liquid fuel, telecommunication, transportation, and water and wastewater systems are commonly referred to as "lifelines" because they sustain modern communities and are vital for the economic well-being, security, and social fabric of the people they serve (NIST, 2014). Lifelines are often distributed over large geographic regions and have numerous interdependent levels of operation, making them especially exposed to the impacts of earthquakes, hurricanes, and other hazards that affect broad areas. As a result, lifelines can sustain distress and malfunction at many locations which, in turn, can impede response and recovery. Lifeline system failures and disruptions can displace people, degrade the social and economic institutions that comprise communities, and in worst cases lead to deaths, injuries, and long-term negative societal consequences.

*Resilience* involves the ability of people and communities to adapt to changing conditions and withstand and rapidly recover from disruptions (Executive Office of the President, 2011). With respect to lifelines, community resilience involves a complex interaction among the people who depend on lifeline systems and the physical characteristics, operation, and management of those systems. People need access to the resources and services supplied by lifeline systems to withstand and recover from hazard-related disruptions. Also, the rate at which the functionality of lifeline systems is restored can have a major influence on a community's recovery trajectory and outcomes.

## 1.1 Impetus for the Project

The long-term social and economic hardships caused by the devastation of Hurricane Katrina in 2005, Hurricane Sandy in 2012, and other recent disasters have led to a number of initiatives and activities to improve community disaster resilience that have been supported by federal, state and local governments, as well as by the private sector, including non-profit organizations. They include the resilient city framework developed by the San Francisco-based civic organization SPUR (2009a), Baseline Resilience Indicators for Communities (BRIC) (Cutter et al., 2010), the Community and Regional Resilience Institute community resilience system (CARRI, 2013), Oregon Resilience Plan (OSSPAC, 2013), United Nations International Strategy for Disaster Reduction's *Disaster Resilience Scorecard for Cities* (IBM and AECOM, 2014), and *City Resilience Framework* developed by the Rockefeller Foundation and Arup (2014).

### 1.1.1 NIST Community Disaster Resilience Program and Community Resilience Planning Guide

The National Institute of Standards and Technology (NIST) Community Disaster Resilience Program is a multi-year, multi-faceted research and development program that also responds to *The President's 2013 Climate Action Plan* (Executive Office of the President, 2013b). The main objective of the NIST program is to develop guidance to assist communities in developing both short- and long-term measures to enhance resilience through improvements to buildings and infrastructure systems that the community depends upon for its social and economic functions. Examples of these functions include the provision of shelter, food, and water; access to health care; financial security; educational opportunities; and employment.

A central facet of the NIST program is the *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (NIST, 2015), which was released by NIST in October 2015. The *Guide* defines a six-step voluntary process for engaging community stakeholders and representatives to define key social and economic needs and functions of their community; inventory the community's building stock and infrastructure systems; establish goals for the desired performance of buildings and infrastructure to serve the community's key social and economic needs and functions in a series of hazard types; identify and evaluate gaps between the desired and anticipated performance of buildings and infrastructure; and set priorities and define strategies to reduce risks and improve the resilience of buildings and infrastructure systems in their community.

Specifically, the *Guide* suggests that communities define desired performance goals for both safety and functionality of buildings and infrastructure systems. Community performance goals are based on social and economic functions, such as education, healthcare, and banking needs. It also recommends that functionality goals be organized by timeframes, using the sequential disaster response and recovery phases defined by the *National Disaster Recovery Framework* (FEMA, 2011). As shown in Figure 1-1, they are: Short-term Recovery (focused on rescue and stabilization and generally lasts days following a disaster); Intermediate-term Recovery (focused on restoration and lasts weeks to months); and Long-term Recovery (focused on rebuilding and reconstruction and possibly lasts many months to years).

Once performance goals are established, the *Guide* also recommends that communities determine the anticipated performance of existing buildings and infrastructure systems and prevailing hazard types (e.g., wind, earthquake, inundation, fire, snow or rain, and technological or human-caused) that may significantly impact the built environment within a range of hazard levels. These hazard levels are defined as: Routine (events that occur frequently and are below the design level); Design (events typically addressed in codes and standards); and


Figure 1-1 Disaster recovery continuum in the National Disaster Recovery Framework (FEMA, 2011).

Extreme (events that exceed design levels and are sometimes referred to as maximum considered events). When goals and performance are compared, there are likely to be gaps between the anticipated and desired performance of buildings and infrastructure systems; those gaps can then be used to develop alternative temporary and permanent solutions and implementation strategies to enhance the resilience of buildings and infrastructure systems. Following the *Guide*, Figure 1-2 shows a hypothetical community example of the anticipated versus desired performance goals for transportation infrastructure and critical facilities in an extreme flood. In this example, the anticipated performance of key elements of the community's transportation infrastructure is generally lower and takes longer to recover its community functions than the desired restoration targets in the different phases of recovery.

In addition to its development of the *Guide*, the NIST Community Disaster Resilience Program has launched a Community Resilience Panel for Buildings and Infrastructure Systems that will bring together a diverse set of stakeholders to continue developing guidance metrics and tools needed to develop community resilience (for more information, see www.crpanel.org). In February 2015, NIST also announced establishment of a Community Resilience Center of Excellence that is focusing on tools to support community resilience, including the development of integrated, systems-based computational models to assess community infrastructure resilience and guide community-level resilience investment decisions. The center, led by Colorado State University, in collaboration with 10 other universities (for additional information, see resilience.colostate.edu/), will also develop a data management infrastructure, as well as tools and best practices to improve the collection of disaster and resilience data.

### *1.1.2 NIST Research, Development, and Implementation Roadmap for Earthquake Resilient Lifelines*

The NIST Community Resilience Program is part of a broader disaster resilience effort that includes the oversight of the National Earthquake Hazards Reduction Program (NEHRP), which was established by the U.S. Congress with its passage of the Earthquake Hazards Reduction Act of 1977 (USA Public Law 95-124, 1977).

| Disturbance [1] | |
|---|---|
| Hazard Type | Flood |
| Hazard Level | Extreme |
| Affected Area | Regional |
| Disruption Level | Severe |

| Restoration Levels [2,3] | |
|---|---|
| 30% | Function Restored |
| 60% | Function Restored |
| 90% | Function Restored |
| X | Anticipated Performance |

| Transportation Infrastructure | Support Needed[4] | Design Hazard Performance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Phase 1 Short-Term | | | Phase 2 Intermediate | | | Phase 3 Long Term | | |
| | | Days | | | Weeks | | | Months | | |
| | | 0 | 1 | 1-3 | 1-4 | 4-8 | 8-12 | 4 | 4-24 | 24+ |
| **Ingress (goods, services, disaster relief)** | | | | | | | | | | |
| Local Roads | R, S | | | 30% | 60% | 90% | X | | | |
| State Highways and Bridge | R, S | | | 30% | 60% | 90% | X | | | |
| Regional Airport | R, S | | | 30% | 60% | 90% | X | | | |
| **Egress (emergency egress, evacuation, etc)** | | | | | | | | | | |
| Local Roads | R, S | | | 30% | 60% | 90% | X | | | |
| State Highways and Bridge | R, S | | | 30% | 60% | 90% | X | | | |
| Regional Airport | R, S | | | 30% | 60% | 90% | X | | | |
| **Community resilience** | | | | | | | | | | |
| **Critical Facilities** | | | | | | | | | | |
| Hospitals | R, S | 30% | 60% | 90% | | X | | | | |
| Police and Fire Stations | R, S | 30% | 60% | 90% | | X | | | | |
| Emergency Operational Centers | R, S | 30% | 60% | 90% | | X | | | | |
| **Emergency Housing** | | | | | | | | | | |
| Residences | R, S | | | 30% | 60% | 90% | X | | | |
| Emergency Responder Housing | R, S | 30% | 60% | 90% | X | | | | | |
| Public Shelters | R, S | 30% | 60% | 90% | X | | | | | |
| **Housing/Neighborhoods** | | | | | | | | | | |
| Essential City Service Facilities | R, S | | | 30% | 60% | 90% | X | | | |
| Schools | R, S | | | 30% | 60% | 90% | X | | | |
| Medical Provider Offices | R, S | | | 30% | 60% | 90% | X | | | |
| Retail | R, S | | | 30% | 60% | 90% | X | | | |
| **Community Recovery** | | | | | | | | | | |
| Residences | R, S | | | 30% | 60% | 90% | X | | | |
| Neighborhood retail | R, S | | | 30% | 60% | 90% | X | | | |
| Offices and work places | R, S | | | 30% | 60% | 90% | X | | | |
| Non-emergency City Services | R, S | | | 30% | 60% | 90% | X | | | |
| All businesses | R, S | | | 30% | 60% | 90% | X | | | |

**Footnotes:**

**1** Specify hazard type being considered
Specify hazard level – Routine, Design, Extreme
Specify the anticipated size of the area affected – Local, Community, Regional
Specify anticipated severity of disruption – Minor, Moderate, Severe

**2** 30% | 60% | 90% Desired restoration times for percentage of elements within the cluster

**3** X Anticipated performance for 90% restoration of cluster for existing buildings and infrastructure systems
Cluster recovery times will be shown on the Summary Matrix

**4** Indicate levels of support anticipated by plan
R = Regional; S= State; MS=Multi-State; C = Civil (Corporate/Local)

Figure 1-2 Hypothetical examples of estimated current restoration times for community functionality conditions versus desired percent restoration levels for transportation infrastructure and critical facilities in an extreme flood (NIST, 2015).

NIST has served as the lead NEHRP agency since 2006, and has conducted numerous projects to meet NEHRP goals, including the development of improved techniques for reducing earthquake vulnerabilities of facilities and systems. In 2014, NIST released the NIST GCR 14-917-33 Report, *Earthquake Resilient Lifelines: NEHRP Research, Development, and Implementation Roadmap* (NIST, 2014), which identified a wide range of needed studies and is intended to guide the investments made by NIST and other NEHRP agencies in generating national performance and restoration goals and accompanying guidelines, manuals, and standards for lifeline systems and components.

Element I of the *Earthquake Resilient Lifelines Roadmap* identifies the priority research, development and implementation topics necessary for establishing national lifeline system performance and restoration goals. Topic 2 of Element I of the *Roadmap* specifically calls for a national assessment of societal expectations of acceptable lifeline performance levels and restoration times as a high-priority and a necessary part of the development of resilient design and construction goals for interdependent lifeline components, systems, and the communities those systems serve. While this roadmap specifically addresses resilience issues in the context of earthquakes, those priority research and development topics, including Topic 2, are valid for other hazards as well.

## 1.2 Project Scope and Purpose

NIST asked the Applied Technology Council (ATC) to address Topic 2 of the NIST GCR 14-917-33 Report, with an expansion of scope to address all hazards, with the goal of supporting NIST's efforts to develop tools and guidance as part of the NIST Community Disaster Resilience Program. The NIST Task Order specifically called for ATC to: *Assess current societal expectations of acceptable lifeline performance levels and restoration timeframes that are informed by the phases of response and recovery, distinguishing those that are hazard independent and those that are specific for seismic (including tsunami), wind (including hurricane and tornado), flood, snow/ice, and wildfire hazard events.* An additional goal of the project was to provide a technical foundation for first-generation systems-based models that will analyze community resilience and account for interdependencies among infrastructure systems and the social and economic functions that they support.

This ATC study included a series of assessments of electric power, natural gas and liquid fuels, telecommunications, transportation, water and wastewater systems, and more broadly considered the societal considerations and interdependencies associated with the performance of these systems. Among other things, these assessments summarize current codes, standards, guidelines, manuals, and performance requirements for each lifeline system. Consistent with the *Earthquake Resilient*

*Lifelines Roadmap*, the following definitions for codes, standards, guidelines, and manuals also apply in this study:

- *Codes*: Legally binding requirements that are adopted by entities having jurisdiction over the system or project, and that specifically state what must be done.
- *Standards*: Voluntary design requirements that are written in mandatory language and specifically state what needs to be done to meet the requirements of the standards.
- *Guidelines*: Design requirements that are written in non-mandatory language by subject matter experts, groups or organizations having appropriate expertise and experience relevant to the topic covered. Application of all or part of the guideline is at the discretion of the user. Guidelines often form the basis for pre-standard documents that are then taken through the consensus process to become standards.
- *Manuals*: Practical instructions to assist designers in the use of guidelines, standards, or codes. They often include techniques for applying the procedures, key assumptions that need to be made, and design examples.

Each lifeline assessment also examines the societal expectations, considerations, and lifeline interdependencies associated with system performance; disaster lessons; and key gaps and discrepancies between anticipated lifeline system performance and the performance required to support societal needs. Each assessment also makes a series of recommendations for improvements.

## 1.3 Report Organization

The report is organized as follows. Chapters 2 through 8 contain detailed analyses of societal considerations and expectations, interdependencies, and assessments for electric power, natural gas and liquid fuel, telecommunication, transportation, water and wastewater systems. The discussion on societal considerations and expectations (Chapter 2) uses terminology that may be new to some readers (see Terminology Notes sidebar, next page) and addresses a variety of issues, including societal expectations for the performance of lifelines both during and after natural hazard occurrences. Chapter 9 synthesizes the findings from Chapters 2 through 8 to form a common picture of current lifeline system performance requirements, societal considerations, lifeline interdependencies, disaster lessons, gaps between lifelines performance requirements and societal considerations, and future considerations and trends that are beyond the scope of this study but merit further attention over time. Chapter 9 also provides a series of recommendations that identify the needs associated with: lifeline standards, research, modeling, and lifeline system operations. A series of appendices contains supplemental materials from the analyses as well as additional, detailed information about codes, standards, guidelines, manuals, and practices associated with various lifelines.

### Terminology Notes

***"Societal considerations,"*** *as addressed in Chapter 2 and elsewhere in this report, pertains to a variety of issues related to life-safety, health, and economic impacts of lifeline performance.*

***"Societal expectations,"*** *as used here, refers to what different groups within the population want or hope for with respect to lifeline performance and post-disaster restoration times.*

*The term,* ***"disaster,"*** *as used herein, is defined as "a sudden calamitous event bringing great damage, loss, or destruction (per the Merriam-Webster Dictionary definition); in some instances the term may pertain to a past event occurrence that was officially declared a disaster by the Federal government, or a state government. It is also used as a general term for significant past or potential future disruption to lifeline and community functions due to a hazard event.*

*A "****hazard event"*** *is a disruptive occurrence caused by an earthquake, hurricane, flood, or other natural, technological, or human-made hazards.*

# Chapter 2
# Societal Considerations

## 2.1 Introduction

A primary focus of this report is the assessment of societal considerations and expectations pertaining to the performance of lifelines following hazard-related disruptions, taking lifeline interdependencies and various hazard types into account. Carrying out such assessments is challenging in part because of the almost total lack of empirical data on what members of the general public regard as acceptable lifeline performance following hazard-related disruptions. Gauging societal perceptions of lifeline performance is also challenging because U.S. society is highly diverse. A disaster-induced eight-hour power outage might be tolerable for a resident of a suburban home, but less so for a wheelchair-bound occupant of a high-rise building who is dependent on the use of an elevator. The same power outage would be intolerable and life threatening for a disabled individual who is living alone and in need of electrically-operated life-support equipment. In general, members of the public are differentially affected, depending on factors such as age, physical health, weather conditions, built environment characteristics, and conditions at their locations at the time of the outage. These kinds of differences clearly influence performance expectations.

Similarly, some businesses may be able to sustain their operations during a power outage of that duration, while others, which are highly dependent on power, telecommunications, and the cyber-infrastructure, would likely have to suspend operations and sustain business interruption losses unless they made alternative plans. Surveys conducted in the 1990s indicate that businesses in general are highly dependent on electrical power. A survey on a randomly-selected sample of businesses in Memphis and Shelby County, Tennessee found that across the board businesses were more dependent on power than on other lifelines and that 59% of them would have to shut down immediately if they lost power (Tierney and Dahlhamer, 1997). Businesses of all types nationwide are increasingly dependent on information technology, which in turn requires electric power, and as a consequence, those numbers are certainly higher today than they were twenty years ago when the survey was conducted. The appropriate way of conceptualizing “society,” then, is to think in terms of different sub-populations and utility service users with diverse needs.

Public perceptions of the importance of different types of buildings and lifelines and willingness to pay for upgrades are reflections of societal expectations. A survey conducted in 1999 with a randomly selected sample of Alameda County, California, residents sought to determine the importance residents assigned to various elements of the built environment that are at risk from seismic hazards and to gauge their willingness to support seismic upgrades. Of twenty types of structures and systems, including various lifelines and facilities, survey respondents placed the highest priority on the continued functionality following an earthquake of major hospitals, natural gas pipelines, electrical power, water utilities, and public safety buildings (Tierney, 2001). These assigned importance factors are clearly related to the priority the public places on life safety and the basic needs of everyday life. Willingness to pay for the seismic rehabilitation of different elements of the built environment, including lifeline systems, varied in this survey as a function of factors such as education, gender (with women expressing greater willingness to pay), trust in government, and other factors—again indicating that societal views on continuity of lifeline performance are diverse (Tierney and Sheng, 2001). While somewhat informative, these findings are location- and earthquake-specific, and they contain no information on the duration of lifeline outages members of the public would find acceptable.

Public expectations are shaped by available information on the impacts of disruption, and expectations might change if members of society had access to more complete information on the various ways in which the disruption of lifeline services can affect community life. Greater societal understanding of these aspects of lifeline service provision and interruption will no doubt have an influence on performance expectations. Obtaining such information is an important challenge for both research and risk communication.

In addition to taking into account *societal expectations*—what different groups within the population want or hope for with respect to lifeline performance and post-disaster restoration times—this chapter also focuses on a broader set of *societal considerations*, or the impacts to life-safety, health, and economic well-being that may result from lifeline service disruptions. These effects are documented in the research literature. As the NIST *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (NIST, 2015) points out, buildings and lifelines exist to support community institutions, which include family and kinship, the economy, government, health, education, community service organizations, religious and cultural institutions, and the media. All these institutions and the functions they serve contribute to community well-being and quality of life. However, the *Guide* emphasizes that some needs are more fundamental than others. Using a modification of Maslow's "hierarchy of needs" framework, physical survival is the most basic human need, followed by needs related to safety and security, "belonging" (that is, having friends and social networks), and growth and achievement. Consistent with that framework, when discussing societal considerations, this chapter focuses on how lifeline disruptions threaten the most basic needs and community institutions: human health, health-care institutions, and economic activity.

The NIST *Guide* also distinguishes among short-term (days), intermediate-term (weeks to months) and longer-term (months to years) response and recovery needs that planning activities must take into account. While recognizing that all three time periods are important, this chapter focuses primarily on the short-term period and immediate impacts, disruption, and responses, again with respect to health and the economy.

The rationale for limiting the discussion of societal considerations to life-safety, health, and economic impacts and a short-term time frame is threefold. First, life safety and health are overriding values for communities. Economic activity follows life safety as a priority for communities. As indicated in the NIST *Guide*, economic activity provides the means through which a wide range of community needs are satisfied; other institutions depend in major ways on the functioning of the economy. Educational, religious, and cultural institutions are clearly critical for communities, but are not as directly tied to basic needs. Second, although the consequences of lifeline disruption can increase over time, impacts such as deaths, injuries, and business interruption losses are generally most acute during the immediate post-impact period. Finally, more research exists on shorter-term than on longer-term disruptions. With this rationale in mind, the chapter will focus primarily on *how lifeline performance and disruptions can have deleterious effects on life safety, health and economic well-being during the post-impact response period.*

## 2.2 Factors Affecting Lifeline Performance Expectations

### *2.2.1 Hazard-Related Considerations*

An important question is whether societal expectations pertaining to lifeline performance vary as a function of hazard type. There is a lack of information on that question, as well as considerable variation in the hazard-specific and lifeline-specific information on societal considerations that is currently available. A targeted research program that directly addresses societal expectations associated with specific lifelines across various types of extreme events is needed.

However, even in the absence of direct empirical data, it seems likely that the public’s expectations will take disaster characteristics—if not disaster types—into account. The NIST *Guide* classifies expected hazard levels as routine, design, and extreme; these levels of severity are likely to be related to societal expectations. Other things being equal, disruptions may be tolerated for longer periods in very severe and catastrophic events than in less serious ones because the public will likely be more willing to accept that such events are more difficult for lifeline service providers to anticipate and mitigate. The public may also be more understanding of disruptions stemming from events that are atypical and unexpected in specific community settings, reasoning that providers should be cognizant of and prepared for familiar and common hazards, but not necessarily as well-prepared for low-probability events.

### 2.2.2 Risk Perception and Communication Considerations

Public expectations regarding lifeline performance are shaped by both risk perception and risk communication activities. Perceptions of risk include attitudes and beliefs regarding the likelihood of various disaster events, as well as their perceived impacts. A voluminous research literature has identified factors that influence the perception of natural and technological risks. That literature also points to factors that can prevent members of the public from accurately assessing risk. One body of research identifies cognitive heuristics and biases that influence hazard-related perceptions. For example, when the probability of a disaster is seen as low, individuals may ignore that risk, even if the consequences of an event would be catastrophic if it should occur.[1] This is thought to happen because such events do not reach a *threshold level of concern.* The *availability heuristic* refers to people's tendency to overestimate the likelihood of an event that has occurred in the recent past or of an event that made a strong emotional impression, while underestimating the likelihood of other types of events that may be equally or more likely. The *anchoring heuristic* refers to the tendency to "anchor" perceptions of future risks in information that is based on experience or that has previously been communicated. For example, some people who did not evacuate when Hurricane Katrina threatened New Orleans referred to the fact that they had experienced Hurricanes Camille and Betsy decades before and believed that Katrina would be no worse than those disasters. Another example of this tendency occurred when Hurricane Rita struck the Houston, Texas, area a month after Hurricane Katrina; in that case, masses of people took to the roads in an attempted evacuation of Houston, recognizing the consequences of Hurricane Katrina (Lomax, personal communication). *Myopia* is the term researchers use to describe the tendency toward short-term, as opposed to long-term thinking with respect to hazards. Myopia can lead people to underestimate the risks associated with low-probability/high-consequence hazard events, such as earthquakes, or those hazard events whose effects are perceived in the distant future, such as climate change.

[1] There are exceptions to this pattern with respect to other types of risk, however. For example, Lichtenstein et al. (1978) showed that people overestimate the frequency of rare causes of death. Barberis (2013) suggests that while the general tendency is to underestimate the likelihood of low probability events, the availability heuristic can cause overestimations as well.

Residents may have a general sense that their community could experience an earthquake or a flood without necessarily feeling personally at risk; this is referred to in the literature as the *optimistic bias*—the idea that "it won't happen to me."

According to the "risk as feelings" perspective, emotions also play a role in risk perception. Feelings of worry and anxiety can stimulate concern about hazards and may even lead those who are anxious to overestimate the likelihood of certain disaster events. Emotional reactions are one dimension of the availability heuristic; we generally overestimate risks when events have dramatic, shocking content, such as when an airline accident kills all on board and leads members of the public to believe that the risk of airplane crashes is higher than it actually is. Highly emotional reactions to hazards, however, are relatively uncommon during normal conditions; hazards may not even be salient enough to raise levels of concern to a point where individuals will take precautionary action.

Other factors that have been shown to influence risk perception include gender, race and ethnicity, and trust in institutions. Women, members of minority groups, and those who place less faith in the institutions that are charged with managing risk tend to show more concern about risks of various kinds. (For representative research and discussion of factors influencing risk perception, see: Tversky and Kahneman, 1974; Kahneman et al., 1982; Flynn et al., 1994; Slovic, 1999, 2010; Michel-Kerjan and Kunreuther, 2011; Tierney, 2014).

Although there is scarce research in the area, there is evidence that in addition to often misunderstanding the *likelihood* of events, people have difficulty perceiving what the *impacts* of disasters will be—that is, the types and severity of losses and disruptions they will experience in a hazard event. This is especially true when people lack prior experience with particular types of disruptions, such as low-probability/high-consequence events. Recent research on the perception of flood hazards among residents of New York City floodplains suggests that individuals tend to underestimate the magnitude of the losses they will suffer in floods, even when they *overestimate* the likelihood that they will experience flooding. The researchers who conducted the study concluded that this may be one reason people fail to purchase flood insurance when they should do so, and also why they do not invest in hazard mitigation. One of the conclusions of this research was that "it is important that residents in flood-prone areas are more actively provided with information on objective flood damage, including worst-case scenarios" (Botzen et al., 2015, p. 379).

If people have a tendency to underestimate their losses from flooding, they may also underestimate the severity of impacts of other types of events, including disaster-induced lifeline disruptions—particularly disruptions that last for long periods. Even if most people have some experience with electric power outages that last from minutes to hours, such experiences may not provide a basis for understanding the impacts of extended outages or for knowing what to do to cope under such circumstances. Prolonged lifeline service disruptions, especially those associated with power and water, can have profound and cascading effects on communities and vulnerable populations, requiring residents to respond and adapt in a variety of ways, but there is virtually no current research on public understanding of these impacts or of appropriate coping strategies.

Risk communication involving hazards is another area in which there is a large body of research that can only be briefly addressed here. Risk communication strategies are guided by theories in a variety of disciplines, including communication, psychology, social psychology, sociology, crisis management, and anthropology. Insights from empirical research in these fields have resulted in the development of a wide variety of models and practical guidance focusing both on risk communication under normal conditions and on warnings and crisis communication during disaster events (see, for example Mileti and Sorensen, 1990; Morgan et al., 2002; Wood et al., 2012; Mileti et al., 2011; Sheppard et al., 2012).

Communication regarding hazard-related risks takes place throughout the hazard cycle: under normal conditions, in the warning period preceding disaster impact, during and immediately after impact, and during restoration and recovery. Communications regarding risk take a variety of forms, including elaborate and detailed scenarios used for public education, public service announcements, web-based guidance, and terse warning messages that appear on mobile phones before disaster impact. Ideally, risk communication activities should seek to accomplish a number of objectives: explaining the likelihood of events of different magnitudes; identifying hazard zones—that is, locations of greatest threat; providing information on potential hazard impacts; providing early warnings and expedient pre-impact warnings; informing members of the public what they need to do to reduce their risk at various stages of the hazards cycle (mitigation, preparedness, response, and recovery); specifying when they need to take such actions; providing information on populations and locations that are *not* at risk, as well as when those who have been at risk can stop taking protective action (e.g., when it is safe to return after an evacuation); and correcting erroneous information regarding risks.

Risk communication strategies and processes have changed markedly over time. Original models of risk communication saw information as originating from an authoritative *source*, having specific *message content*, being distributed over specific *channels*, to designated *recipients*. Owing in part to advances in information technology and social media, this centralized, linear approach to risk communication has been replaced by decentralized dissemination processes involving multiple information sources, diverse message content, multiple two-way communication channels, and heterogeneous groups of recipients. Particularly during disasters, the ability of authorities to exercise tight control over risk communication processes has diminished. Given all these challenges and the dynamic nature of disasters, it is easy to understand why risk communication is so difficult and how mistakes can be made.

Like risk communication in other areas, risk communication involving disaster-induced lifeline disruptions should be thought of as a collaborative activity that at various stages involves a variety of participants, including physical scientists, social scientists, and engineers with expertise regarding specific hazards; risk communication experts; lifeline and infrastructure service providers; emergency managers; public officials; conventional media; social media; and representatives of interested publics. Risk communication strategies should build on one another across the stages of the disaster cycle. Communication under normal conditions should seek to convey information on hazard-related lifeline risks and impacts, as well as appropriate self-protective measures. Such information provides community residents with the basic context through which they will interpret subsequent risk-related information. During and after crises, warning information and guidance should be timely and specific with respect to who is (and who is not) at risk and what actions to take to avoid or reduce risk, and when. For example, with respect to "boil water" orders, risk communication messages should include information such as which geographic locations and populations are affected by the order, how long water should be boiled, which uses require boiled water, how long the order will be in effect, and other key details. Information will need to be disseminated and updated frequently and through multiple channels.

Addressing the expectations of households, businesses, and community institutions is a key element in disaster risk communication. When disasters strike, both the demand for information and the amount of information that needs to be conveyed increase dramatically. Regarding lifelines, members of the public will want to know, among other things, which lifelines are affected, how severe the impacts are, how long disruptions are likely to last, what risks are associated with disruption, what to do to reduce those risks, what resources are available to help cope with disruptions, and how to access those resources. Providing this kind of detailed information requires collaboration between lifeline service providers and the range of organizations that are involved in managing the disaster.

In addition to *addressing* societal needs, risk communication often also aims at *managing* them. For example, for decades local emergency management agencies have been telling community residents not to expect immediate assistance in a hazard event and that they should anticipate being on their own for at least 72 hours after the event. More recently, there has been a trend toward emphasizing that in some cases, such as catastrophic events, aid will be unavailable for even longer periods. Similarly, agencies that are responsible for wildfire disaster management have been informing residents of at-risk communities that firefighters may not be able to save their homes—and indeed may not even attempt to—should a fire break out. Both of these risk communication activities aim at ensuring that members of the public have reasonable expectations about agency performance, so they can plan accordingly. A key lesson of disaster risk communication is that the public can handle bad news if it is communicated appropriately by authoritative and credible sources. However, the public has little tolerance for withholding of information, over-promising, or communication that appears deceptive. The section that follows focuses more specifically on public expectations regarding the performance of lifeline service providers during disasters and what can happen if those expectations are not addressed.

### *2.2.3 Public Opinion Regarding Lifeline Service Providers: Outrage and Recreancy*

What lifeline customers expect and will tolerate is also likely to be influenced by public confidence in lifeline service providers, which is in turn likely to be linked to providers' previous performance during both routine operations and past disasters. To avoid damaging public confidence, infrastructure owners and managers must be viewed as engaging in good faith efforts to provide reliable services and to restore services when they are disrupted. Circumstances that negatively affect public perceptions regarding providers' competence and honesty will also affect public expectations.

Members of the public may be especially dissatisfied if they believe that providers should have learned lessons and improved their performance based on past emergencies. For example, Connecticut Power and its parent company Northeast Utilities were criticized by the public when there were problems with power restoration following Tropical Storm Irene in 2011 and then again in a nor'easter that occurred later that same year (Cox, 2011). The following year, the Connecticut legislature passed Public Act 12-148 with the intent of improving utility system performance in emergencies; the passage of this law can be seen as a reaction to the 2011 events and an expression of the public's expectations regarding lifeline performance. (Chapter 3, which covers electrical power systems, provides additional information on regulatory changes at the state level that have followed recent disaster-related disruptions).

Similarly, in 2012 the Potomac Electric Power Company (Pepco) was criticized for being slow to respond to a derecho—a widespread, long-lived wind storm— when there was also a perception that the company had skimped on routine maintenance in previous years. Additionally, Pepco restoration times were noticeably longer than those of other providers in the affected region, and the situation was made worse by the fact that the outages occurred during very hot weather (Easterbrook, 2012).

These examples also highlight the importance of how service providers communicate with consumers in the context of crisis-related service disruptions. Part of the public outrage against Connecticut Power following the 2011 outages stemmed from the fact that the utility provided vague information and over-promised on restoration times. A study by Emergency Preparedness Partnerships (EPP, 2012) found that many criticisms of lifeline service providers following Tropical Storm Irene centered on poor communication with the public about electrical power restoration times. As indicated in preceding discussions on risk communication, members of the public will react negatively if they believe that authorities are not being truthful about how long it will actually take to deal with disruptions.

Nearly three decades ago, risk communication specialist Peter Sandman (1989, 1993) identified the "outrage factor" as a key element in public risk perception. Causes of outrage include the imposition of risks and losses on members of the public by outside entities—which could include lifeline service providers. The outrage factor is related to the sociological concept of recreancy, or the loss of trust in entities that have fiduciary responsibilities in areas such as the management of technology (Freudenburg, 1993). This research indicates that perceptions of risk and feelings of outrage are closely tied to perceptions about the institutions that are responsible for managing risk. Public indignation results when institutions are perceived as behaving in an irresponsible, untrustworthy, or deceptive manner. The public reaction to the 2010 PG&E San Bruno pipeline explosion contained a strong element of outrage and recreancy that not only focused on the disaster itself but also carried over into negative public views on the utility's close relationship with its regulator, executive compensation, the cost of utility improvements, and PG&E's Smart Grid program (Johnson, 2011; Johnson and Rogers, 2011).

Once the public loses trust in an institution, regaining trust is very difficult (Slovic, 1993) but not impossible. An exception is when the loss of trust occurs as a result of what is perceived as deceptive behavior on the part of an institution, in which case trust may never be regained (Schweitzer et al., 2006). Institutions of all types, including utility providers, run the risk of losing the public's trust when they do not communicate in a straightforward manner and when they are seen as withholding information that the public needs. Because trust is difficult to regain, public perceptions stemming from past events may continue to influence expectations over time.

### *2.2.4 Substitutability and Need*

Societal expectations pertaining to lifeline performance will also likely be influenced by the extent to which substitutes are available for lost services and the degree to which a particular service is needed following a disaster. Although the loss of drinking water due to a disaster is a serious problem, the public may not see that disruption as unacceptable as long as other potable water sources are made available in a timely manner to those who are affected. Damage to the natural gas distribution system may be acceptable if gas is used mainly for heating and if the damage occurs during warm-weather parts of the year. Expectations will be highest when substitutes and work-arounds are not available and when current needs are high.

### *2.2.5 Relevance of Resilience Concepts*

Societal expectations regarding lifeline performance can thus be characterized as diverse, variable, situation- and hazard-specific, and subject to a variety of contingencies. Using terminology from vulnerability science and resilience research, different segments of the population and sectors of the economy are differentially *exposed* and differentially *sensitive* to lifeline service disruptions, and they also differ in their *adaptive capacities* when disruptions occur. Regarding population vulnerability, exposure and sensitivity are generally inversely related to socio-economic status, while adaptive capacity increases with socio-economic status. Community residents living at or below the poverty level, members of racial and ethnic minority groups, low-income women-headed households, and marginalized populations, such as undocumented immigrants, are more likely to live in substandard housing that is susceptible to damage, to lack the financial means to prepare adequately for disasters, and to have fewer resources with which to cope after a disaster strikes. Those in higher positions on the socio-economic ladder are better able to take pre-disaster preventive actions and to respond and recover in a resilient manner when disasters occur (Tierney et al., 2001; Thomas et al., 2013). Disaster vulnerability and dependence on lifeline system performance also varies as a function of age and physical condition.

These factors can be expected to influence disaster-related needs and performance expectations. For example, an affluent retired couple that has the financial means to purchase a large generator for their home may be relatively indifferent to the potential for an eight-hour electrical power outage because the couple has a source of continuous power, will not suffer a diminished quality of life if an outage occurs, and can survive comfortably for days on generated power without requiring additional fuel. Severely disabled persons who are living in the community and require electrically-powered medical devices and individuals who are receiving in-home hospice care may be unable to tolerate even short-term outages. In addition to the need for electricity to power assistive devices, many medications require refrigeration, which is in turn dependent on power.

The situation is similar with businesses. Larger businesses are likely to be in a better position to protect themselves against lifeline service disruptions than smaller ones—for example by purchasing generators, having business continuity plans, and having backup locations from which to operate should outages occur. Although all businesses depend on robust lifeline system performance, some businesses are more likely than others to sustain losses in the event of disruption. A manufacturing facility may be able to make up for lost production following a day-long electrical power failure, but the same is generally not the case for a hotel or restaurant that loses a day's worth of revenues. Health regulations may require restaurants to dispose of perishable items following a power outage, causing further losses. Businesses in the e-commerce and financial sectors depend critically on uninterrupted power and telecom services and thus are highly vulnerable to disruptions.

Lifeline outages have disparate economic effects in other ways as well. Workers who are paid on an hourly basis and who cannot do their jobs because of lifeline disruption lose income, while salaried workers typically do not. In the case of localized outages, some employees may simply be asked to telecommute until service is restored, while others whose jobs are tied to the business location may be out of work, often for extended periods. A financial planner or an engineer may be able to work from home when lifeline services are lost at his or her place of business, but a janitor or window-washer cannot. Many low-wage households and those in which there is a single breadwinner struggle to make ends meet on a day-to-day basis, and in those circumstances the loss of even a few days of wages can be a serious financial blow.

The needs and performance expectations of households and businesses are thus linked to their vulnerabilities and adaptive capacities. Households and businesses with greater exposure and sensitivity and lower adaptive capacity are especially dependent on continued lifeline performance both under normal conditions and in disruptive situations, and this dependency can be expected to influence their performance expectations. Additionally, as noted earlier, expectations cannot be viewed in isolation from other public attitudes and beliefs, such as views on whether service providers are trustworthy and engaging in good-faith efforts to manage risk; these views are also likely to differ across population subgroups.

## 2.3 Impacts of Lifeline Service Disruptions on Health and Health-Care Systems: Societal Considerations

### *2.3.1 Human Health Considerations in Recent Events*

It is difficult to link specific health outcomes to the disruption of lifeline services in disasters. Statistics on disaster-related deaths and injuries are available, but typically the specific causes of those outcomes are not tallied in systematic ways. This section discusses studies and reports that have documented the health effects of electrical power and water outages, first discussing the 2003 blackout and then moving on to the impacts of other U.S. disasters.

The massive power outage that struck parts of the eastern and midwestern United States and Canada in August 2003 is perhaps the best-documented case of electrical power service disruption, in terms of its effects on health and health-care systems. It also provides a number of examples of how failures in electrical power systems can have cascading effects. The blackout began with a series of small events that led to progressive degrading and total failure of power systems in eight eastern U.S. states and the Canadian province of Ontario. It started around 2 pm on August 14, and it wasn't until the morning of August 17 that the entire affected system was restored and operating reliably. Approximately 50 million people were affected by the blackout, including residents of large cities such as New York City, Toronto, Cleveland, and Detroit.

Several reports and studies have focused on the impacts of the blackout on interdependent infrastructure systems in New York City, where according to one report (DOT, 2004, p. 2):

> "Subways were stopped in their tunnels, airports halted operations, and elevators stalled mid-ride. Water systems shut down. The communications network was disrupted; cellular telephones ceased to work; emergency response networks were hampered; and automatic teller machines went dark. Many restaurants and shops shuttered their doors, and streets were rapidly overwhelmed by vehicles and pedestrians trying to find their way home. Without air conditioning, many buildings rapidly became stifling. Stranded commuters spent the night in train stations, hotel lobbies, and emergency shelters."

Four hundred thousand people were trapped on New York subways when the power failed. The city lost all of its 11,000 traffic signals, and no mass transit was able to operate, except for water ferries and buses. There was congestion on streets, sidewalks, and bridges as residents and commuters tried to make their way home. Eight hundred people trapped in elevators had to be rescued. High-rise buildings lacked water because they lost pumping capacity. Raw sewage was released because of the loss of power at wastewater treatment plants (DOT, 2004).

The blackout caused 90 excess deaths in New York City alone—a rise in mortality of 28%, with those aged 65-74 most affected (Anderson and Bell, 2012). Hospital emergency department visits and admissions due to respiratory problems increased, especially among women, elderly persons, and those suffering from chronic bronchitis (Lin et al., 2011). Respiratory illnesses were made worse by the hot August weather, poor air quality resulting from the blackout as people took to the roads in automobiles, and the extra exertion required by residents to get around without elevators and public transportation. Food spoilage and other factors led to an increase in diarrheal illnesses, and calls increased to 911 and other emergency services, including poison control centers (Lin et al., 2011).

At the same time, the blackout made the management of illnesses more difficult. Pharmacies were forced to close, making it impossible to access prescription drugs, and hospital operations were compromised. Based on their research, Anderson and Bell (2012) concluded that the impacts of electrical power outages on mortality and morbidity have been underestimated.

Studies involving disaster-induced electrical power outages shed additional light on the health impacts of such failures. Among all forms of poisoning, carbon monoxide (CO) poisoning is responsible for the most fatalities in the United States. When winter storms and other disasters cause power outages, the incidence of CO poisoning can increase as those affected seek other means of heating and cooking. One study conducted in Maine following the historic 1998 ice storm illustrates this pattern. Over 600,000 people in Maine lost electrical power in that event, and many residents turned to gasoline powered-generators and fuel-powered space heaters in order to keep warm. A survey conducted after the event found that 100 cases of CO poisoning were reported in the hardest-hit part of the state (Daley et al., 2000). A more recent study that focused on a January 2009 ice storm in Kentucky found that ten deaths occurred from CO poisoning in that state in the two weeks after the storm. The most common cause of death was the use of gasoline-powered generators. CO poisoning also accounted for 202 hospital emergency visits and 26 admissions in that event. Minority group members suffered disproportionately from severe CO poisoning; many of those cases were associated with burning charcoal indoors (Lutterloh et al., 2011).

A review sponsored by the Center for Disease Control of studies on disaster-related CO poisonings in the United States found that between 1991 and 2009 there were 362 such incidents reported in the literature, accounting for approximately 1,900 cases of disaster-related CO poisoning, of which 75 were fatal. Half of the cases involved hurricanes, 46% occurred as a consequence of winter storms, and 4% were flood-related. The most common cause of both cases and fatalities was the use of generators (Iqbal et al., 2012). This review includes only published accounts and thus almost surely underestimates the severity of the problem.

Even where exact statistics are unavailable, reports clearly recognize that power outages are significant contributors to disaster mortality and morbidity. A literature review focusing on the health impacts of windstorms identified several effects of storm-related power outages on health, including electrocution, fires and burns, CO poisoning, and infections resulting from reduced levels of sanitation (Goldman et al., 2014). Another review on the health effects of coastal storms and flooding in urban areas of the United States (Lane et al., 2013) noted that mortality and morbidity in such events are the result of multiple factors, including direct exposure to storm impacts; evacuation-related health problems; hazards stemming from utility outages; problems associated with displacement and subsequent health care service disruption; impacts on mental health; and cleanup- and recovery-related hazards. Health-related hazards associated with power outages that were cited by the authors included the following: CO poisoning; increased physical demands posed by non-functional transportation systems; lengthened ambulance call times; closed pharmacies and retail outlets; and increased air pollution leading to respiratory problems. The review noted that power outages typically result in increased emergency medical services calls and demands on hospital emergency departments on the part of community residents who rely on electrically-powered medical equipment, and that the health of frail elderly persons in nursing homes and similar facilities can be seriously compromised when electrical power service is disrupted. It also called attention to the increased risks borne by other institutionalized populations, such as inmates. Homing in on power-related problems that emerged during and after Hurricane Sandy in New York City, one study cited sequelae that included CO-poisoning-related emergency calls and emergency department visits, hypothermia-related emergency department visits, exacerbation of chronic illnesses, and vulnerability to foodborne illnesses (Lane et al., 2013).

### *2.3.2 Impacts on the Health-Care Sector*

In the Alameda County study discussed in Section 2.1, residents indicated that they considered major hospitals to be the most important elements in the built environment—that is, that they placed the highest priority on hospitals remaining operational in the event of an earthquake. Experiences in U.S. disasters indicate that hospitals are extremely vulnerable to disaster-induced electrical power and water system disruptions and that outages have significantly curtailed the ability of hospitals to perform their functions in disasters and have forced hospital evacuations.

In 2001, Tropical Storm Allison had a major impact on facilities at the Texas Medical Center in Houston, the world's largest medical complex. A combination of flooding, power loss, and inoperable generators resulted in hospital evacuations and the loss of research data, laboratory facilities, and tens of thousands of experimental animals. Patient care was rendered untenable in several Texas Medical Center hospitals, and patients had to be evacuated manually because elevators and escalators ceased to function.

In Hurricane Katrina in 2005, New Orleans hospitals lost power, communications, water, and sewer services and were unable to re-supply drugs, blood, food, and other supplies. As temperatures reached 100 degrees Fahrenheit, hospitals had no cooling capacity, resulting in sweltering conditions for occupants. Nearly 2,000 patients and 8,000 staff and family members were trapped in the 11 most seriously affected hospitals. There was no power for lighting, telephones, electronic devices for IV equipment, laboratory and x-ray equipment, dialysis machines, and ventilators. Patient evacuations, including evacuations of intensive care units and hospice patients, had to be undertaken under the worst possible conditions. There were dozens of deaths in New Orleans hospitals, including alleged mercy killings by staff at Memorial Hospital (Fink, 2013).

In the aftermath of Hurricane Sandy in 2012, flooding and power service disruption forced the evacuation of five New York City hospitals. At New York University's Langone Hospital, 260 patients had to be evacuated, including more than 20 newborns in the hospital's neonatal intensive care unit (Cohen, 2012).

Following Hurricane Sandy, the Department of Health and Human Services (DHHS) conducted a survey of 174 hospitals and carried out site visits in ten selected Medicare-certified hospitals in Connecticut, New York, and New Jersey. The study found that 69 hospitals in the sample reported electrical power outages and that generators did not function reliably in 28 of the affected hospitals. Hospitals reported that due to electrical power disruptions, they had problems accessing medical records; evacuees from other hospitals arrived without medical records because those hospitals had lost power; fuel for generators was difficult to obtain, often because gas stations could not pump gas; and hospitals experienced an influx of oxygen-dependent community residents who had lost power at home (DHHS, 2014).

The U.S. Department of Homeland Security (DHS) *Sector Resilience Report* for hospitals (DHS, 2014) assesses hospitals' dependence on various infrastructure systems. Based on site visits and interviews, the report indicates that the hospitals included in the study would experience a loss of 67-99% of their core operations within five minutes of losing electrical power unless they could continue operations using generated power; within ten minutes without information technology; and within two hours after the loss of water and wastewater services. Regarding the use of generators, the report notes that "many hospitals do not have large on-site fuel reserves nor guaranteed fuel contracts, and during prolonged, widespread power outages such as those following a hurricane or severe winter storm, fueling the backup generators may be problematic" (DHS, 2014, p. 7). The Joint Commission, which is responsible for hospital accreditation, requires hospitals to have the capacity to function on emergency generator power for 72 hours, but it is unclear whether many hospitals affected by extreme events will be able to do so in light of the issues cited in the DHS assessment, the problems associated with hospital generators in recent U.S. disasters, and the potential for very long power outage times in major disasters.

Nursing homes constitute another setting in which the need for reliable utility services is great. An estimated 70 residents died in thirteen nursing homes during and after Hurricane Katrina (Laditka et al., 2008). Because of the Katrina experience, DHHS has been monitoring emergency preparedness activities in Medicare- and Medicaid-certified nursing homes around the country. A recent DHHS report documents serious and ongoing deficiencies in nursing home emergency planning and training. Because federal law requires it, the vast majority of nursing homes have some sort of written emergency plan, but planning activities are by no means comprehensive. Among many problems identified are deficiencies in planning for power outages. An in-depth DHHS study of 24 nursing homes found that 19 lacked sufficient fuel for power generation in the event of an outage, despite the fact that many of their plans called for sheltering-in-place in the event of a disaster (DHHS, 2012). The Katrina experience also showed that nursing homes outside the impact area were not well prepared to receive evacuees (Laditka et al., 2008). Moving elderly persons for any reason can result in negative health impacts, but these data suggest that many nursing homes will be forced to evacuate patients if lifeline services are disrupted for extended periods in future disasters.

Risks are also high for elderly and disabled persons living in the community. A recent article noted that there are currently an estimated 54.4 million people in the United States with functional needs and that with the passage of the Affordable Care Act, people with functional needs will increasingly be remaining in their communities, whereas in the past they might have required institutional care (Jan and Lurie, 2012). The article notes that "[w]ith or without a major emergency, the ability of people with functional needs to remain in their community setting depends on a stable electrical grid" (Jan and Lurie, 2012, p. 2272). It also cites some of the kinds of issues that developed among residents with functional needs in Hurricane Sandy because of electrical power outages:

> "Some residents depend on the electrical grid for refrigerating critical medications or for powering lifesaving medical equipment. Many residents, particularly those requiring ongoing respiratory care, streamed into emergency rooms to receive respiratory treatments, refill oxygen tanks, or recharge batteries. Some residents whose medical needs had not escalated but who needed to recharge medical equipment were turned away from shelters whose operators believed their needs could not be met in a general shelter." (Jan and Lurie, 2012, p. 2272)

### *2.3.3 Climate Change, Lifeline Services, and Health Considerations*

The U.S. National Climate Assessment (NCA) provides information on how future climate conditions are likely to affect the energy supply and energy consumption demands. Among its most general findings is that "projected impacts of climate change will increase energy use in the summer and pose additional risks to reliable energy supply" (Melillo et al., 2014, p. 114). NCA projections indicate an increase in extreme weather events such as heat waves and wildfires; more intense drought conditions and heavy precipitation events; and more high water in coastal areas. As periods of extreme heat increase over time, the demand for energy for cooling will increase; at the same time, with fewer cold days, the demand for heating will decline.

In addition to challenges associated with increasing peak energy demands and extreme weather events, the NCA concludes that energy production is threatened by water supply problems that can affect production, as well as by sea level rise. It notes that a significant proportion of the infrastructure for producing and distributing energy is located in low-lying and coastal areas and that "[r]ising sea levels, combined with normal and potentially more intense coastal storms, an increase in very heavy precipitation events, and local land subsidence, threaten coastal energy equipment as a result of inundation, flooding, and erosion" (Melillo et al., 2014, p. 119).

With approximately 80% of the U.S. population living in cities and metropolitan regions, the NCA sees climate change as particularly challenging for urban areas. Climate change is expected to add to the already existing vulnerabilities of urban populations, particularly those associated with poverty, disabilities, and chronic health problems such as asthma (Cutter et al., 2014).

In the United States, extreme heat is the natural hazard that results in the most fatalities; its negative impacts on life and health were highlighted in the recent NCA report on climate change and human health. Many health conditions are worsened by high heat, including cardiovascular and respiratory diseases. Extreme heat has its greatest effects on the very young and very old. Additionally, research indicates that members of minority groups are disproportionally exposed to the negative effects of extreme heat and urban heat islands (Harlan et al., 2006, 2012). Electrical power failures occurring during heat waves—whether or not they are disaster-induced—will constitute an increasingly significant threat to human life and health.

## 2.4 Economic Impacts of Lifeline Service Disruption: Societal Considerations

### *2.4.1 Introduction*

This section focuses to a significant degree on economic and societal considerations associated with the electrical power grid, because more research has been done on the economic impacts of disruptions in that lifeline system than on others and because electrical power is relied upon by other infrastructure systems. The high dependence of communication systems (e.g., cell phone technology, the internet) on electric power, economic impacts of disruptions of water supply systems and drinking water contamination, as well as transportation systems, are also discussed.

### *2.4.2 The Societal Significance of Electrical Power*

In assessing societal needs and functions associated with power and the other systems that depend on it, it is important to take into account the broader societal context and ongoing economic trends. The demand for high reliability in electrical power systems has grown significantly in U.S. society and is likely to increase. The shift from a manufacturing to an information economy; the growth of e-commerce; the expansion of the financial services sector, which relies on continuous power and virtually instantaneous communications capabilities; the growth of "cloud"-based services that require functioning communication links; increases in telecommuting; and cost-cutting and efficiency measures such as the movement toward just-in-time inventories, are major contributors to that demand. With the rise of globalization, economic activity is increasingly reliant on global telecommunications networks for tasks ranging from collaborative work to banking and investing—networks that are in turn dependent on lifeline services, particularly power. A report by the National Renewable Energy Laboratory (NREL) notes that:

> "There is a growing awareness that continuous power supply and improved power quality are critical underpinnings of the nation's post-industrial, digital economy. That economy is increasingly based on the continuous real-time flow of information and increasingly dependent on machines controlled by digital components, such as microprocessors. This can also translate into increasing vulnerability. For many high-tech businesses, power outages are unacceptably expensive." (NREL, 2003)

That report went on to note that based on data from the early 2000s, firms in the U.S. digital economy lost $13.5 billion a year on average to electrical power outages, that the U.S. economy as a whole lost between $119 and $188 billion annually from outages and power quality issues (see also Lineweber and McNulty, 2001), and that industries are increasingly taking power reliability and quality into account in their facility siting decisions.[2]

Considering the ways in which the economy has been transformed by changes such as those cited above, there is no doubt that societal views on lifeline performance have become less forgiving. Disruptions that may have been tolerated in the past are much less likely to be tolerated in the present and going forward because of the extent to which economic activity depends on highly reliable service provision.

At the same time, changes in the regulatory environment and in industry structure present new challenges for risk management in the electric power sector. Power generation, transmission, and distribution are less integrated and more de-coupled from one another than they have been in the past. Ideally, performance capabilities should be assessed on a "whole system" basis, but de-coupling has made such assessments more difficult. Additionally, with greater industry consolidation and service provision at larger geographic scales, corporations that are responsible for

[2] A Los Angeles Times article indicated that in 2001, Intel's then-CEO Craig Barrett stated that because of California's power crisis and the grid's lack of reliability, Intel would be avoiding California in its plans to expand (see LA Times, 2001).

power provision are increasingly far removed from the communities they serve and thus may be less aware of the hazards that local communities face and less responsive to local community concerns.

### *2.4.3 Business-Level Impacts of Lifeline Disruption: Societal Considerations*

Many accounts of how lifeline outages affect businesses are anecdotal or case studies of individual businesses. While instructive, such accounts do not provide a basis for generalizing about the overall impacts of infrastructure disruption. Surveys with representative samples of businesses in disaster-affected areas, from which it is possible to generalize, indicate that lifeline service disruptions are major contributors to business interruption. For example, in the fall of 2013, the Federal Reserve Bank of New York surveyed 950 small businesses in New Jersey, New York City, the Hudson Valley, and coastal Connecticut to gauge how they were affected by Hurricane Sandy. The study found that one-third of the businesses in the sample incurred financial losses. Of that number, 43% attributed their losses to utility service disruption (Federal Reserve Bank of New York, 2014).

#### 2.4.3.1 Water and Power Systems

Water and power are critical for business operations, and disruptions in those services are major contributors to business losses, even when businesses escape other types of damage. For example, a business survey conducted in Des Moines/Polk County, Iowa following the 1993 Midwest floods found that while relatively few businesses were flooded, 80% of businesses were without water because the flooding inundated the Des Moines Water Works. Additionally, 40% of businesses lost sewer and wastewater treatment, and one-third were without electricity. Forty-two percent of the businesses surveyed were forced to shut down for at least some period of time; 64% of the businesses that closed indicated that the loss of water was the reason for closure, followed by 42% who cited the loss of electrical power and 35% who cited the loss of sewer and wastewater services (Tierney, 1997).

A similar survey conducted in Los Angeles following the 1994 Northridge, California earthquake found that 56% of businesses closed for at least some period of time, and of that number, 59% cited electrical power service disruption as a reason for having to close. Loss of power was the second most frequently mentioned source of business interruption in the earthquake, after closure in order to clean up debris at the business location (Tierney, 1997).

Survey data collected in Santa Cruz, California following the 1989 Loma Prieta earthquake and in Los Angeles following the 1994 Northridge earthquake found that the loss of electricity and water was among the most significant predictors of business financial losses. In Los Angeles, when power outages lasted longer than 24 hours, losses began to escalate significantly (Dahlhamer et al., 1999). As noted earlier, a survey conducted in Memphis/Shelby County, Tennessee during normal conditions found that businesses are highly dependent on lifeline services, particularly electrical power, with nearly 60% indicating that they would have to close immediately in the event of a power system failure.

A survey conducted by the Ohio Manufacturers' Association following the 2003 blackout estimated the direct cost to Ohio manufacturers at approximately $1.1 billion. An estimated 12,300 manufacturing companies, or about 55% of all manufacturers in the state, were affected, with average direct costs of nearly $88,000 each. Power outages to these manufacturing firms averaged 36 hours (cited in Electricity Consumers Resource Council, 2004).

#### 2.4.3.2 Transportation Systems

Two studies on the impact of transportation system disruptions resulting from the Northridge earthquake provide information on how such disruptions affect businesses. One study surveyed over 2,000 firms in the Los Angeles metropolitan area, as well as firms in Orange County, California, which was farther from the earthquake's epicenter. That study found that damage to transportation networks was a significant source of business losses, contributing nearly 40% to losses, and was roughly equivalent to that of structural damage (Boarnet, 1998). Another study found that business interruption losses totaled approximately $6.5 billion (Gordon et al., 1998). Of that amount, an estimated $1.5 billion was attributable to transportation disruptions. Job losses due to transportation damage were estimated at more than 15,700 person-years. Damage affected businesses in various ways, such as restricting customer and employee access and disrupting shipping.

### *2.4.4 Community Level and Regional Impacts: Societal Considerations*

#### 2.4.4.1. Water and Power Systems

As noted elsewhere in this report, water systems serve a variety of societal functions, ranging from firefighting to cooling, industrial processing, irrigation, and human consumption, and different demands for water quantity and quality are associated with these functions. Analyses indicate that disruptions of water supplies supporting these diverse community needs can result in substantial economic losses. For example, for benefit-cost analysis purposes, the Federal Emergency Management Agency (FEMA) estimates the economic cost of total potable water outage at a per capita rate of $97 per day (in 2011 dollars) for community residents and businesses (FEMA, 2010). One study carried out analyses to help FEMA make assumptions about the cost of water disruptions more precise (Aubuchon and Morley, 2013). They found that those costs can range from $67 to $457 per day. Clearly disaster-induced water supply disruptions, particularly in large population centers, can be extremely costly, especially in light of the fact that outages can be lengthy because it takes considerable time to repair water system damage.

Using residential interviews and focus groups in four different sites, one study conducted research on the costs to households of routine water service disruptions, including contamination, leaks, and loss of pressure (Heflin et al., 2014). Their study took into account how community residents adapted to water service disruptions and the costs of those adaptations. Many affected residents purchased bottled water or boiled or bleached tap water. Cooking and food consumption changed. Even though service disruptions resulted in the closure of restaurants, some residents reported eating out or purchasing take-out food more often. Travel increased as people made extra trips related to lodging and bathing; some residents relocated completely as a result of outages. Service disruption also had an impact on children's schooling and on work-related activities. Taking these impacts into account, average household costs were approximately $94; economic impacts ranged widely, from savings of over $1,400 (mainly from some households eating out less and some employees working longer hours than usual) to costs of over $1,000. This was a study of routine, non-disaster-related disruptions. It is reasonable to assume that disruptions resulting from disasters would be even more costly for households, because other damage and disruption (e.g., transportation system damage, school closures, and household damage) would make adapting to water loss even more difficult.

Costs associated with water contamination can be quite substantial, particularly when the contamination endangers public health. Walkerton, Ontario, a town of about 5,000, experienced a severe E. coli water contamination crisis that began in May of 2000. Seven people died of contamination-related illnesses, and an estimated 1,600 adults and 551 children became ill—just over 40% of the population. The contamination was so pervasive and severe that households and businesses were unable to use municipal water for eight months. Subsequent research estimated that the economic costs to Walkerton households totaled $6.7 million (Canadian), including costs associated with purchasing over-the-counter medication, contaminated food, eating takeout and restaurant food, and other bills households incurred. Among other major costs, remediation and repair of the system cost over $9 million, obtaining drinking water for the duration of the crisis cost $4 million, and business costs and lost production totaled $2.6 million. Overall costs associated with the contamination event were estimated at $64.5 million, or nearly $13,000 per resident (Livernois, 2001).

Studies employing loss estimation methodologies also highlight the large economic losses that can result from disruption of water services. One study focused on potential business and residential losses in the San Francisco Bay Area resulting from water supply disruption in a magnitude-7.1 Hayward Fault and a 7.9 San Andreas Fault event. For the Hayward event, residential losses were estimated at $37 million, and business losses were estimated at $9.3 billion. For the San Andreas event, those losses were $279 million and $14.4 billion, respectively (Brozovic et al., 2007). One study estimated losses from earthquake-induced water supply disruptions in Memphis, using a suite of six New Madrid Fault earthquake scenarios (Chang et al., 2002). Calculations took into account earthquake magnitude, average peak ground acceleration, physical damage to the system, and repair times. Mean losses ranged from $5 million to $2.4 billion, depending on the scenario.

Another study estimated the total regional economic losses in Los Angeles County resulting from water supply disruptions caused by an earthquake in the Northern California Delta that would shut down the California Aqueduct (Rose et al., 2012). The scenarios that were used took into account a number of factors, including the timing of the disruption, hydrologic conditions, resilience measures that might be undertaken, and system restoration times. The estimated losses varied considerably. For example, a six-month closure of the aqueduct at a time when hydrologic conditions are normal, and when resilience tactics such as conservation and production recapture are employed, would have almost no negative economic impact. On the other hand, a 24-month shutdown under adverse hydrological conditions could result in $160 billion in gross domestic product (GDP) losses and 1.6 million job-years of employment. Other factors such as water-pricing policies, would also affect loss levels.

Economic loss estimates were calculated for the U.S. Geological Survey's ShakeOut Scenario for Los Angeles, which covered an eight-county region in Southern California. That scenario was based on a magnitude-7.8 earthquake occurring on the Southern San Andreas Fault. Total economic losses from the scenario earthquake were estimated at $191 billion in the affected region. Total direct and indirect effects of property damage were estimated at $112.7 billion. Significant for this discussion, total business interruption losses stemming from earthquake-induced disruption of the water and electrical power systems alone were projected to be $24.2 and $22.4 billion, respectively, or around one-fourth of all losses (Rose et al., 2011).

Turning next to electrical power service disruptions, various studies have focused on the economic losses that resulted from the August 2003 electrical power blackout. ICF Consulting (2003) estimated that the blackout caused $7-10 billion in losses. The U.S. Department of Energy's estimate was $6 billion at the time the blackout occurred (Parks, 2003). These losses are substantial. Put into context, that amount totals $7.74 billion in 2014 dollars. Hurricanes Charley and Ivan, both of which occurred in 2004, the year after the blackout, caused total economic losses in 2014 dollars of $18.7 and $17.2 billion, respectively.

Many loss estimation studies involving electrical power disruptions have focused on earthquake-induced outages. A loss estimation study on potential power system disruptions in Memphis and Shelby County, Tennessee resulting from earthquakes in the New Madrid Seismic Zone found that direct economic losses would be "quite severe across all industries in the economy" (Chang, 1997, p. 92), with most industries experiencing an average of 40-50% loss in production immediately after disruption occurs. Subsequent impacts would vary across different economic sectors. Service restoration times would also vary, and as a consequence different industries would rebound at different rates. Focusing on the same community and taking into account indirect losses, another study estimated that gross regional product and gross output would be reduced by 59% and 62%, respectively (Rose and Benevides, 1997).

A study of business interruption losses that could result from a terrorist attack on the electric power system in the City of Los Angeles (Rose et al., 2007) analyzed the resilience of electrical power customers—for example, their use of substitute energy inputs and production re-scheduling—as well as the resilience of the larger regional economy. Even with the implementation of resilience strategies, the total negative impact of a two-week disruption of the power supply would be a loss of $20.5 billion in economic activity, or just under 4% of the county's yearly economic output. Keeping in mind that this simulation focused only on business interruption losses and not impacts on life and health, on property, or on infrastructure repair costs, electrical power disruption could result in significantly larger losses.

#### 2.4.4.2 Transportation Systems

There has been substantial research on the potential human and economic impacts that could result from transportation system disruption in an earthquake in the New Madrid Seismic Zone (Elnashai et al., 2009; CUSEC, 2000). A major New Madrid earthquake is the prototypical low-probability/high-consequence event. Research by the Mid-America Earthquake Center indicates that a magnitude-7.7 New Madrid earthquake would damage 3,500 bridges and result in the closure of fifteen bridges in the eight-state impact area (Elnashai et al., 2009). Ports, highways, and airports would be damaged and disrupted. Oil and natural gas pipelines that traverse the New Madrid Seismic Zone would sustain major damage; estimates suggest that there could be as many as 425,000 breaks and leaks in interstate and local pipelines. Loss scenarios indicate that approximately 40,000 personnel would be needed just to carry out search and rescue activities, but extensive transportation system disruption would make the movement of those personnel extremely difficult. Although not directly related to transportation systems, estimates from this study also indicate that there would be widespread and lengthy electrical power outages throughout the impact region. These outages would cause massive direct and indirect losses and compromise emergency response efforts.

There are large gaps in the existing literature on the economic impacts of transportation system disruption. More is known about transportation system disruption resulting from earthquakes than from other hazards, raising questions about how much can be generalized from previous findings. The 2011 Tohoku earthquake and tsunami in Japan had a serious negative impact on the global supply of semiconductors and automobile parts, and the 2011 floods in Thailand crippled the global computer hard drive supply for months. Both of these events raised questions regarding the impact of both physical damage and transportation disruptions on supply chains.

Given the prevalence of global supply chains, disasters that are geographically distant can now have far-reaching national, regional, and local effects. There are substantial, ongoing studies of supply chain management (e.g., Shefi, 2005), from which it is clear that loss of transportation and other lifeline services is a major contributor to supply chain disruption. Within the transportation sector, the Transportation Research Board (2012) has developed methodologies for exploring how disruptions both within and across transportation modes affect supply chains and has provided a series of brief case studies that include the Northridge earthquake and the September 11, 2001 terrorist attacks, as well as the 2002 shutdown of the ports of Los Angeles and Long Beach. At a general level, the economic impact of transportation-related supply chain disruptions is seen as varying as a function of commodity characteristics (value, volume, and time sensitivity); the characteristics of the disruption (duration, geographic scale, availability of alternative routes and modes, sector-specific impacts); and associated costs for transport, inventory, and lost output and productivity.

### 2.4.5 Societal Considerations Involving Low-Probability/High-Consequence Events

The NIST *Guide* distinguishes among three levels of hazard events communities may face: *routine* events that may occur frequently but that do not disrupt infrastructure systems or community functions; *design level* events in which buildings and lifelines should remain functional at a level to support response and recovery; and *extreme or maximum considered* events in which structures and infrastructure systems should remain at least minimally functional and should perform at a level that protects life safety. Most events that communities experience will fall somewhere along this continuum. However, societal considerations also include the potential for low-probability/high-consequence events, which may exceed those defined as extreme, such as the nuclear disaster that occurred at the Fukushima Daichi reactors following the 2011 Tohoku earthquake and tsunami in Japan. The tsunami-induced flooding of the nuclear power plant resulted in loss of on-site backup generators to power the plant cooling systems. As that example shows, loss of water for reactor cooling or electrical power for pumping water can result in reactor core meltdown and the release of nuclear material, leading to catastrophic impacts.

Loss of water for firefighting following a major disaster, such as an earthquake, could potentially result in catastrophic losses, as seen in the 1906 San Francisco earthquake. During the 1989 Loma Prieta earthquake, both the primary water supply and the auxiliary water supply in San Francisco—meant for fighting fires—lost functionality. Fire losses were only contained because the city was able to employ a portable firefighting system and because there was almost no wind on the evening the earthquake occurred. While the magnitude-6.9 earthquake of 1989 was a design level earthquake, the cascading impacts caused by water system disruption could have been catastrophic.

Hurricane Katrina in New Orleans was a catastrophic event that was caused by infrastructure failures: numerous breaches of levees that were intended to provide protection from flooding. The vast majority of those who perished in Katrina were not able to evacuate and drowned as a result of the levee failures. Additionally, as discussed earlier, many of the deaths that occurred as a result of Katrina can be traced to electrical power system disruptions. Analyses indicate that similar impacts could result from an earthquake or major flood event in the Northern California Delta, where numerous levees are vulnerable and where population growth behind levees has been substantial (Tierney, 2014). These events highlight the need to take a "whole system" view that incorporates flood protection systems (e.g., levees, sea barriers) at the same level as other parts of the water and wastewater systems.

The 1995 Chicago heat wave resulted in the deaths of nearly 800 people—and lifelines were functioning during that period. The 2003 heat wave in Europe killed more than 70,000 people. Heat is the nation's deadliest natural hazard, and extreme heat accompanied by power outages could lead to high death tolls in many U.S. urban areas.

Low-probability/high-consequence disasters can be expected to have both immediate and far-reaching impacts. By their very nature, such events can result in large-scale mortality, morbidity, damage, loss, community disruption, population displacement, and permanent demographic shifts. As seen in the Fukushima incident, they can also result in public loss of trust and confidence in government and other societal institutions—outrage and recreancy—and in major shifts in public opinion. Additionally, they can stimulate significant legal, policy, and other forms of social change. While planning activities may center largely on *design level* events, and while mitigating against very low-probability but high-consequence events may not be economically feasible, it is still reasonable to direct some attention to the societal implications of rare but catastrophic disasters.

## 2.5 Potential Indicators of Societal Expectations for Lifeline System Performance

Although there are virtually no current data on societal expectations for the performance of lifelines under various disaster conditions, there are other indicators and types of information that can influence and reflect societal considerations under the right circumstances. These include information provided by emergency managers and utility providers as well as real-time outage trackers that provide situational awareness and information about post-outage restoration. Other broad indicators of societal concern include legislation and standards.

### *2.5.1 Emergency Management Advisories*

One point of reference community residents can use to calibrate their expectations regarding post-event disruption is risk communication from emergency management offices and other community organizations. As noted earlier in Section 2.2.2 on risk communication, residents of communities around the country are typically told that they should expect to be on their own for 72 hours or more following major disaster events. As shown in the histogram in Figure 2-1 (a), a survey of emergency management recommendations to residents of 22 U.S. cities indicates that most emergency management agencies are telling residents of their communities to prepare for three days without services, although the duration of disruption could be seven days or more in some cities vulnerable to significant hazards, including Seattle, Los Angeles, Houston, and Miami. These advisories may have an influence on societal expectations, but there is a lack of direct evidence on how much influence they actually have on public perceptions and whether they are having an impact on mitigation and preparedness behavior. Appendix E, Table E-3 lists publicly disclosed recovery expectations from public entities.

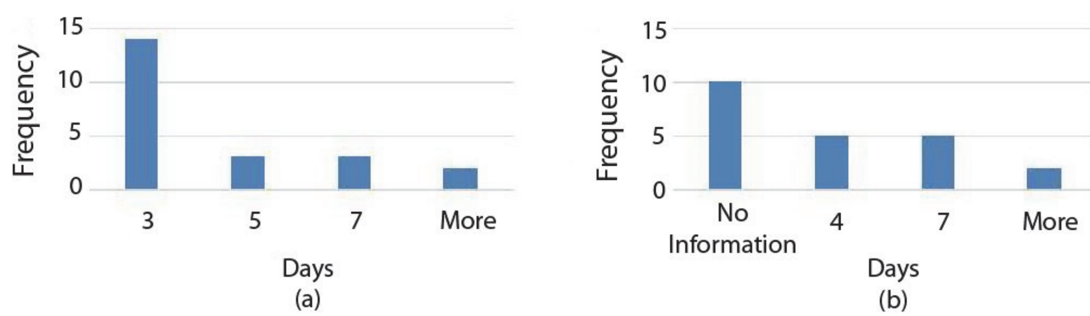


Figure 2-1 Emergency management advisories and utility providers projected restoration times: (a) recommendations to communities given by 22 local emergency management agencies on number of days to expect to be without services following a disruption; and (b) projected electric power restoration times from 22 utility service providers.

### *2.5.2 Utility Providers and Restoration Targets*

Electric power networks are among the most critical infrastructure systems that jumpstart community recovery after disasters. Restoration times for these systems are mainly shaped by operational concerns and are used by power companies to estimate customer reliability indices. These indices use methodologies that rely on historical averages (typically 5 years), while monitoring deviations from them. Major event days resulting from extreme events are typically handled separately to maintain useful customer reliability indices' averages (IEEE, 2004), whereas the restoration times tend to be governed by scenario events, such as the largest disruptions experienced in the region or the most recent disaster.

As a consequence of disaster experience, utility providers are starting to share restoration targets, which may identify gaps between providers' expectations and users' expectations. For example, CenterPoint Energy in the Houston region indicates that power will be restored 7-10 days after a Category 1 hurricane and 6-8 weeks after a Category 5 event (Prochazka, 2009). Such estimates may be misleading, however, because restoration is typically incremental, with service being provided in some areas sooner than estimated and, in other areas, restoration takes longer than estimated, depending on localized damage and restoration priorities. In another example, Sumter Electric Cooperative in Florida recommends that each individual store 7 days of water, which may suggest to members of the public that they should anticipate a 7-day restoration schedule (Sumter Electric Cooperative, 2007). Figure 2-1 (b) shows the electric power recovery expectations disclosed to the public by 22 utility companies, reinforcing the notion that citizens can potentially expect restoration times to range between 3-7 days in key cities across the United States. (Appendix E, Table E-2 lists publicly disclosed recovery expectations from utility companies.)

There is an important caveat, however, regarding restoration data: most utilities do not make information on projected restoration times available to the public, while others instead opt for live updates after an actual event. Although live updates may comfort consumers because they will know when power will be restored (mainly for small events), this does not help them plan ahead for disruptions.

Figure 2-2 shows that 95% of observed power outages last less than four hours in a typical year, indicating that the vast majority of power outages that people experience are caused by ordinary operational interruptions. As noted earlier in Section 2.2.2 on risk perception, these experiences may "anchor" risk perceptions and thus are unlikely to be helpful in terms of motivating community residents to prepare for more lengthy outages.

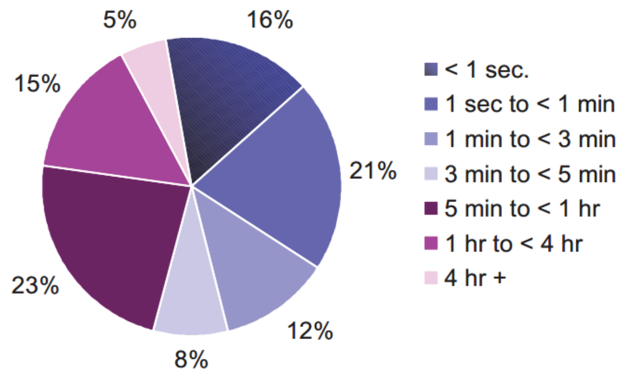


Figure 2-2 Average length of electric power outages in a typical year. Reprinted from Lineweber and McNulty, 2001.

### *2.5.3 Power Outage Trackers and Situational Awareness*

Raw data based on monitoring the natural and built environment are becoming available at unprecedented rates. One example comes from power outage trackers across major cities in the United States. These trackers report outage locations and restoration estimates, and because they are updated frequently (typically at 15-minute intervals), analysts can establish electric power restoration times with a high degree of accuracy. Figure 2-3 depicts such an effort for the Houston region after Tropical Storm Bill in 2015, highlighting hot spots and recurrent problems across the city. Such data could be useful in communicating with the public and managing expectations in disaster situations.

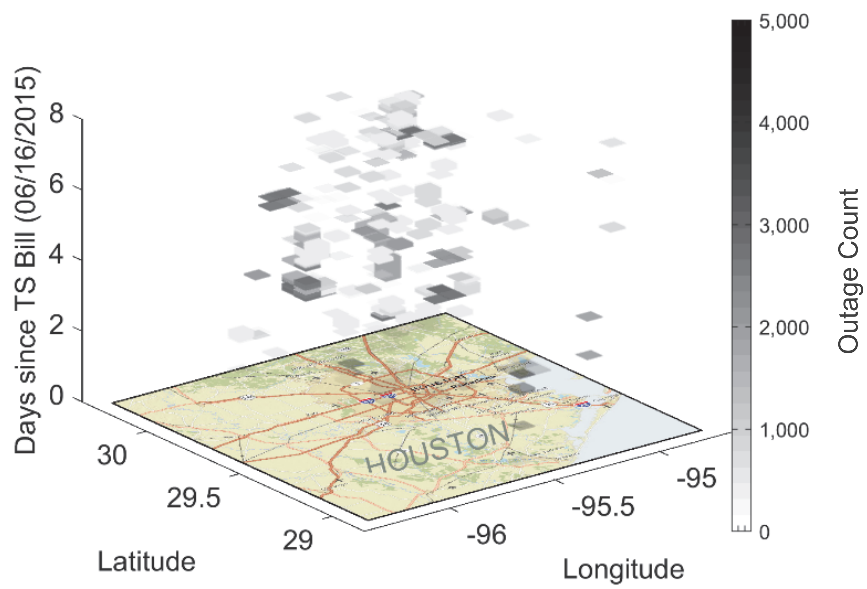


Figure 2-3 Spatio-temporal distribution of electric power outage counts and their durations across the Houston region after Tropical Storm (TS) Bill (Courtesy: Rice University).

### *2.5.4 Post-Event Restoration Information*

Empirical studies that build upon various correlation analysis methods using post-event restoration data provide yet another reference point with respect to performance goals and restoration times. Analytic approaches range from the use of expert judgement (Ho Oh et al., 2010), to point estimates of pairwise restoration correlations (Mendonça and Wallace, 2006), to time-series analyses (Dueñas-Osorio and Kwasinski, 2012), to spatial-temporal varying approaches (Chan and Dueñas-Osorio, 2014; Paredes-Toro et al., 2014; Wu et al., 2012). Figure 2-4 shows typical restoration curves, where outages decrease rapidly early in the post-event restoration process, and then are reduced at a decelerating rate, typically because crews and system operators have to deal with more challenging distribution-level cases. Systematic meta-analyses of post-event restoration cases and local improvement services projects provide indicators that indirectly encapsulate decision making processes, resource availability, and, more broadly, community resilience, as evinced in recent earthquakes (EERI, 2015).

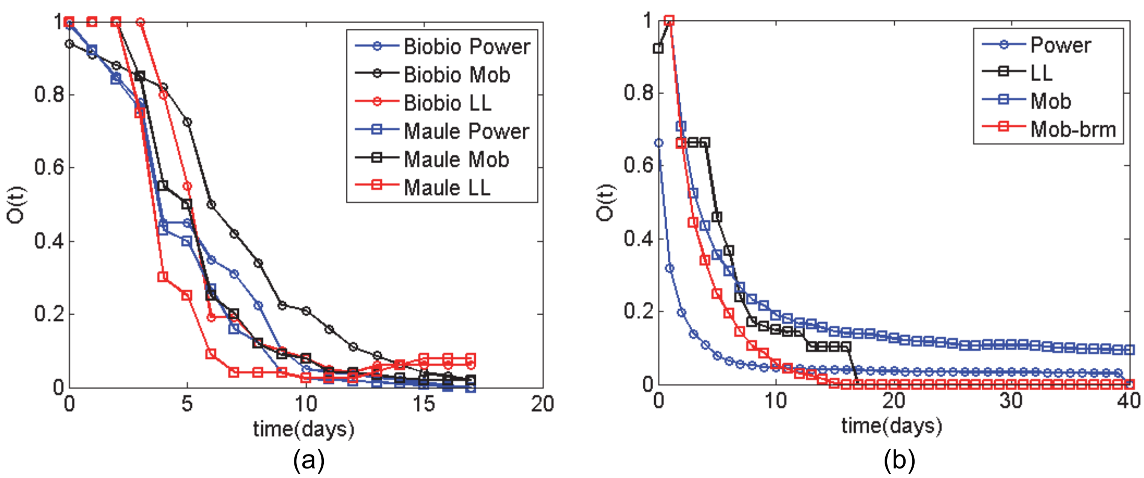


Figure 2-4 Typical utility restoration curves for power, mobile, and landline telecommunication systems in the aftermath of (a) the 2010 Chile earthquake; and (b) the 2011 Tohoku, Japan earthquake (Dueñas-Osorio and Kwasinski, 2012). (Note: O(t) = Outage ratio of post-event to pre-event service; LL = Land line system; Mob = Mobile system; Mob-brm = Mobile systems but removing base-stations and service areas destroyed; Biobio and Maule refer to affected regions in Chile.)

### *2.5.5 Other Reflections of Community Expectations*

**Modeling, Scenarios, and Performance Expectations.** Providing information to other utilities, government agencies, and the general public is a key goal for service providers following disaster-induced disruptions. During normal times, another important goal is the development of computational simulation tools and scenarios that help government agencies, private organizations, and the public better understand what to expect when disasters occur. Some studies have found that gaps exist between what models predict and what the public expects with regard to lifeline performance—as shown by recent Chile, Japan, and New Zealand disasters, among others (Araneda et al., 2010; Cyranoski, 2011; Dueñas-Osorio and Kwasinski, 2012; Kongar et al., 2015; Rudnick et al., 2011). For example, the public in New Zealand assumes the high-voltage transmission system is highly resilient, but recent experiences show that the system on average is only moderately resilient and locally vulnerable. If members of the public act on their assumptions regarding system performance, they are likely to under-prepare for power outages (National Infrastructure Unit, 2014). In the San Francisco Bay Area, SPUR, a research and planning organization, seeks to identify performance expectation gaps, with the goal of obtaining resources to bring performance more in line with public expectations (SPUR, 2009b).

**Policies and Resource Allocations.** Local, state, and national level laws and policies also reflect judgments regarding preferred performance and restoration times. In Houston, for example, frequent flooding led to the institution of a drainage fee that created a fund for infrastructure projects despite being unpopular among many ratepayers (Kimley-Horn and Associates Inc., 2012). Willingness to pay for system improvements—for example, through additional taxes and fees—is at least a crude indicator of societal preferences.

**Guidelines and Standards.** Guidelines and standards can also serve as rough indicators of public expectations regarding lifeline performance. Within the telecommunications arena, for example, consensus documents from the International Electrotechnical Commission (IEC) (IEC, 2003) advance standards for the design of automated electrical substations that rely on telecommunication protocols running over high-speed networks for fast response times and secure interoperability. IEC’s principles have been applied to various other energy fields such as wind (IEC 61400-25) and hydro power (IEC 61850-7-410). Also, the Centre for Energy Advancement through Technological Innovation (CEATI) started issuing best practices for telecommunications in power system automation (Smart Grid Task Force (SGTF) - CEATI, 2015), providing industry surveys and recommendations for selecting technologies appropriate to smart distribution applications.

Other chapters in this report identify various lifeline-specific codes and standards. However, it is important to note that *the vast majority of these standards relate to the normal day-to-day operations of lifeline service organizations and not to their performance during disaster events.* They thus offer little guidance for communities wishing to better understand how well service providers will perform during and after disasters.

**Exercises and Scenarios.** Many organizations, such as the U.S. Geological Survey (USGS) and the California Geological Survey (CGS) have developed scenarios for earthquakes, a major flood event in Northern California, and a tsunami affecting West Coast ports that are aimed at informing the public and community institutions about a range of likely disaster impacts and improving mitigation, preparedness, response, and recovery activities. Used appropriately, such scenarios can lead to greater public understanding of event impacts and cascading effects. Similarly, the NIST *Guide* is meant to initiate a process that will enable communities to better understand the potential impacts of disasters, identify gaps between expectations and performance, and address those gaps.

## 2.6 Summary, Conclusions, and Recommendations

### *2.6.1 Review of Key Points*

This chapter focuses on the limited information available on societal expectations regarding lifeline performance in extreme events, as well as on broader societal considerations. Other chapters discuss expectations that are embedded in codes and standards, but here the focus is on information gleaned from several surveys that have addressed the topic. In keeping with the "hierarchy of needs" model used in the NIST *Guide* (NIST, 2015), the focus has been on the ways in which lifeline service interruption can negatively affect human health, health-care institutions, and the economic well-being of disaster-stricken communities. The following are key points emphasized in this chapter:

- There is a lack of empirical data on societal expectations for lifeline performance;
- The best strategy for assessing performance expectations is through studies that employ randomly-selected representative samples of units of analysis that are of interest, such as households and businesses;
- Societal expectations are likely to be related to the vulnerability and resilience of community residents and commercial entities;
- Expectations are also likely to be related to event severity and probability, service alternatives and immediate needs, and public perceptions of the trustworthiness and competence of lifeline service providers;
- Impacts on life safety and human health resulting from lifeline service disruptions are significant;
- Members of the public assign high priority to the continued operation of hospitals, but hospital operations can be seriously compromised by lifeline service interruptions, particularly those involving electrical power and water;
- Elderly and disabled persons—both those living in institutional settings and those living in their communities—are highly vulnerable to service disruptions, particularly those associated with electrical power;

- Based both on actual events and on loss estimation studies, business and community-wide economic impacts resulting from service disruptions can be costly;
- Increased economic dependence on a continuous supply of electrical power means that disruptions result in even greater losses in the future;
- The effects of climate change have the potential for exacerbating the impacts of lifeline service disruption on the health and economic well-being of community residents, and also for threatening the nation's energy supply; and
- Low-probability/high-consequence scenarios should be considered in assessments of societal needs and considerations.

### *2.6.2 Lifeline Standards Development Needs*

Subsequent chapters in this report discuss codes, standards, and performance goals for individual lifeline systems and also discuss their limitations. As indicated in the chapters that follow, some general concerns include an emphasis on component performance, as opposed to overall system performance; the tendency for standard development processes to be reactive and based on past data, rather than on future projections; variations in regulation and enforcement; variations in the hazards that are considered; and in particular a focus on everyday performance, as opposed to performance during and restoration after extreme events. Standards take into account societal considerations such as life safety, environmental protection, and emergency response requirements. However, they do not consider disparate impacts on social groups, economic sectors, or key service-providing institutions. As this chapter and those that follow emphasize, current measures of lifeline performance are deficient in that they do not account for the full range of societal impacts resulting from disruptions, differences in vulnerability and resilience within the U.S. population, and the ways in which societal needs and expectations have evolved and will continue to evolve over time.

Additionally, current standards, performance objectives, and restoration plans do not take into account lifeline system interdependencies, the potential for cascading impacts, or potential "choke points" that can amplify interdependencies.

### *2.6.3 Research Needs*

The literature on lifeline service disruption resulting from extreme events is uneven, both with respect to research on the services themselves and with respect to the events that have been studied. Perhaps as a consequence of the National Earthquake Hazards Reduction Program, more is currently known about the lifeline impacts of earthquakes, compared with other hazards. As already noted, even less is known about societal expectations regarding such disruptions. The situation is further complicated by the fact that a service such as water supply is complex, and different community sectors assign different levels of importance to water for drinking, firefighting, irrigation, and other uses. Transportation systems are even more diverse.

Even given the patchwork nature of the literature, it is clear that the societal considerations associated with lifeline service disruptions are numerous and significant. Because of lifeline dependencies, threats to the electrical power supply also threaten the continued operation of other lifeline services. Power system failures have direct impacts, but they also have indirect ones because of their potential for triggering cascading failures. Such disruptions compromise the operations of the very institutions that the public values most highly in disaster situations—hospitals and other health-care organizations. At the same time, as illustrated in cases such as the 2003 northeastern blackout, disruptions increase the demand for health-care services by negatively affecting the health of community residents. Among natural hazards, heat waves are the largest contributors to hazard-related mortality in the United States. Electrical power service disruptions are correlated with periods of extreme heat. In the context of a changing climate, an aging population, an aging infrastructure, and policies that are increasingly enabling elderly and disabled persons to remain in their homes, vulnerability is increasing, particularly in urban areas and inner-city neighborhoods. Because vulnerability and resilience vary as a function of exposure, sensitivity, and adaptive capacity, risks associated with lifeline service interruptions are not borne equally by all members of society but are imposed disproportionately on already vulnerable populations. It is important that research takes into account changing and variable societal vulnerabilities as well as the physical vulnerabilities of infrastructure systems.

As discussed previously, the loss of lifelines can have substantial local, regional and national economic consequences. As illustrated by the Tohoku earthquake and tsunami, damage to the Fukushima Daiichi Nuclear Power Plant led to closure of all 54 nuclear reactors in Japan, with only two returned to service as of the preparation of this report. Moreover, the Fukushima disaster led to policies being enacted in Germany and Switzerland to reduce their dependency on nuclear power, and also resulted in increased risk assessment and attendant costs worldwide for nuclear power. Given the close relationship between lifeline functionality and economic impact, continued research into the economic effects of lifeline disruption is needed. Such research should focus on improved collection and assessment of data on economic losses associated with various hazards, improved modeling of the economic consequences of lifeline disruptions and the spatial distribution of lifeline and economic losses, and improved modeling to quantify the economic improvements associated with community resilience.

Many earlier research findings are now out of date as a consequence of social and technological change. For example, as noted in the chapter on telecommunications, research requires updating in light of the rapid pace of change in the nation's communications infrastructure. What are the consequences of lifeline service disruptions as medical records are increasingly stored in electronic form, when medical conditions are monitored remotely, when so many more disabled people are living in U.S. communities, and when business enterprises increasingly rely on cloud-based information technology services? Questions like these can only be answered through systematic pre- and post-event studies.

### 2.6.4 Modeling Needs

As noted throughout this report, despite many recent advances, lifeline interdependencies are still not well understood. Studies such as San Francisco's Lifelines Interdependency Study (City and County of San Francisco, 2014) represent a good start, but more research of this type is needed. The National Science Foundation has moved in the direction of funding various interdependent infrastructure modeling efforts, mainly through two of its programs: Resilient Interdependent Infrastructure Processes and Systems (RIPS) and Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP). Some of the research that is being funded under the new CRISP program takes into account both interdependencies among infrastructure systems and how those interdependent systems are related to the populations they serve. Infrastructure-population interactions are an important topic that should be a major focus for research and modeling efforts.

Integrated modeling of lifeline vulnerabilities related to hazards, population, buildings, and the environment could lead to a better understanding of where problems with service delivery and severe societal consequences are most likely. This kind of modeling is already being performed in a basic way for some lifelines and hazards—for example, through HAZUS (FEMA, 2012). What is needed is a "next generation" approach that models vulnerabilities related to lifeline dependency relationships while also modeling vulnerabilities associated with structural and environmental factors (e.g., urban heat island effects) and the characteristics of exposed populations (e.g., race, class and poverty, gender, age, and social capital). Such modeling efforts will require intensive engagement of multi- and interdisciplinary teams. They should also address cost-effective strategies for reducing vulnerabilities.

### 2.6.5 Lifeline Systems Operational Needs

Other chapters in this report discuss operational needs that are specific to different lifelines and hazards. Viewed from the perspective of societal needs and considerations, at a minimum lifeline systems should perform in ways that do not lead to additional deaths, injuries, and disabilities and that limit lifeline-related economic losses to the extent feasible. In geographic areas and in hazard contexts in which lifeline failures are likely to represent threats to life and health, lifeline service providers should engage with other key community institutions, such as emergency management agencies, to develop contingency plans to minimize those threats. Such measures could include heatwave warning and response plans such as those that exist for several U.S. cities and (to the extent possible) the development of restoration plans that take community vulnerabilities into account.

As discussed in Section 2.2.2 on risk communication, service providers should work with emergency management and other community institutions to communicate with the public about the likely impacts of different hazard events on service provision and disruption, the potential consequences and cascading effects of outages, and what members of the public can do to cope with such outages. Because research suggests that community residents have a tendency to either ignore or underestimate how hazards can affect them, and also to anchor their expectations on past experience, guidance to the public should be specific with regard to potential outage times for different disasters and levels of severity. Communications should include information on how disaster-induced lifeline disruptions differ from the occasional outages during normal conditions. Guidance should be provided to the public across all phases of the hazards cycle—during normal times, during impact, and during the restoration and recovery period—and should be made available in multiple formats and in the languages spoken by community residents. Just as emergency management agencies routinely inform the public that emergency services will not be able to respond immediately to their needs when major disruptions occur, service providers should provide information on what the public can reasonably expect in the event of disaster-induced service disruptions. Where there are barriers to the disclosure of such information, those barriers should be addressed.

Recent research on risk communication (see Wood et al., 2012) emphasizes that a key element in all risk communication is informing community residents about what they can do to reduce their risks and manage the consequences of disaster-related disruptions. Risk communications should be tailored to help residents understand both how they will be affected and what measures they should take in order to avoid danger and inconvenience. In the case of anticipated power outages, such measures could include making sure generators are in working order and that they have sufficient fuel; keeping additional cash on hand in case automatic teller machines are not operational; fueling the car when a hurricane warning is issued to make it easier to evacuate in case service stations are inoperable; and checking with neighbors who may need assistance. Many such measures require little time and effort but can increase household and business resilience. These kinds of detailed, practical advisories are also important for businesses and other types of organizations, such as community- and faith-based organizations that will be expected to provide services following hazard events.

### 2.6.6 Future Considerations and Trends

This chapter has emphasized a number of changes and trends that are shaping societal expectations pertaining to the performance of lifelines and that warrant increasing emphasis. It has also focused on broader societal considerations that must be taken into account in planning for and management of disaster-induced lifeline disruptions. Significant trends include climate change, which will affect both population health and well-being and lifeline service provision; the aging of both the U.S. population and lifelines; increased societal reliance on electrical power and telecommunications for both economic activity and life-safety-related services; an increase in public needs for better performance and recovery of lifeline systems; and the disparate effects of lifeline service disruption on different groups within the population. As indicated in Section 2.6.3, social and technological change is so rapid and far-reaching that many earlier research findings—for example, findings on the economic impacts of service disruption—may be out of date. An emphasis on societal needs and considerations requires an aggressive program of research on topics addressed here and elsewhere in this report.

# Chapter 3

# Electric Power

The frequency and severity of electric power outages are a growing concern for local, state, and federal governments. Power outages can cause substantial economic loss and societal disruption in part because virtually all other lifeline systems are dependent upon electric power. The importance of power is further confirmed by assessments such as the Energy Assurance Plan produced by Portland, Oregon: from a statewide assessment of economic interdependencies in the energy sector, it was found that "disruptions to the electricity supply have the greatest economic impact" and would be more significant than natural gas or oil supply disruptions (City of Portland, 2012).

According to the Executive Office of the President (2013a), between 2003 and 2012, power outages due to severe weather[3] cost the U.S. economy an average of $18-33 billion per year. In years with major storms, these costs can be substantially higher. In 2008 (with Hurricane Ike), power outages cost the economy $40-75 billion, and in 2012 (with Hurricane Sandy), the estimates are $27-52 billion. Other estimates using different methods yield similar results. A Congressional Research Service study estimated that weather-related outages cost the economy $25-70 billion per year (Campbell, 2012, cited in Executive Office of the President, 2013a). Research by the Berkeley National Laboratory found the cost of power outages to be in the range of $30-130 billion annually, at a yearly average of $80 billion (Eto and LaCommare, 2005, cited in Executive Office of the President, 2013a). Economic losses include repair costs to the electric power grid, spoiled inventory, lost output and wages, delayed production, and inconvenience.

The approach taken here, therefore, is to outline current performance guidelines and standards for power systems, review different approaches to assessing power systems performance in hazard events, and summarize how power systems have performed in actual natural hazard events. Throughout, attention is paid to available information on societal expectations, including indirect evidence.

The remainder of this chapter is organized as follows. Section 3.1 provides an overview of electric power systems. Section 3.2 provides an overview of codes,

[3] Severe weather (e.g., thunderstorms, hurricanes, and blizzards) is the leading cause of blackouts in the United States; since 2002, it has accounted for 87% of outages that affected over 50,000 customers (DOE, Form OE-417, cited in Executive Office of the President, 2013a). In the decade 2003-2012, some 679 widespread outages occurred because of severe weather. The frequency of such incidents is increasing (Executive Office of the President, 2013a).

standards, guidelines, and performance requirements that shape current industry practice in the electric power sector. It finds that current practice is geared towards designing components for hazard loads rather than for system performance, and that industry measures of systems-level performance are narrowly defined. Section 3.3 summarizes several key aspects of social considerations, including available direct and indirect information on societal expectations in disasters, key societal serving functions of electric power across the phases of recovery, and differential vulnerability of social groups to power outages. Section 3.4 provides a brief overview of interdependencies between electric power and other lifeline systems. Section 3.5 summarizes relevant lessons on electric power system performance in disasters, especially recent events in the United States. It confirms that information and models are dominated by storm events, that basic outage information is readily available (e.g., customers without service, time to restoration), but that information is very sparse on societal impacts that are most relevant to societal expectations. Section 3.6 identifies gaps and deficits, and Section 3.7 provides conclusions and recommendations.

## 3.1 System Overview

Electric power infrastructure is composed of generation, transmission, and distribution systems (Executive Office of the President, 2013a; NIST, 2015). Electricity is generated at central power stations or by distributed generation where fuel sources (e.g., coal, natural gas, hydro, solar, wind) are converted into electric power[4]. It is then transmitted over long distances on transmission system lines. Transmission system assets consist of high-voltage substations, towers, and lines. Nearer the point of consumption, the transmission system substation "steps down" the power to sub-transmission voltages and transmits this power to distribution substations. Distribution system assets consist of distribution-voltage substations and lines. The distribution substations then "step-down" the voltage further to distribution voltages and distributes the power through a network of distribution lines (either carried overhead by poles or buried underground) to the consumer. In the United States, the electric power system or grid connects 5,800 major power plants via 450,000 miles of transmission lines to over 144 million customers. Within the United States, there are three major AC High Voltage systems/regions (Eastern, Western, and Texas) between which electricity transfer is limited. Regulatory constraints (e.g., California's regulations regarding renewable power shares) limit transfers of electric power across state lines.

The electric power system is a substantially private but highly regulated sector. Ownership of utilities can be public, private (investor-owned), or by cooperatives. While some 62% of utilities are public, 68% of customers are served by investor-

[4] Generation assets are outside the scope of this report.

owned utilities (American Public Power Association, cited in Executive Office of the President, 2013a). Nationwide, the transmission grid is overseen by the North American Electric Reliability Corporation (NERC), which is responsible for bulk power reliability in the United States and Canada as well as the development and enforcement of reliability standards. NERC is in turn overseen by the Federal Energy Regulatory Commission (FERC). Because of deregulation, ownership of the infrastructure varies, with generation and transmission controlled by the same utility in some states and separately in others. Individual states have their own public service commissions that also regulate utility operations. Regulation at the state and federal levels seeks to balance goals of low prices, safety, and reliability.

## 3.2 Summary of Codes, Standards, Guidelines, and Performance Requirements

Numerous codes, standards, guidelines and manuals related to natural hazards shape current practice in the electric power industry. The primary codes and standards used for design and construction in the electric power industry are the National Electric Safety Code (NESC) for transmission system assets and the Rural Utilities Service (RUS) design standards and manuals for distribution system assets. The American Society of Civil Engineers (ASCE) Standard 7, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010), is also referenced and increasingly used (NIST, 2015). IEEE 693, *Recommended Practice for Seismic Design of Substations* (IEEE, 2005), is currently being used when specifying transmission equipment.

The NIST *Guide* (NIST, 2015) provides a thorough review and discussion of these codes and standards (see in particular, Volume II Section 13.5 on Codes and Standards and Section 13.6 on Strategies for Implementation of Plans for Community Resilience). In addition, the Smart Grid Interoperability Panel (SGIP), a private-public partnership established by NIST in 2009 to identify and address gaps in current standards, maintains an extensive Catalog of Standards (SGIP, 2015).

The NIST *Guide* promotes consideration of current design criteria in relation to various levels of loading (e.g., design event, extreme event) that are defined in that document. Based on current design practice, system performance in a design event[5] could expect few failures to new electric power assets taller than 18 meters (60 feet) if they were designed for ASCE 7 wind and ice hazards. Distribution assets less than 18 meters (60 feet), however, are more likely to experience failures in a design ice or wind event, and some limited failures can also be expected in a routine event.

[5] The NIST *Guide* "recommends using three hazard levels: *routine, design,* and *extreme*. These address a range of potential damage and consequences, and are helpful in formulating response and recovery scenarios. Where defined by building codes, the *design* hazard event (e.g., for earthquake, high winds) is the level used to design structures." (NIST, 2015, p. 18)

Several issues related to codes and standards are especially relevant from the perspective of societal expectations pertaining to electric power system performance in natural hazard events: (For further details, see Appendix A, Section A.1.)

- The design philosophy is based on constructing individual assets or components (e.g., transmission towers) for specified loads, rather than on designing the entire system to meet a specified level of service delivery (see also NIST, 2014);
- Load criteria in codes and standards are primarily governed by wind and ice loading, with seismic hazards treated separately;
- Transmission systems remain most vulnerable to earthquake loads even through their assets are generally designed to higher standards than distribution systems;
- For wind and ice hazards, transmission assets are generally less likely to experience damage than distribution assets due to higher design standards;
- Because of changes in codes and standards in the last few decades, newer assets are likely to sustain less damage than older assets;
- The time lag between code development and code adoption and enforcement can be substantial in many localities; codes and standards tend to be prescriptive and based on past information; and they are often not up-to-date with the most recent information regarding hazards (e.g., in the case of transmission towers, the 2012 NESC uses wind maps from ASCE 7-05, rather than the more recently revised maps in ASCE 7-10 (NIST, 2015);
- Design of electric power assets and systems has also been influenced by factors such as floodplain management practices that are not addressed in industry codes[6];
- In addition to design-related codes and standards, numerous factors affect the performance of electric power systems in hazard events (e.g., deterioration of transmission and distribution system components, or failure of nearby lifelines and non-utility facilities, may disrupt electric power service);
- Electric power utilities are required to report certain measures of system performance to regulators, but these are operational measures and often exclude performance in extreme events;
- Existing measures of system performance in the industry are not directly informed by or linked to societal expectations; and
- Societal expectations may be indirectly reflected in industry practices regarding restoration of service following outages.

[6] Utility commission regulations have also encouraged substation relocation (DOE, 2010).

In addition to codes and standards, as reflected in the design of infrastructure assets, numerous factors affect the performance of electric power systems in hazard events. (For a review of electric power system performance in disasters, see Section 3.5.) In this discussion, system performance refers generally to physical damage, service disruption (i.e., power outages and brown-outs), and time to restore service. Performance will, in the first instance, be affected by characteristics of the hazard event, such as wind speeds or ground shaking and the geographic extent of the affected area. It will also be affected by system design attributes and condition at the time of the hazard event as well as location of assets and whether distribution lines are overhead or buried underground. While overhead lines are more vulnerable to wind or ice events, underground distribution lines may be more vulnerable to earthquakes (from liquefaction or ground displacement) or flooding (e.g., from storm surge). Since overhead lines are easier to access and repair than buried infrastructure, overhead distribution infrastructure may sustain more widespread failures but typically require shorter times to restore service. Maintenance programs related to tree-trimming will affect distribution system damage, and emergency management related to repair crews, resources, and response plans will also affect the speed of restoration (NIST, 2015; Fenrick and Getachew, 2012; EEI, 2014b). It should be noted, however, that some types of failures and the implications of some types of decisions are not yet well understood; for example, the implications of burying cables underground or of using new materials.

System performance that is routinely assessed and reported by the electric power industry is largely operational and often excludes performance in design events or even routine hazard events. For recent California earthquakes, there are examples of utility performance reported in terms of outage percentages over time after the main shock. Standard metrics of electric power grid reliability include: System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI).[7]

The purpose of the standard industry indices is to measure system operation, absent any unusual event, for the reason that the utilities and regulators want to know how systems compare with each other using a simple rating number. Many jurisdictions require utilities to report reliability indicators (often in publicly accessible formats), and in such cases, SAIFI, SAIDI, and CAIDI are almost always required (Fenrick and Getachew, 2012). SAIFI refers to the average number of outages for a given period; SAIDI indicates the average outage duration; and CAIDI refers to the average duration of a single outage event. Reporting criteria for reliability statistics differ,

[7] SAIDI = ($\sum_i$ minutes customer $i$ is without service) / (total number of customers)
SAIFI = ($\sum_i$ frequency that customer $i$ is without service) / (total number of customers)
CAIDI = SAIDI / SAIFI
(Fenrick and Getachew, 2012)

however, across jurisdictions; for example, several states exclude extraordinary events or "major event days," which primarily arise from major storms. Moreover, state regulatory commissions differ in their definitions of what constitutes a "major event day" (see also Eto et al., 2012). Some utilize the IEEE standard 1366-2003, *IEEE Guide for Electric Power Distribution Reliability Indices* (IEEE, 2003),which defines a major event day as when outages on a given day exceed 2.5 standard deviations from the "normal day," where the latter is determined by data from the past three years. Others use different definitions, such as when over 10% of customers experience outages lasting longer than 24 hours (Fenrick and Getachew 2012; see also NIST, 2015).

These existing standard measures of system performance in the industry are of limited use when considering societal expectations of electric power performance in hazard events. As noted above, data reporting practices and definitions differ by jurisdiction and often exclude outages caused by extreme events such as major storms. Furthermore, the performance measures themselves are not directly informed by or linked to societal expectations. For example, the vast majority of state commissions do not require utilities to compensate customers for outages (Costello, 2012). However, system performance measures are sometimes used in reliability regulation and legislation and may be intended as a reflection of societal expectations (see further discussion below).

It should be noted that utilities' knowledge about their systems' performance capacity, while high for normal service conditions, may in some cases be quite low for hazard events. Large utilities may have sophisticated models for anticipating outages under different hazard conditions, but this capacity is not common among small utilities.

## 3.3 Societal Considerations

Electric power is used in virtually all aspects of modern life and community functioning. It may be helpful to consider electric power as providing two key societal serving functions: (1) energy for operating other lifelines and essential facilities; and (2) energy for consumption by end users such as households and businesses. Thus, power outages disrupt society by causing failures to dependent infrastructures (e.g., outages rendering water system pumps inoperable; see Section 3.4) as well as by directly affecting end users (e.g., outages causing loss of refrigeration and food spoilage).

As noted in the NIST *Guide* (NIST, 2015), the societal issues and needs associated with power outages differ across the three phases of disaster recovery. In the short-term recovery phase of a disaster, which is typically expected to last for days, power outages may be widespread. Infrastructure operators and essential facilities such as hospitals would activate their emergency response plans and resort if possible to backup power, typically from on-site generators. Because emergency generators are usually intended to only meet a fraction of the normal electricity demand at a facility such as a hospital, and because they would need to be refueled within days during a time of potential fuel shortage, disruptions to dependent infrastructures and essential facilities may become more severe over time if an electric power outage is prolonged. In the short-term recovery phase, power outages will disrupt households and businesses in many ways, such as through loss of lighting, heating, cooling, and other building functions, or loss of power for communications such as internet access and cell phone charging. The effects of these disruptions can range from merely inconvenient to life-threatening, depending on season and weather conditions, fuel alternatives available, and the needs of highly vulnerable populations such as those dependent on electrically powered medical equipment (see also Chapter 2). In the intermediate recovery phase, which typically lasts from weeks to months, remaining power outage would hamper activities to restore fully functional neighborhoods, for example, reopening businesses, restoring jobs, providing services (e.g., by grocery stores), enabling people to shelter in their neighborhoods, and facilitating rapid recovery of the community. Redundancy and alternate power sources can supply temporary or interim solutions while final repairs are being made. Power outages in natural disasters typically last from hours to days, or in severe cases, to weeks; hence, the societal issues in the long-term recovery phase (months to years) may be few or limited to issues such as power restoration to neighborhoods that were severely damaged.

Societal expectations are also being shaped by the increasing use of renewable energy sources California, for example, has set a goal for its electric power providers to obtain 50% of their power from renewables by 2030 (California Energy Commission, 2016). The use of distributed energy resources (DER) involves the combined use of solar panels, small-scale turbines, wind towers, storage devices and microgrid systems. The disruptive entrance of DER into the electricity industry is changing the way power is managed, distributed and used, shifting to a decentralized model from a centralized one (Sawyer et al., 2015). The distributed model involves more participation from customers, who can generate electricity from solar panels and store and recharge power with electric cars, and businesses, which can generate electricity from wind and small-scale turbines. Decentralization and the growing deployment of smart grid technologies will substantially increase societal interaction, changing perceptions and expectations. Additional information on treatment of renewables and decentralized power is provided in Section 3.7.6.

There is a lack of data available on societal expectations of acceptable electric power performance levels and recovery timeframes. Appendix A, Section A.2 reviews current approaches to measuring electric power system performance, emphasizing whether and how they reflect societal expectations of acceptable lifeline performance levels and recovery timeframes. The review examines the approaches of the power industry itself and those of state and local governments (through their roles in utility regulation and energy security planning). Briefly, the findings are:

- Industry measures of electric power system performance (e.g., SAIDI) have limited applicability for hazard assessment. Not only do many utilities omit major disruption events from their statistics, but the measures themselves do not consider societally important aspects such as differential impacts related to duration and customer types;
- State regulatory activities—including outage reporting thresholds and criteria, post-event reviews of utility performance, and post-event changes in regulations—may provide some insights into societal expectations of electric power disruption and recovery in hazard events;
- In rare cases, policy and regulations may provide direct evidence of societal expectations; for example, the State of Maryland requires that in major events, at least 95% of outages be restored within 50 hours;
- Societal expectations of outages and restoration may be changing, so that disruptions are becoming less tolerated; and
- Energy assurance plans (EAPs) demonstrate how communities are trying to prepare for and mitigate against the adverse effects of power outages.

## 3.4 Interdependencies

Almost all other types of infrastructure systems are dependent upon electric power (see NIST, 2015; and Chapters 4 through 8 of this report). For example, transportation systems rely on electric power to operate traffic signals, gas station pumps, airports and rail stations, moveable bridges, lighting in tunnels, and electrical rail and subways. Communications systems are highly dependent on electric power for operating telecommunications, internet, cable television, and other systems, and for cooling critical equipment in buildings. Communications and power infrastructure are also often physically co-located, with wires being carried on common utility poles; damage to both systems can occur from a single source such as a falling tree. Water and wastewater systems require electricity to run pumps, operate treatment processes, and maintain laboratory and office operations; only some of these functions may be supported by backup generators. Credit card transactions also depend on electric power, thereby exposing commercial activities to hazard-related disruptions.

Electric power itself is dependent upon other infrastructure systems, particularly in a post-disaster situation. For example, debris-obstructed roads or traffic congestion can impede electric power crews from rapidly making repairs. The crews also need communications systems to coordinate and prioritize their repairs, and their vehicles require fuel. Under normal and disaster situations, electric utility operations and control centers rely on communications systems to monitor and to some extent control different elements of the system. (Although generation is beyond the scope of this report, it should be noted that some generation systems rely on water for storage and cooling, and on rail, barge, or pipelines to bring in fuel in the form of coal, refuse, or natural gas.)

As noted in the NIST *Guide* (NIST, 2015), well-defined governance processes between and among infrastructure providers and government emergency managers are needed to coordinate system restoration according to priorities that best serve the interests of the community, especially when recommended restoration sequences may not be optimal for the infrastructure provider. For example, restoration of power after earthquakes may need to be coordinated with repair of natural gas systems to avoid electric sparks causing fire ignitions.

## 3.5 Disaster Lessons

Most large blackouts in North America have been caused by storms or other weather events. Of the 15 largest power outages that occurred between 1984 and 2006, seven were caused by hurricanes, three by ice storm and winter storms, and the remainder by cascading failures (Hines and Talukdar, 2009). Table 3-1 provides descriptive statistics for outages caused by different types of natural hazards. Outages caused by hurricanes affect by far the largest number of customers, on average, and are relatively frequent. Blackouts due to ice storms are also frequent but affect fewer customers. Earthquake-related outages affect relatively large areas, on average, but are infrequent.

**Table 3-1 Descriptive Statistics for Outages by Cause, Natural Hazards, 1984-2006 (after Hines and Talukdar, 2009)**

| Natural Hazard | Percent of Outage (see Note) | Mean Size (MW) | Mean Size (No. of Customers) |
|---|---|---|---|
| Wind/rain | 31.4 | 679 | 235,840 |
| Ice storm | 11.1 | 1,664 | 431,184 |
| Hurricane or tropical storm | 10.1 | 2,684 | 912,870 |
| Other cold weather | 8.8 | 1,045 | 271,924 |
| Lightning | 8.8 | 794 | 200,617 |
| Tornado | 3.6 | 721 | 227,073 |
| Earthquake | 1.6 | 1,124 | 526,260 |

Note: For other types of sources, see original table in Hines and Talukdar (2009). Data include only events affecting more than 50,000 customers. Some event sizes interpolated.
MW: Megawatt

The number of customers losing power is affected by the damage type and extent. Hurricane-force winds represent the main cause of electric utility infrastructure damage, with about 90% of outages occurring in distribution systems (DOE, 2010; Eto et al., 2012). Widespread outage typically occurs because of the size of the area affected by strong winds. Because of the structure of the electric power grid, however, outages caused by point-source disruption to the transmission system can also affect extremely large areas and communities that are located very far from the damage location. For example, a series of electrical, human, and computer incidents in northern Ohio on August 14, 2003, led to cascading failures that affected Ontario, Canada, and multiple states in the Northeast and Midwest of the United States—an area populated by over 50 million people (U.S.-Canada Power System Outage Task Force, 2004). Local damage to electrical distribution systems, in contrast, can be more directly linked to customer outage areas.

Appendix A, Section A.3 provides an overview of trends in electric power system performance in natural hazard events, especially recent disasters in the United States, with an emphasis on the relationship to societal expectations. It is anticipated that such information can help to inform societal expectations regarding damage extent and recovery rates that are typical in U.S. disasters. Briefly, the main findings are as follows:

- Information on system performance for hazard events is most commonly available in three forms: (1) SAIDI and related industry measures; (2) peak number of customers without power; and (3) time to restore power to all (or almost all) customers;
- The preponderance of outage events and data pertain to storm (and other weather-related) events; data on peak number of customers without power and time to fully restore service are readily available;
- A few empirical models of power outage have been published, almost all for hurricanes and ice storms; these have been used for both predictive and explanatory purposes;
- Substantial detailed data are available for major outage events, particularly with regard to technical aspects of component and system failure and restoration; information on societal impacts and expectations is available for some events, but not consistently or from a single source;
- A few models have been developed for societal impacts of power outages, especially in earthquakes; and

- Key information gaps include: data on spatial patterns[8] of outage (especially in relation to societally important aspects such as service to critical facilities and vulnerable populations), information on societal impacts and consequences, and sufficient data on power outages in hazard types other than storms (e.g., floods, earthquakes).

More detailed data, including that pertaining to societal considerations, are available on an *ad hoc* basis for power outages in large disasters. A few such events are highlighted here. These demonstrate lessons in terms of the durations of power outages in different types of hazard events, disruptions that commonly occur to dependent lifelines, and some key types of societal impacts.

Hurricanes have caused some of the most extensive and lengthy power outages in the United States. The U.S. Department of Energy (DOE) reports that in 2005 Hurricane Katrina, the peak number of customers without power was 2.7 million across four states (DOE, 2009). Within two weeks of first landfall, power was fully restored in Alabama, Florida, and Mississippi; however, over 40% of customers in Louisiana were still without power. Because of flooding, power was not fully restored in New Orleans for several months. In some neighborhoods, residential housing and businesses losses were so severe that electric power was not restored for lack of customers. The utility, Entergy New Orleans, faced repair costs of $260-325 million and lost revenue of $147 million, filed for bankruptcy about a month after the hurricane, and emerged from Chapter 11 bankruptcy in May 2007. Power restoration curves for Entergy New Orleans after both Hurricanes Katrina and Rita are provided by O'Rourke (2010).

Hurricane Rita in 2005 struck less than a month after Katrina, causing 1.3 million customers to lose power. New outages were restored within 3 weeks (DOE, 2009). Rita is notable as a storm event in which there was substantial transmission as well as distribution system damage. Reed et al. (2010a) provide an analysis of power system damage and restoration in this storm. Failures included: transmission towers, which were difficult to access for repairs because of their location in marshy areas; substations where essential equipment, raised above the floodplain, were damaged by airborne debris; and distribution systems, for which repair was hampered by tree failures and related debris. One utility, Entergy Gulf States, Inc., lost all its transmission connections between Louisiana and Texas, but was able to restore power to all who could receive it within 3 weeks. Another utility, East Texas Electric Cooperatives, also experienced lengthy outage: restoration times to its 106,000 customers took 11 days on average but ranged from 16 hours to 36 days.

[8] Many utilities, especially large ones, have geographical information system (GIS) data (and sometimes specialized software platforms) that allow outage data to be viewed and analyzed spatially. Social media provides another potential source of data on outage occurrences, including locations and impacts.

Power outages in Hurricanes Katrina and Rita affected other energy supply systems such as oil refineries and petroleum pipelines. Delays in restarting refineries affected regional fuel supply, cost of goods produced at the refineries, the cost of gasoline, and ultimately the national economy (Reed et al., 2010b). Refinery and pipeline shutdowns caused regional petroleum shortages as far away as North Carolina (North Carolina Energy Office, 2013). The Louisiana Offshore Oil Port reportedly did not sustain much damage but delayed restarting because of electric power outage. Power outages also exacerbated health issues arising from flooding-triggered mold growth, which is usually controlled with air conditioning and fans.

Hurricane Wilma in 2005 caused blackouts to 3.5 million customers in Florida; in Miami, power was lost to 98% of Florida Power & Light's customers, along with major airports, hospitals, and Port Everglades. All but 100,000 customers were restored within two weeks (DOE, 2009).

Power outages in the 2008 Hurricanes Gustav and Ike were similar in size to Katrina and Rita, but restoration was faster (DOE, 2009). Interestingly, Gustav (1.3 million customers without power) appears to have affected power generation by disrupting waterborne fuel deliveries to and river access for cooling at the plants, although this did not lead to power outages. Flooding also impaired the mobility of restoration crews. Ike caused the largest blackout (3.9 million customers in 9 states) in North America since the August 14, 2003, great Northeast blackout. Much of Houston was still without power over 10 days after landfall. Power was restored within 3 weeks. As in 2005, electricity outages in the 2008 hurricanes disrupted refineries, gas processors, pipelines, and ports, and prolonged power outages delayed their restoration.

Other types of storms have also caused major power outages. In June 2012, a derecho—intense straight-line winds over large geographical regions—affected multiple states in the Midwest and Mid-Atlantic states, leading to power outages to 4.2 million customers in 11 states and the District of Columbia, exceeding the outage size in most hurricanes (DOE, 2012). Restoration took 7 to 10 days in many cases and was slower than other severe spring and summer storms in the region, in part due to new storms that occurred shortly after the derecho and caused additional power outages. Restoration rates varied considerably by state. One factor that may have lengthened restoration times was that utilities had little warning of the derecho, in contrast to hurricane warnings received days in advance.

Hurricane Irene in 2011 and Hurricane Sandy in 2012 caused some of the largest power outages on record. Across multiple states, some 6.69 million customers lost power in Irene and 8.66 million in Sandy (and the Nor'easter that followed) (DOE, 2013). Other sources estimate that Irene caused power outage to about 9 million customers, and Sandy to approximately 10 million customers in 24 states (EEI, 2014). Restoration to 95% of customers took 5 days following Irene, and 10 days after Sandy (DOE, 2013). In Hurricane Sandy, widespread gasoline shortages in the New York City area were experienced; while caused by supply problems at petroleum product terminals, they were exacerbated by power outages to retail gas stations.

Ice storms have also caused large-scale power outages. The 2013 Toronto Ice Storm caused transmission and distribution system damage that led to over 1 million customers losing power in the city, some for 10 days. The storm caused CAN$11.9 million in damage and CAN$1 million in revenue loss for the utility, Toronto Hydro (QUEST, 2015).

The 1998 ice storm that affected Quebec and areas of eastern Ontario caused damage to 40% of the distribution system owned by the utility, Ontario Hydro. Some CAN$140 million in damage was suffered by Ontario Hydro and CAN$800 million by Hydro-Québec. Some 150,000 people lost power for up to three weeks (QUEST, 2015). Chang et al. (2007) gathered media reports on the societal impacts of the ice storm, focusing on infrastructure failure interdependencies related to power outage. Among the most significant societal impacts of power outage were: major employers shutting down for up to two weeks; communication difficulties among emergency service providers; fuel shortages caused by temporary closure of two refineries; and Hydro Québec's request that businesses voluntarily close to allow more rapid power system repairs. Numerous other impacts ranged from hospital disruptions to CAN$25 million in lost revenues to farmers, and 28 deaths from hypothermia, carbon monoxide poisoning, and fires (Chang et al., 2007). Following the disaster, a public commission gathered information from numerous parties affected by the ice storm and included information on psychosocial impacts (Nicolet Commission, 1999, cited in Chang et al., 2007).

Snowstorms have also caused power outages by damaging transmission and distribution lines. In 2009, heavy snow caused power loss to nearly 100,000 customers of Appalachian Power Company, some for 18 days. Restoration was hampered by a second powerful snowstorm following upon the first. A subsequent review "acknowledged mistakes but noted that the utilities handled the vast scale of the disruption well" (Commonwealth of Virginia, 2012).

A period of unusually cold and windy weather in February 2011 in the Southwestern U.S., while not pertaining to winter storms, caused widespread power outages to a region unaccustomed to such weather. Damage was suffered to generation and transmission systems that triggered several controlled load sheds and rolling blackouts. In the peak outage event, 1.3 million customers lost power, and some 4.4 million were affected over the course of three days (FERC and NERC, 2011).

There are few reports of power outages caused by floods (aside from coastal flooding in hurricanes). Because of their failure modes (e.g., substation flooding) and spatial concentration, power outages caused by flooding tend to be more limited in size than those caused by wind storms or earthquakes. In one recent case, the 2013 flood in Calgary, floodwaters caused temporary loss of a distribution substation that supplied critical power to a hospital in the city (QUEST, 2015). Some 35,000 customers lost power for up to eight days. The utility, ENMAX, suffered CAN$9.6 million in direct damages. As a result of the losses, ENMAX plans to install more smart meters in flood risk areas to allow remote disconnections and reconnections in future floods.

Outage reports related to wildfires are also sparse. Mitchell (2013) discusses the performance of electric power systems in wildfires, including issues of ignition, outage probabilities, and mitigation. Wind speeds are a key factor.

While there are relatively few significant earthquake events, these are often well-documented. In the 1994 Northridge earthquake, power was lost to nearly 2.5 million customers; it was the first time the entire city of Los Angeles had lost power (EERI, 1995). Damage occurred to several transmission towers and high voltage substations from ground shaking, but distribution system damage was light. Restoration was rapid: most customers had power within 12 hours, 93% within 24 hours, and 99% within three days. Grid interconnectedness led to some disruptions far afield; for example, to 150,000 customers in rural Idaho for three hours (EERI, 1995). Performance was considered better than in the 1971 San Fernando earthquake that had struck the same area, and partly credited to changes made in the ensuing time (EERI, 1995). In the 2001 Nisqually earthquake in Washington State, which can be considered a design level event, outages were minor: of the three distribution utilities affected, the most disrupted system entailed power loss to 200,000 or 924,000 customers, virtually all of which had power restored within six hours (Heubach, 2001).

Observations from earthquakes in other countries with similar power infrastructure to the United States provide valuable lessons, since seismic events occur infrequently. Generally speaking, electric power outages in earthquakes tend to be widespread, as in storms, but relatively brief in duration. Transmission system damage is generally minor, with most outages deriving from distribution system damage. The power outage was extensive in the catastrophic 1995 Kobe, Japan, earthquake, but service was restored within several days, much more quickly than water and natural gas (which required several weeks), rail (which took several months) and highway transportation (which took about 21 months) (Chang and Nojima, 2001). The power outage in Kobe led to numerous interdependent infrastructure failures, including malfunction of traffic signals, loss of satellite emergency communications, hospital shutdowns, loss of water filtration plants and pump stations, loss of water and elevators in high-rise buildings, urban fires (when electricity restoration caused sparks that ignited leaked natural gas), and lack of heating at emergency shelters during winter conditions (Nojima and Kameda, 1996). In the less severe 1999 Niigata Ken Chuetsu earthquake in Japan, power was lost to 300,000 customers but 94% were restored within four days and all by the $11^{th}$ day (Scawthorn et al., 2006).

In the 2010-2011 Canterbury series of earthquakes in New Zealand, power was lost to 80% of the Christchurch metropolitan area, but outages were relatively brief, with service mostly restored within one day. The exception was the February 2011 earthquake: while transmission damage was minor and service restored within 4.5 hours, damage was more extensive in the distribution system. Cable failures were highly correlated with liquefaction-induced ground deformation, rather than high levels of ground shaking. Some 90% of customers had power within 10 days, when a temporary 66 kilovolt (kV) line was put into service. Damaged 66 kV and 11 kV underground cables were a cause of the longer outages that affected the availability of power during the subsequent winter months. (There is a need for national and international seismic design guidelines for buried power cables.) The minimal damage to power systems, despite strong ground shaking, has been credited to seismic upgrading implemented in the decade prior to the earthquakes (Kwasinski et al., 2014).

Performance and impact information is also available to a limited degree from outage events other than natural disasters. Miles et al. (2014) documents the broad range of interdependent lifeline and societal impacts arising from a 2011 power outage that affected 3.5 million people in San Diego for up to 12 hours. While not caused by a natural hazard, and while the outage duration was short, the impacts of the power outage are nonetheless very relevant. Particularly notable disruptions were related to fuel access and gas station serviceability, sewage spills from wastewater treatment plant failures, and food-related socioeconomic impacts.

Studies on societal impacts of electric power outages are relatively sparse. McDaniels et al. (2007) and Chang et al. (2009a) analyzed infrastructure failure interdependencies and their societal consequences in several major power outage events: the 2003 northeastern North American blackout, the 1998 Quebec Ice Storm, and three 2004 Florida hurricanes. The impact pattern in the Northeast blackout was distinct from those in the storm events in terms of causing more pronounced economic impacts and transportation problems. Power outages in the storm events, by contrast, caused more significant health-related impacts and disruption to emergency services and building support systems such as heating, ventilation, and air conditioning (HVAC). This contrast may derive from seasonal and outage duration differences.

In a review of recent power outages worldwide, Zeng et al. (2015) found the following common types of impacts: traffic paralysis, including transit;

communication interruption; social disorder; financial and stock market interruptions; industrial safety issues; and government and health sector issues.

Although these cases document impacts in actual power outage events, it should be noted that the severity of impacts can be reduced, in part through more rapid restoration. A key need is therefore to explore how repairs can be strategically sequenced in order to rapidly restore power to where it is needed most for community recovery.

## 3.6 Gaps and Deficits: Codes, Standards, Performance Requirements, and Societal Considerations

With regard to natural hazards, engineering design in the electric power sector is governed by codes and standards at the individual asset or component level, primarily for extreme wind and snow/ice loads. While utilities are required to report on systems-level performance to regulators, the performance measures that are used (e.g., SAIDI) are largely operational, often excluding hazard events. When hazard events are included, definitions differ across reporting jurisdictions. Moreover, such measures are not based on societal expectations of electric power performance in hazards. It is also important to recognize that codes and standards are not the only influence on power system design; factors such as voluntary measures to exceed standards, injunctions of regulatory authorities to improve performance in hazard events, and floodplain management practices also influence the physical resilience of electric power systems.

While there is no evidence of societal performance expectations directly influencing electric power system codes, standards, or design, it may be useful to search for indirect evidence. For example, post-disaster utility performance reviews, sometimes reflecting detailed consultation with stakeholders on the impacts of power outages, can provide evidence of outage tolerance thresholds. Also, as shown in Chapter 2, electric power supply to critical facilities such as hospitals is an important societal consideration. Many utilities do have plans to prioritize hospitals and other key facilities in the restoration process (see Appendix A, Section A.4 for more detail).

## 3.7 Conclusions and Recommendations

### *3.7.1 Review of Key Points*

Electric power outages disrupt communities by affecting both direct consumption by end users (e.g., households and businesses) and the operation of nearly all other lifeline infrastructure systems. Current practice in the electric power industry is geared toward designing components for hazard loads, rather than for system performance. There is an urgent need for quantitative measures and comprehensive data collection on actual and potential performance of power systems in natural hazard events (e.g., across all major hazard types, in relation to different failure modes, and with spatio-temporal detail regarding outage and restoration), as well as on societal aspects such as impacts and performance expectations. Several recommendations are made below.

### *3.7.2 Lifeline Standards Development Needs*

Following are key recommendations to improve electric power system codes, standards, and guidelines**:**

- **Gather comprehensive data on system performance of electric power.** While data from actual disasters provide the most direct evidence on performance, other sources such as disaster preparation exercises should also be tapped, as they can also provide valuable information on potential power outages in areas that have not experienced recent disasters. Such data on systems performance will be important for understanding current vulnerabilities, making the case for reducing those vulnerabilities, and developing systems-based lifeline standards.
- **Develop and use consistent metrics to enable comparisons across events, utility companies, states, and other factors.** Agreement on what types of data should be gathered and how electric power system performance can be consistently and meaningfully measured would in itself represent an important advance.
- **Define system performance measures for electric power that relate to community resilience and reflect societal expectations.** Available information, while sparse, indicates several aspects of societal expectations that are important, as follows:

    1. **Performance measures should reflect outage characteristics that reflect societal considerations.** Outage characteristics include not only the number of customers affected and duration, but also characteristics such as seasonality (e.g., summer vs. winter time) and service to critical facilities such as hospitals. For example, one measure could be the percentage of hospitals in the affected area with power available/restored within 24 hours.
    2. **Performance measures need to consider "downstream" effects on other infrastructure.** For example, hospital operations can be impeded by a power outage. Although hospitals are required to have resources for 72 hours of operations for essential functions following a power outage (FEMA, 2014), emergency power may service only limited operations and may also fail. A DHS survey of 222 hospitals found that while most had backup power in the form of an electric generator, generator power was sufficient to operate only a portion of hospital functions for a short period (i.e., hours to a few days) (DHS, 2014). Indeed, it was estimated that hospitals would suffer 67% to

99% degradation of core operations within five minutes of an outage if no backup sources were available. Notably, 75% of the surveyed hospitals had arrangements with their electric power provider for priority in restoration.

3. **Performance measures should consider electric power service to vulnerable populations.** Society is not homogeneous, and different groups suffer differential losses in the same outage. For example, populations with special health needs such as those reliant on electrically powered medical devices are especially at risk in outages. Moreover, different population groups have different risk perceptions, resources, preparedness, and other considerations.

4. **People and organizations have an inherent adaptability and capacity to withstand power outages, which in turn has societal consequences.** Rose (e.g., Rose, 2007) has written extensively on business' ability to undertake resilience actions such as finding alternative suppliers, delaying production, and shifting schedules. Fujimi and Chang (2014) found that after Japan's 2011 earthquake, tsunami, and nuclear disaster, prolonged power supply reduction due to loss of nuclear power generation did not create an economic crisis; rather, businesses demonstrated a remarkable capacity to curtail electric power consumption. The loss of nuclear power did have macro-economic effects as Japan substantially increased acquisition of external fuel supplies. Such industrial adjustments in response to power reduction are noteworthy, and emphasize the importance of public education, business continuity planning, and other pre-disaster preparation efforts that increase the capacity of people and organizations to withstand power outages.

5. **Societal impacts and expectations are strongly influenced not only by the actual severity of outages, but also by availability (or lack) of information and how information is communicated.** Better information (e.g., regarding expected outage durations) can facilitate pre-disaster planning. Immediately prior to and during an outage, good information is important for emergency response. Numerous post-disaster reviews of electric utility performance have emphasized the need to improve communications (e.g., EPP, 2012).

### *3.7.3 Research Needs*

Following are key research recommendations**:**

- **Systematically gather and assess secondary data (e.g., from industry restoration priorities and post-disaster utility performance reviews) on societal expectations pertaining to acceptable electric power outages and restoration timeframes.** It is important to keep in mind, however, that societal considerations may be changing; in particular, that disruptions may be becoming less tolerable.

- **Conduct focused studies that engage in direct data collection (e.g., surveys) regarding key aspects of the relationship between electric power outages, societal impacts, and expectations.** Such studies are important for certain key aspects of performance, when secondary data may be unavailable or insufficient. One such aspect is duration: it will be important to document and understand how the impacts of blackouts scale up with the duration of outage. For example, what are key thresholds beyond which loss of infrastructure functionality, adverse impacts to vulnerable populations, losses to businesses, or public tolerance rapidly deteriorate? Such understanding may allow translation of outage duration, which is commonly reported, into outage impacts. They may also encourage the development of duration-related standards that reflect societal impacts and expectations.
- **Conduct studies to investigate the differential vulnerability among social groups to power outages.** For example, it can be hypothesized that populations that are "off grid," that is, who have independent sources of power, are different than grid-dependent populations in ways that are relevant to disaster vulnerability, such as having higher financial resources and better health overall.

### *3.7.4 Modeling Needs*

Following are recommendations pertaining to key modeling needs**:**

- **Develop first-generation systems-based models to support exploration of resilience-enhancing options by utilities and communities.** Such models should account for:
    1. Alternative response and restoration strategies that utilities might take, including aspects such as prioritization, mutual aid; and
    2. Alternative pre-event measures and investments that utilities can undertake to enhance the performance and recovery of networks during and after hazard events. These include not only engineering design for improved performance during the event and improved functionality after the event, but also approaches such as relocating substations out of floodplains, grid

modernization[9], and changes to network configurations such as microgrids[10]. Several recent reports provide detailed recommendations on how to strengthen the resilience of electric power systems, including but not limited to hardening components (see Executive Office of the President, 2013a; EEI, 2014a; QUEST, 2015).

### 3.7.5 Lifeline System Operational Needs

Electric power utilities across the nation differ greatly in their understanding of how their systems may perform and recover under natural hazards, particularly extreme events. While large utilities may have sophisticated models to simulate system performance under different hazard conditions, many smaller utilities do not have such capabilities. The industry as a whole would benefit from data on actual performance and societal expectations, performance objectives, and guidelines that reflect system performance, recovery, and key societal functions that use electric power.

### 3.7.6 Future Considerations and Trends

Although beyond the scope of this report, several future considerations and trends are important to consider in further work. They include:

- The changing nature and context of electric power systems. Aspects include increasing available of renewable energy sources, distributed energy, grid modernization (independent of utilities' resilience strategies), as well as increasing dependence on telecommunications and aging and deteriorating infrastructure. (For examples of the use of renewable energy for community resilience, see NASEO, 2009. See also Bay Area Council Economic Institute, 2015). Changes in technology are shifting electricity distribution and management from a centralized approach to a decentralized system (e.g., distributed energy resources, renewable energy, microgrids, and reconfiguring parts of system to "island them").

[9] Grid modernization can involve the use of smart grid technology to remote control and automate activities to better monitor and operate the grid. Such technologies have been credited with more rapid power restoration in events such as Hurricanes Irene and Sandy. For example, "the Potomac Electric Power Company (PEPCO) said it was able to restore power to 130,000 homes in just two days after Sandy thanks to advanced meter infrastructure (AMI) [that it recently] deployed... With smart meters and AMI... PEPCO received "no power" signals that allowed them to quickly pinpoint outage locations." (Executive Office of the President, 2013a, p.10).

[10] "A key feature of a microgrid is its ability during a utility grid disturbance to separate and isolate itself from the utility seamlessly with little or no disruption to the loads within the microgrid. Then, when the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself to the grid in an equally seamless fashion. Technologies include advanced communication and controls, building controls, and distributed generation, including combined heat and power which demonstrated its potential by keeping on light and heat at several institutions following Superstorm Sandy." (Executive Office of the President, 2013a, p.14-15)

- The traditional industry structure is also changing as renewable power sources become more prominent and distributed generation (e.g., power plants built to serve a specific manufacturing facility) and demand-side management (e.g., energy efficiency and storage) become more common (NIST, 2015). These changes are stressing a physical infrastructure beyond its original design; for example, with systems intended to carry electrical flows in one direction now transmitting them in multiple directions depending upon supply and demand conditions at different times of the day. Numerous transmission upgrading projects are being pursued—many involving telecommunications and new technologies—to increase the resilience of the U.S. electrical grid.
- Societal expectations pertaining to electric power performance under hazard conditions may be changing, with decreasing tolerance for outages generally, lower thresholds for acceptable outages, and less tolerance for greater disruptions from outages when they occur.

## Chapter 4

# Gas and Liquid Fuel

### 4.1 Systems Overview

Gas and liquid fuel systems include the equipment and facilities needed for conveyance, such as pipe, valves, fittings, pumps, compressors, storage tanks, pressure regulators, monitoring equipment, and the surface or underground structures required to house these facilities. Pump stations are needed for petroleum and refined products pipelines to overcome flow friction and move the liquids to higher elevations. Pressure reducing stations may be needed when moving the fluids to lower elevations in mountainous terrain. Compressor stations are needed for gas transmission lines to pressurize the gas during transportation. In addition to pipeline systems and associated facilities, the transportation of liquid fuel also involves shipment by barge, tanker, and railroad of crude oil and refined products as well as truck transportation of gasoline to service stations. Liquefied natural gas is transported by specially constructed ocean vessels.

Gathering pipelines transport gas and petroleum from production areas to transmission pipelines. Gathering lines for petroleum production are generally on the order of 2 to 8 inches (in.) in diameter.

Transmission pipelines transport crude oil and natural gas from gathering systems to processing, refining, and storage facilities. They also transport refined petroleum products, such as gasoline and natural gas liquids to distribution terminals. Transmission pipelines vary in diameter typically from 8 to 36 in., although some are as large as 48 in., such as those in the Trans-Alaska Pipeline System. The operating pressures of transmission lines vary from relatively low pressures (< 100 pounds per square inch (psi)) to over 1,000 psi.

Distribution pipelines transport natural gas from transmission facilities to customers. Their diameters vary typically from 4 to 12 in., although lines as large as 36 to 48 in. are found in large urban communities. Cast iron distribution mains are often operated at low pressures equivalent to about 0.4 to 0.5 psi. Steel and plastic (typically high and medium density polyethylene) distribution mains are operated at maximum pressures frequently ranging from 60 to 100 psi. Gas is conveyed from distribution lines to customers by service lines or services, which are typically 0.5 to 1.0 in. in diameter.

U.S. statistics for natural gas show there are a total of 303,663 miles (mi.) of transmission lines that supply 22% of U.S. energy consumption per year (PHMSA, 2015). Figure 4-1 shows the spatial distribution of the nation's system. For example, pipelines originating in Louisiana and crossing the Mississippi Valley are subject to disruption by hurricanes, river flooding, and earthquakes originating in the New Madrid Seismic Zone. These lines convey natural gas essential for heating and cooling in heavily populated areas of the Northeast and Midwest. Many liquid fuel transmission lines follow similar routes and are subject to the same disruptions. They transport fuel essential for all modes of transportation, as well as heating, into the Northeast and Midwest. Some locations, like Portland, Oregon, are serviced by a single line as shown on the map. More than 90% of Portland's refined petroleum products follow a similar route through a 6-mile stretch of the Willamette River that is at risk from liquefaction-induced ground failure during an earthquake (NIST, 2015).

Cushing, Oklahoma is a location of special note for the U.S. liquid fuel transmission system. It has been described as the most significant trading hub for crude oil in North America with a strategic location that controls oil transmission from Gulf

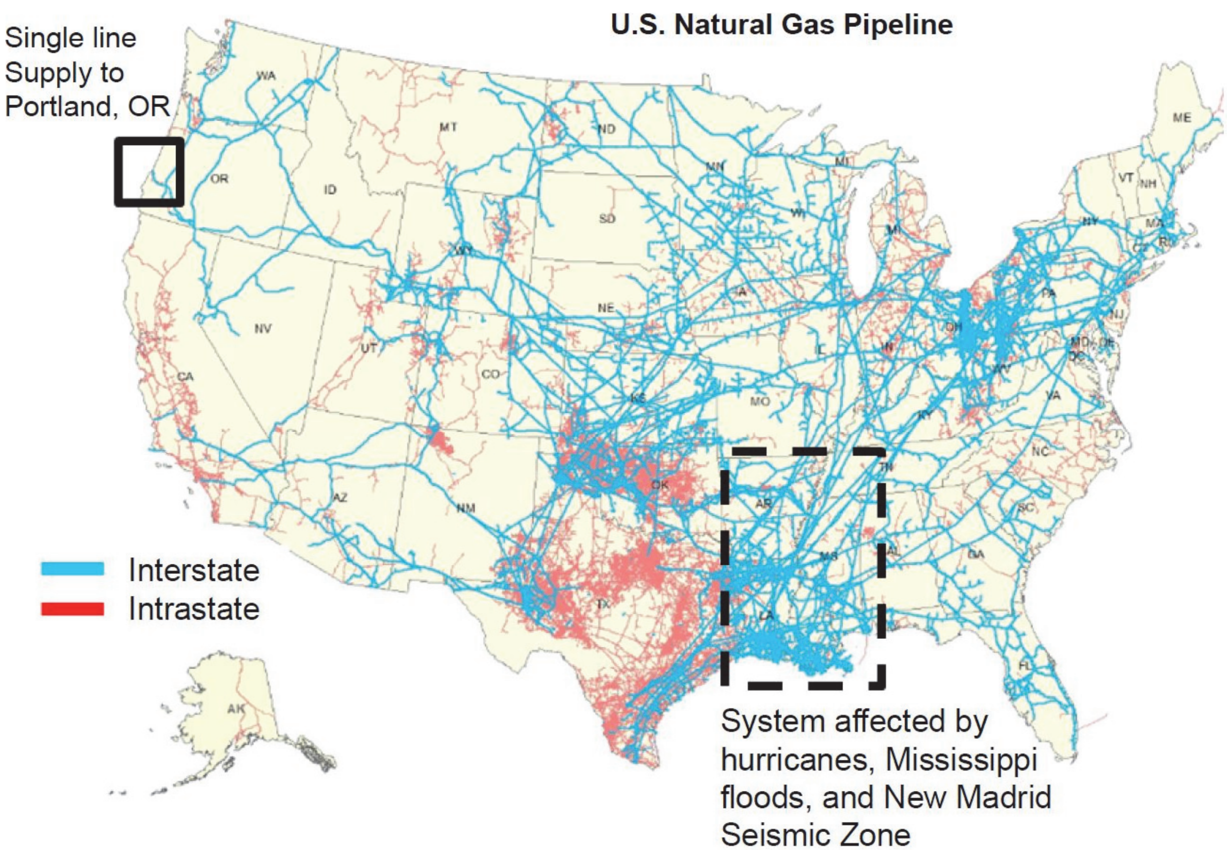


Figure 4-1 Map of U.S. natural gas interstate and intrastate transmission system (NIST, 2015).

Coast oil ports to Midwest and Northeast U.S. customers (Oklahoma Office of the Secretary of Energy, 2005).

Besides the main transmission lines, natural gas systems also include 17,591 mi. of gathering lines, 1,263,987 mi. of distribution lines and an estimated 67,199,258 services accounting for 901,209 mi. of service lines.

Liquid fuel pipelines include those that convey petroleum, refined fuel products, highly volatile liquids (HVLs), and carbon dioxide ($CO_2$). The HVLs include propane, butane, and ethylene, which are gases that liquefy under pressure. U.S. statistics for liquid fuels show there are a total of 192,414 mi. of transmission lines, which include 60,902 mi. for petroleum, 63,549 mi. for refined products (including ethanol), 62,768 mi. for HVLs, and 5,195 mi. for $CO_2$ (PHMSA, 2015).

One study pointed out that refineries and processing facilities are often engineered as separate complexes and thus treated as end nodes and not modeled as part of the gas and fuel delivery system (NIST, 2014). Consistent with previous treatment, this chapter focuses on transmission of fuels. Refineries, however, are an important part of the regional fuel supply chain and their disruption by flooding and/or loss of electricity had a major impact on the restoration of transportation capabilities after Hurricane Sandy (City of New York, 2013a) and fuel prices after Hurricane Ike (Ailworth, 2008). For these reasons, a recommendation is made at the end of this chapter to improve knowledge, databases, and modeling of refineries and their impact on regional recovery.

## 4.2 Summary of Codes, Standards, Guidelines, and Performance Requirements

The regulatory framework for gas and liquid fuel systems is based on the Natural Gas Pipeline Act of 1968, Hazardous Liquid Pipeline Act of 1979, Pipeline Safety Improvement Act of 2002, and Pipeline Inspection, Protection, Safety and Enforcement Act of 2006. The Pipeline and Hazardous Materials Safety Administration (PHMSA) was created in 2004 to administer the Department of Transportation national regulatory program for the transportation of natural gas, petroleum, and other hazardous fluids by pipeline, including regulations pertaining to the safety of pipelines and associated facilities. It also oversees the implementation of risk management by pipeline operators and provides technical and resource assistance for state pipeline safety programs. State regulatory agencies also provide oversight. For example, California operators are regulated by the California Public Utilities Commission (CPUC) whose rules affecting pipeline systems are codified under *State of California Rules Governing Design, Construction, Testing, Operation, and Maintenance of Gas Gathering, Transmission, and Distribution Piping Systems* as part of General Order 112E (NTSB, 2011).

Table 4-1 summarizes the codes, standards, and guidelines governing gas and liquid fuel pipeline systems that affect community resilience. Key features of codes, standards, and guidelines and related performance requirements are discussed in this section. A more detailed review of the regulatory framework and a detailed description of key codes, standards, and guidelines associated with gas and liquid fuels systems are presented in Appendix B.

**Table 4-1 Summary of Key Codes, Standards, and Guidelines for Gas and Liquid Fuel Systems**

| Category | Title | General Description |
|---|---|---|
| Code | 49 CFR Part 192 *Transportation of Natural and Other Gas by Pipeline* (Office of the Federal Register, 2013a) | Minimum safety requirements for pipeline facilities and transportation of natural gas promulgated by the federal government. |
| Code | 49 CFR Part 195 *Transportation of Hazardous Liquids by Pipeline* (Office of the Federal Register, 2013b) | Minimum safety and reporting requirements for pipeline facilities used in the transportation of hazardous liquids promulgated by the federal government. |
| Standard | ASME B31.8 *Gas Transmission and Distribution Piping Systems* (ASME, 2014) | Requirements for the design, materials, construction, assembly, inspection, and testing of pipelines transporting liquid fuels. |
| Standard | ASME B31.4 *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids* (ASME, 2010) | Requirements for the design, fabrication, installation, inspection, testing, safety aspects of operation, and maintenance of facilities used for the transportation of gas. |
| Standard | API Recommended Practice 1162 *Public Awareness Programs for Pipeline Operators* (API, 2010) | Guidance for pipeline operators on the development, implementation, and evaluation of public awareness programs. |
| Guidelines | *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (PRCI, 2004) | Recommended procedures and methods for the assessment of new and existing natural gas and liquid hydrocarbon pipelines subject to seismic-related loading conditions. |
| Guidelines | *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984) | Guidelines for the seismic design of buried oil, gas, or refined petroleum product pipelines and surface facilities, such a pumping and compressor stations, storage tanks, and miscellaneous terminal facilities. |

Title 49 of the Code of Federal Regulations (CFR) Parts 190-199 address gas and liquid fuel pipeline systems. The most important and extensive parts of these regulations are 49 CFR Part 192 *Transportation of Natural and Other Gas by Pipeline* (Office of the Federal Register, 2013a) and 49 CFR Part 195 *Transportation of Hazardous Liquids by Pipeline* (Office of the Federal Register, 2013b). The CFR sets minimum requirements, and additional requirements may be promulgated through state administrative codes, which are enforced by public utility or public service commissions. Various professional society standards are incorporated in 49 CFR Parts 192 and 195 by reference. The most extensive and frequently referenced standards in 49 CFR Parts 192 and 195 are ASME B31.8 *Gas Transmission and Distribution Piping Systems* (ASME, 2014) and ASME B31.4 *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids* (ASME, 2010), respectively. In addition to ASME B31.8, 49 CFR Part 192 references over 40 standards developed by the American Society of Mechanical Engineers (ASME), American Petroleum Institute (API), American Society for Testing and Materials (ASTM), Pipeline Research Council International (PRCI), Manufacturers Standardization Society for Valve and Fitting Industry (MSS), National Fire Protection Association (NFPA), Plastics Pipe Institute (PPI), National Association of Corrosion Engineers International (NACE), and the Gas Technology Institute. Standards pertaining to public awareness programs for hazardous pipelines are provided by API Recommended Practice 1162 *Public Awareness Programs for Pipeline Operators* (API, 2010). Guidelines for the earthquake design of gas and liquid fuel pipelines are contained in *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (PRCI, 2004) and *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984) developed by the Technical Council on Lifeline Earthquake Engineering (TCLEE) of the American Society of Engineers (ASCE).

Brief descriptions of the codes, standards, and guidelines summarized in Table 4-1 are provided in the following subsections.

### *4.2.1 49 CFR Part 192 Transportation of Natural and Other Gas by Pipeline*

49 CFR Part 192 is the federal regulation that prescribes minimum safety standards for pipeline facilities for the transportation of natural gas. The regulations are detailed and extensive, and address: pipe materials; pipe and component design; welding in steel pipelines and joining of other types of pipe; general construction requirements; customer meters and services; corrosion control; test requirements; uprating pipelines to a higher internal pressure; operations; maintenance; personnel qualification; and gas transmission and distribution integrity management. The code includes protection from hazards, by requiring the operator to take all practical steps to protect each transmission pipeline from washouts, floods, unstable soil, landslides, or hazards that may cause the pipeline to move or to sustain abnormal loads. Offshore pipelines must be protected from damage by mudslides, water currents, hurricanes, anchor dragging, and fishing operations. Operational requirements covered by the code include surveillance and damage prevention programs, emergency plans, and public awareness programs that comply with API Recommended Practice 1162, which is discussed in Section 4.2.5.

Four class locations defined in 49 CFR Part 192 are summarized with respect to design factors in Table 4-2. Each design factor represents the percentage of steel yield strength that can be allowed as pipe circumferential (hoop) stress for each class location. For example, design factors of 0.72 and 0.40 apply for pipe in Class 1 and 4 locations, respectively, and indicate that the pipe must be designed with sufficient wall thickness to limit hoop stress to 72% and 40% of yield strength in Class 1 and 4 locations, respectively, before other reductions are applied depending on the presence and type of longitudinal welds and operating temperature. From Table 4-2, it can be seen that the class representing the greatest population density (Class 4) results in a reduction in allowable stress to nearly one-half that permitted for the lowest population density (Class 1).

**Table 4-2 Class Locations and Design Factors in 49 CFR Part 192 (Office of the Federal Register, 2013a)**

| Class Location* | Description | Design Factor |
|---|---|---|
| 1 | 10 or fewer buildings intended for human occupancy. | 0.72 |
| 2 | More than 10 but fewer than 46 buildings intended for human occupancy. | 0.60 |
| 3 | 46 or more buildings intended for human occupancy; or an area where a pipeline lies within 100 yds. of either a building or a small, well-defined outside area (such as a playground, recreation area, outdoor theater, or other place of public assembly) that is occupied by 20 or more persons on at least 5 days a week for 10 weeks in any 12-month period. | 0.50 |
| 4 | Buildings with four or more stories are prevalent. | 0.40 |

*An onshore area that extends 220 yds. either side of the centerline of any contiguous 1-mi. length of pipeline.

### *4.2.2 49 CFR Part 195 Transportation of Hazardous Liquids by Pipeline*

49 CFR Part 195 is the federal regulation that prescribes minimum safety standards and reporting requirements for pipeline facilities used for the transportation of liquid fuels. The code includes by reference 40 standards developed by the ASME, API, ASTM, PRCI, MSS, NFPA, PPI, and NACE. The code addresses annual accident- and safety-related condition reporting, design requirements, construction, pressure testing, operation and maintenance, qualification of pipeline personnel, and corrosion control.

Similar to 49 CFR Part 192, the code for gas liquid fuel pipelines establishes the design pressure for steel pipe, or maximum allowable operating pressure, on the basis of hoop stress, and prescribes methods for determining the tensile strength of the pipe steel as well as a design factor and longitudinal joint factor. The design factor is 0.72

except that a design factor of 0.60 is used in offshore and inland waterway locations. A design factor of 0.56 is specified for certain fabrication and heating conditions. The regulations require that pipeline design account for external loads, such those related to earthquakes, vibration, and thermal expansion/contraction.

Public awareness programs that comply with API Recommended Practice 1162 see Section 4.2.5) are required. The program must include provisions to educate the public, appropriate government organizations, and persons engaged in excavation activities. In addition, each operator must carry out a written program to prevent damage from excavation activities and adjacent construction disturbance.

The code requires operators to develop a written integrity management program that addresses the risks affecting pipelines in high consequence areas. Such areas include navigable waterways, highly populated areas (as defined in the regulations), and areas that would be unusually sensitive to a liquid hydrocarbon release (e.g., wetlands and water supply sources).

### *4.2.3 ASME B31.8 Gas Transmission and Distribution Piping Systems*

ASME B31.8 covers the design, fabrication, installation, inspection, and testing of pipeline facilities for the transportation of natural gas. It also covers safety aspects of the operation and maintenance of gas pipeline facilities. It is referred to extensively in 49 CFR Part 192 and is one of the backbone standards that supports the federal code with respect to natural gas pipeline safety. The standard covers materials and equipment; welding, piping system components and fabrication details; design, installation, and testing; operating and maintenance procedures; corrosion control; offshore gas transmission; and sour gas (gas containing significant amounts of hydrogen sulfide) service. It applies predominantly to gas transmission and distribution systems, service lines, and some gathering lines.

The maximum allowable operating design pressure equation is identical to that in 49 CFR Part 192, which is derived from the ASME B31.8 code. In addition to design based on allowable hoop stress, ASME B31.8 also provides design procedures for fracture control as well as equations for longitudinal stress design. The standard also calls for protection of pipelines and mains from natural hazards, such as washouts, floods, unstable soil, landslides, earthquake-related effects, or other conditions that may cause serious movement of, or abnormal loads on, the pipeline. The standard identifies protective measures for natural hazards, such as increased wall thickness, construction of revetments, erosion control, and anchors. Little additional guidance is given for how to deal with natural hazard conditions.

### *4.2.4 ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids*

The ASME B31.4 standard (ASME, 2010) covers the design, materials, construction, assembly, inspection, and testing of pipelines transporting liquids between production facilities, tank farms, natural gas processing plants, refineries, pump stations, ammonia plants, terminals, and other delivery and receiving points. It is referred to extensively in 49 CFR Part 195 and is one of the backbone standards that supports the federal code with respect to liquid fuel pipeline safety. The standard covers design; materials; dimensional requirements; construction, welding, and assembly; inspection and testing; operation and maintenance procedures; corrosion control; and offshore liquid pipeline systems.

ASME B31.4 classifies loads as sustained, occasional, construction-related, and transient. Sustained loads include internal pressure, external hydrostatic pressure, self-weight, residual loads, and those resulting from subsidence. Occasional loads include earthquake effects related to ground vibrations, soil liquefaction, landslides, and active faulting.

The standard calls for consideration of slope failure at locations of potential mudslides, steep slopes, and areas of seismic slumping. Also, design for earthquake-induced soil liquefaction is required for areas of known or expected occurrence. If it is not practical to design the pipeline system to survive slope failure, the pipeline shall be designed for controlled breakaway with provisions to minimize the loss of pipeline contents. In earthquake prone areas, including active fault crossings, consideration shall be given to flexibility by means of breakaway couplings, slack loops, flexible pipe sections, and other means. Little additional guidance is given for how to deal with natural hazard conditions.

### *4.2.5 API Recommended Practice 1162 Public Awareness Programs for Pipeline Operators*

API Recommended Practice 1162 provides guidance for pipeline operators to develop and manage public awareness programs to promote safety for communities near gas and liquid fuel pipelines. It is contained in 49 CFR Parts 192 and 195 by reference in Sections 192.616 and 195.440, respectively. The principal objectives of the standard are to provide a framework for pipeline operators to establish and manage a public awareness program, as well as a process for periodic program evaluation.

API Recommended Practice 1162 is intended to help pipeline operators comply with 49 CFR Parts 192 and 195 through public education, emergency responder liaison activities, and damage prevention. As described in the standard, a public awareness program consists of five activities: (1) define objectives; (2) obtain management commitment; (3) establish program administration; (4) identify pipeline assets; and (5) identify stakeholder audiences. The standard addresses the frequency and methods of message delivery. Delivery methods include operator web sites, media news coverage, community and neighborhood newsletters, drills and exercises, open houses, community events, operator employee participation, and pipeline markers.

The standard covers program implementation, which involves the actions of a pipeline operator to plan, conduct, review, evaluate, document, and improve public awareness programs. Program evaluation includes pre-test effectiveness of public awareness materials, including focus groups with in-house and external participants. Program evaluation includes formal annual assessment of the program, using internal self-assessment, third-party assessment, or regulatory inspection. It also includes measures of program effectiveness, such as surveys that are operator-designed and conducted, surveys pre-designed by a third party or industrial association, and trade association conducted surveys. The standard contains example forms for annual, self-assessment and additional information on conducting surveys.

#### *4.2.6 Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines*

*Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (PRCI, 2004) provide recommended procedures and methods for the assessment of new and existing natural gas and liquid hydrocarbon pipelines subject to seismic-related loading conditions. They provide guidance for determining pipeline response to specific seismic hazards. They are intended to be an update of the *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984; see Section 4.2.7) to account for improvements in knowledge and more recent research findings.

The guidelines address general provisions, quantification of seismic hazards, pipeline performance criteria, pipeline analysis procedures, and mitigation options. Seismic hazards include surface faulting, liquefaction, landslides, seismic wave propagation, and transient ground movements related to narrow valleys with weak soils and sites experiencing liquefaction in soil confined by non-liquefiable material.

#### *4.2.7 Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*

*Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* were issued as a collaborative effort among pipeline system operators, consultants, and academic researchers, and were accepted as an informal standard for seismic design within the gas and oil industry for over 20 years. The guidelines address seismic hazards; quantification of seismic hazards; design criteria for pipeline systems; differential ground movement effects on buried pipelines; wave propagation effects on buried pipelines; seismic response and design of liquid fuel tanks; seismic response analysis of structures, equipment, and aboveground pipelines; and operations and maintenance. Although they are a valuable supplement to the *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines*, access to these guidelines is limited since they no longer are available in published form through ASCE.

### *4.2.8 Performance Requirements and Restoration Timeframes*

Public safety and environmental protection are de facto performance requirements for gas and liquid fuel lifelines established by federal code under 49 CFR Part 192 and 49 CFR Part 195. Gas and liquid fuel code requirements and standards involve core practices for public safety that can be adapted more broadly for resilience programs addressing multi-hazard conditions. As required by federal code, the identification of high consequence areas, pipeline integrity management programs, emergency response plans, and public awareness programs (with reference to API Recommended Practice 1162) provide a framework and necessary starting point for addressing public safety in community resilience.

The restoration time frame for gas and liquid fuel transmission facilities is driven by economics and management commitment to public safety, environmental protection, and business continuity. For example, loss of service of the Trans-Alaska Pipeline System after the 2002 Denali Fault earthquake resulted in an estimated loss of $1 million per hour in accordance with crude oil prices at the time (Honegger et al., 2004). Thus, there is ample economic incentive to recover operations quickly. The restoration-of-service goal is to return to functionality as rapidly as possible after confirming pipeline system integrity and safety.

The restoration of gas and liquid fuel service in urban areas involves complex interactions with other lifeline systems, which in turn require integrated understanding and planning for interdependencies. Such interdependencies involve risks resulting from physical proximity and inter-operational relationships among the different lifelines, as discussed in Section 4.4 with respect to the restoration of electric power after the 1995 Kobe and 1989 Loma Prieta earthquakes.

## 4.3 Societal Considerations

Gas and liquid fuel systems are critical for modern industrial societies as a primary source of energy. They are fundamentally important for commercial enterprise and economic well-being. They support local, national, and international competiveness. They are potentially hazardous due to the combustible and/or polluting nature of the fuels, and require high standards of design, maintenance, and operation to ensure public safety, health, and environmental protection.

The main purpose for establishing and maintaining a fuel supply is to provide geographically distributed energy for widespread public and private uses that is safe and can accommodate environmental concerns. Gas and liquid fuel systems generally serve the following functions:

1. Providing distributed energy for all modes of transportation, heating and cooling, electric power, manufacturing, commerce, and public and private services.
2. Providing a safe and protected fuel supply throughout land, coastal, and ocean-based environments, as well as the rural and urban communities that require gas and liquid fuel resources.

Gas and liquid fuel systems are critical for all three phases of disaster recovery (NIST, 2105). In short term recovery (lasting days), fuel is required for emergency response. In intermediate term recovery (lasting weeks to months), gas and liquid fuel are needed to address basic transportation requirements as well as provide heating to support life safety in winter. In long term recovery (lasting months to years), the restoration of fuel delivery is essential for commercial and economic recovery, and electric power generation.

Societal considerations pertaining to gas and liquid fuel lifelines are strongly influenced by concerns about public safety and environmental protection. Such concerns are reinforced by accidents, especially those that receive significant media coverage and merit investigation by the National Transportation Safety Board (NTSB). In exceptional circumstances, such as those related to the San Bruno pipeline rupture and fire (described in Section 4.5), public reaction can be severe.

Uninterrupted access to gasoline and diesel fuel is expected for emergency responders, and reliable fuel supply is expected for heating in the winter. The availability of gasoline at local service stations is anticipated as soon as there is sufficient restoration of roads, bridges and tunnels for safe travel. Hazard-specific needs for fuel include ice storms, when fuel is required for heating, and earthquakes, when leaking gas pipelines represent a source of ignition for fire following earthquakes.

A comprehensive study of pipeline safety and land use practices was conducted by the Transportation Research Board (2004) with recommendations for PHMSA. To address those recommendations PHMSA supported the establishment of the Pipelines and Informed Planning Alliance (PIPA), which is a broad stakeholder initiative to improve safety through risk-informed land use and development near gas and liquid fuel transmission pipelines (PIPA, 2010). The NIST *Guide* (NIST, 2015) points out that PHMSA (2013) has identified five areas for local governments to improve protection of pipelines and increase the resiliency of the gas and liquid fuel transmission system: (1) pipeline awareness (education and outreach); (2) pipeline mapping; (3) excavation damage prevention; (4) land use and development planning near transmission pipelines; and (5) emergency response to pipeline accidents.

Recommended practices are presented by PIPA (2010) for risk-informed land use planning in relation to two scenarios: (1) baseline recommended practices implemented by stakeholders in preparation for future land use and development; and (2) new development recommended practices implemented by stakeholders when specific new land use and development projects are proposed. Each recommended practice includes a practice title, brief statement about the practice, stakeholder audience to implement the practice, practice details, and references if applicable.

*State Energy Assurance Guidelines* are available through the National Association of State Energy Officials (NASEO, 2009) to assist states in the design, development, and writing of state energy assurance plans. This document provides state energy and emergency officials with a standard set of guidelines for understanding and evaluating how their jurisdictions respond to energy outages and to promote the protection of critical energy infrastructure associated with electric power and gas and liquid fuel systems. Specific measures that can be taken during gas and liquid fuel outages are presented. Guidance on preparing energy assurance plans are also provided by the Public Technology Institute (PTI, 2011).

## 4.4 Interdependencies

Key upstream dependencies for gas and liquid fuel systems include electric power for pumping and compressor stations and diesel fuel for emergency generators and pumps. Key downstream dependencies involve the need for fuel in all modes of transportation. Especially important is fuel for vehicles operated by emergency responders. Gas and liquid fuels are also used for the generation of electricity at power plants. Couplings and pairings between different systems involve the interaction between leaking gas and electric power as a source of ignition after a disaster and the availability of water supply for fire protection, given the risk of ignition from leaking gas and fuel.

As previously indicated, the safe operation of gas and liquid fuel pipeline facilities is a major interdependency factor in the post-disaster performance of lifelines, including plans and schedules for restoration. The restoration of electric service, for example, needs to be carefully coordinated with the restoration of gas and liquid fuel pipelines. This need was illustrated by O’Rourke (1996) with respect to the restoration of electric power after both the 1995 Kobe and 1989 Loma Prieta earthquakes. Disruption in the recovery of electric power after the 1995 Kobe earthquake was caused by post-earthquake fires that burned overhead electric power lines and buildings that collapsed on exposed distribution cables. The rapid restoration of electric power, which is an ignition source, contributed to post-earthquake fires in areas of leaking gas.

In Kobe, electric power and natural gas facilities are operated by two independent companies, Kansai Electric Power and Osaka Gas, both of which compete in the same energy market. Community resilience must therefore consider the organizational constraints among separate commercial entities in developing an integrated plan. In contrast, electric power and natural gas facilities in San Francisco are operated by the same company. Full restoration of electric power in San Francisco after the Loma Prieta earthquake took approximately two days while gas leak surveys were conducted by company personnel (O'Rourke, 1996).

The close interdependency in restoration between electric power and gas distribution systems is important for hazards that cause damage to gas distribution pipelines. As illustrated by past earthquakes affecting Kobe and San Francisco, permanent and transient ground deformation will damage gas distributions systems with vulnerable lines. Field surveys and inspections for leaking gas may take days, thus delaying electric power restoration. In such cases, the restoration of power will be linked with that of the gas system. Coordinated planning at the local level is required between electric power and gas providers to ensure safe and time-effective restoration of service.

Damage to underground pipelines will generally be less severe after wind storms and flooding, except where erosion-related undermining occurs. The upstream dependencies are most important in these cases, where loss of electricity can lead to loss of functionality at pump and compressor stations. To offset electric power losses, it is possible in principle to provide combustion engines for pumping with sufficient fuel storage to maintain operation even under prolonged power outages. In practice, however, stations generally have diesel generators to power critical electronics, control systems, etc., but not to drive mainline pumps and compressors. Flooding can lead to prolonged loss of transportation routes and fuel shortages, which must be considered with respect to sustained pumping capacity.

A study on the 1989 train derailment near Cajon Pass, just north of metropolitan Los Angeles, California illustrated the importance of colocation (NIST, 2014). The derailment was followed by a catastrophic fire when a damaged gasoline transmission pipeline near the railroad tracks exploded, destroying a number of homes and causing several deaths (FEMA, 1991). In response to the tragedy, Congress authorized FEMA to investigate lifeline interdependencies in the Cajon Pass, where a large number of critical lifelines are co-located, and to consider the broader vulnerability issues of colocation for lifeline systems elsewhere in the United States (FEMA, 1991, 1992a, 1992b).

The proximity and potential effects of hazards on gas and liquid fuel pipeline facilities are core issues with respect to colocation. These issues are addressed in federal code requirements and ASME standards regarding high consequence areas and pipeline integrity management programs to enhance public safety related to corrosion and third-party damage. Because high consequence areas and pipeline integrity management programs include the identification of important colocation areas, they provide a baseline from which community resilience plans can be expanded to consider multi-hazard effects.

There is currently a gap between the need to identify the locations of gas, liquid fuel, and other critical infrastructure and the actual access to information about these facilities from lifeline system operators. The absence of readily accessible information also includes electric power and telecommunication systems. As discussed later in this chapter, PHMSA has developed a Pipeline Information Management Mapping Application that has the potential for identifying areas of high consequence where hazardous pipelines are located in proximity to other underground facilities, including electric power and telecommunication cables.

## 4.5 Disaster Lessons

Community resilience involves a complex interaction between the people affected by critical infrastructure and the physical characteristics, operation, and management of those systems that supply needed resources and services. It is important, therefore, to examine how gas and liquid fuel lifelines have performed in terms of previous accidents and response to natural hazards. Four key events, in particular, are reviewed: Hurricane Katrina, Hurricane Sandy, San Bruno pipeline rupture and fire, and the Denali Fault earthquake effects on the Trans-Alaska Pipeline System.

### *4.5.1 2005 Hurricane Katrina*

After Hurricane Katrina, the supply of crude oil and refined petroleum products was interrupted because of a loss of electric power at the pump stations for three major transmission pipelines: the Colonial, Plantation, and Capline Pipelines (O'Rourke, 2010). As a result of Katrina, major lines of crude oil and refined products were not available for delivery to southern and eastern states, and gasoline and diesel production in the Midwest was seriously affected by lack of supply.

The interruption of crude oil and refined petroleum product pipelines after Hurricane Katrina points out the vulnerability of critical liquid fuel supplies for the Midwest and Northeast United States. Some of the same lines are also vulnerable to earthquakes in the New Madrid Seismic Zone. The seismic vulnerability of crude oil pipelines to soil liquefaction and landslides near or adjacent to the Mississippi River has been identified in several studies (e.g., Beavers et al., 1986; Ariman et al., 1990). The multi-hazard exposure of critical liquid fuel transmission lines in the Mississippi

Valley and adjacent riverine areas is a major source of vulnerability for U.S. regional fuel supplies.

### *4.5.2 2012 Hurricane Sandy*

Hurricane Sandy demonstrates the impact of widespread flooding and storm damage on regional fuel supplies. After Sandy, disruptions occurred at nearly every level of the fuel supply chain, reducing all fuel flow into and within the New York City metropolitan area. Disruption in the fuel supply is described in detail in *A Stronger, More Resilient New York* (City of New York, 2013). Storm surge damage to electrical equipment at two of six refineries reduced regional refining capacity by 26%. Electric power outages in New Jersey caused the Colonial and Buckeye transmission pipelines to shut down for four days, reducing total supply of fuel in the region by another 35% to 40%. Eight to ten days after the hurricane, 21% of the New York metropolitan fuel terminals were shut down, with dramatic effects on supply to gas stations. Within one week of Sandy's landfall less than 20% of vehicle service stations were able to sell fuel at any given time. The loss of fuel not only affected the general population, but created severe refueling difficulties for entire fleets of supporting personnel critical for storm response.

### *4.5.3 2010 San Bruno, California, Pipeline Rupture and Fire*

On September 9, 2010, a 30-in.-diameter segment of an intrastate natural gas transmission pipeline, operated by the Pacific Gas and Electric Company (PG&E) ruptured in a residential area of San Bruno, California (NTSB, 2011). The ensuing fire destroyed 38 homes and damaged 70. Eight people were killed and many others were injured. Fire-fighting operations continued for two days.

The NTSB found that rupture was caused by a fracture in a partially welded longitudinal seam in pipe that did not meet generally accepted quality control and welding standards when constructed. The NTSB found that the pipeline integrity management and public awareness programs were deficient. It was also determined that the CPUC failed to detect inadequacies in the operator's integrity management program. Of particular significance, the NTSB found that the San Bruno pipeline rupture and fire was an organizational accident in that it arose from a multitude of inadequate operational procedures and management controls that persisted over time until the pipeline rupture occurred.

Graphic news coverage had a large impact on public perceptions and opinion. Media exposure was further amplified by subsequent actions in which the Lieutenant Governor made a state of emergency declaration. Litigation was initiated by multiple plaintiffs. The PG&E Chief Executive Officer and CPUC Chair resigned their positions, and a federal grand jury in the U.S. District Court, San Francisco, indicted the operator for multiple violations of the Natural Gas Pipeline Safety Act of 1968.

The CPUC fined PG&E $1.6 billion, a record amount. The accident also led to PHMSA requiring and enforcing stricter and more comprehensive pipeline integrity management programs, including improved public awareness.

#### *4.5.4 2002 Denali Fault Earthquake*

The effects of the 2002 Denali Fault earthquake on the Trans-Alaska Pipeline System have been described by Hall et al. (2003) and Honegger et al. (2004), and only the salient aspects of those reports are presented here. The Denali Fault earthquake effects on the Trans-Alaska Pipeline System are unique in that fault rupture and seismic wave interaction with the pipeline system were sustained at levels consistent with the maximum conditions envisioned in design. The earthquake represents a full-scale test of the design process and operating procedures adopted for seismic resilience of the system.

The Trans-Alaska Pipeline System is operated by the Alyeska Pipeline Service Company. Over its 800-mi.-long route, the 48-in.-diameter pipeline is exposed to numerous seismic hazards. Major seismic design requirements were adopted that stipulate that the entire pipeline system should be capable of withstanding all reasonably anticipated effects of earthquakes without impairing the structural integrity of the oil pipeline or associated pressure containing system components (Nyman et al., 2014).

Hall et al. (2003) reports that ground motions approached the seismic design criteria for the section of the Trans-Alaska Pipeline System in the vicinity of the Denali fault. The fault rupture passed beneath the pipeline producing approximately 18 feet of right lateral offset and 2 feet of vertical displacement. There was no damage to the pipeline or release of oil. Limited displacements of underground portions of the pipeline occurred in liquefaction areas, but no damage was observed in the pipeline as verified by excavation at a remote gate valve where surface liquefaction effects were noted and subsequently by in-line inspection. Incidental damage to the above-ground support system was observed proximate to the fault rupture.

Emergency response and post-earthquake inspections were administered in accordance with an Earthquake Preparedness Program developed by Alyeska. Emergency response was governed by an oil spill contingency plan in combination with the Incident Command System that addresses command, plans, operations, logistics, and finance. An emergency monitoring system (EMS) was developed for guiding field reconnaissance and facility recovery after an earthquake, and was used in the post-earthquake response (Nyman et al., 2003). Using the EMS data in conjunction with detailed checklists, damage assessment teams, consisting of engineers paired with local maintenance personnel, were dispatched to the field. The use of the EMS-supported field inspection, which was guided by real-time measurements of ground motion, contributed to oil flow restoration after only 66 hours of shutdown.

## 4.6 Gaps and Deficits: Codes, Standards, Performance Requirements, and Societal Considerations

To bridge the gap between societal needs and safety performance, standards and community planning programs have been promoted for gas and liquid fuel systems. Standards, such as API Recommended Practice 1162 and PHMSA-supported stakeholder groups, such as PIPA, are examples with respect to gas and liquid fuel lifelines that involve community engagement in risk reduction planning and practices. They provide a framework that can support community resilience.

The heavy reliance on gasoline and mobility drives societal expectations for reliable local and regional vehicular fuel supplies. There are corresponding expectations for cooling and air conditioning in summer, and the outright dependence on heating for health and safety in the winter. As Hurricanes Katrina and Sandy and risks in the New Madrid Seismic Zone demonstrate, there is a serious gap between expectations for the availability of fuel and the threat to fuel supplies from hurricanes, floods, and earthquakes in individual cities and regions of the country.

There are gaps between codes and standards and the design and operation of gas and liquid fuel systems for natural hazards. Although ASME B31.8 and ASME B31.4 identify natural hazards, such as washouts, floods, unstable soil, landslides, and earthquake-related effects, there is little explicit guidance for how to design, maintain, and operate gas and liquid fuel systems for these conditions. Although guidelines are available for evaluating pipeline response to seismic hazards, similar guidance is not available for floods, coastal storms, and tsunami-related inundation.

The gaps between codes and standards and societal expectations can be closed by appropriate emergency planning and project design. After its World Trade Center (WTC) disaster experience in 2001, Verizon had trucks available to deliver diesel fuel to its facilities with emergency generators. After the Verizon Building at the WTC site was flooded by Hurricane Sandy, an emergency fuel truck replaced fuel tanks that were damaged and disconnected in the flooded basement. The emergency fuel fed a generator on the $10^{th}$ floor of the building that supplied power to this critical central office (personal communication from Verizon management to T. O'Rourke during reconnaissance after Hurricane Sandy, 2012), thereby providing the data services needed to reactivate the New York Stock Exchange.

## 4.7 Conclusions and Recommendations

### *4.7.1 Review of Key Points*

The performance of Trans-Alaska Pipeline System after the 2002 Denali fault earthquake shows the effectiveness of modern, high-quality design and seismic hazard assessment coupled with an earthquake preparedness plan, remote monitoring and well-communicated and rehearsed emergency response procedures. Moreover, the adoption of an oil spill contingency plan in combination with the Incident Command System demonstrates that the operator was well prepared for emergency conditions arising from a variety of causes. As previously indicated, 49 CFR Part 195 requires operators to have a written integrity management program that addresses the risks affecting pipelines in high consequence areas, including drinking water and ecological resource areas. Potential synergies therefore exist between code requirements and hazard preparation that may be utilized in the development of community resilience programs.

Identifying pipeline locations and entering the information into the National Pipeline Mapping System (NPMS) is an important step in community resilience planning (NIST, 2015). PHMSA has developed the Pipeline Information Management Mapping Application for use by pipeline operators and federal, state, and local government officials (PHMSA, 2013). The application contains sensitive pipeline and critical infrastructure information. Recognizing the public needs to know the location of transmission pipelines, the NPMS Public Viewer allows users to access pipeline maps without disclosing sensitive pipeline information. This application deserves further study to assess how it is working at the community level and to determine if it provides a framework for other lifeline systems, including combined systems and collocated facilities.

### *4.7.2 Lifelines Standards Development Needs*

Following are key recommendations to improve codes, standards, and guidelines pertaining to gas and liquid fuel systems**:**

- **Provide additional guidance for evaluating gas and liquid fuel pipeline and facility response to seismic hazards, floods, coastal storms, and tsunami-related inundation.** Such guidance would help fill existing gaps between codes and standards and the design and operation of gas and liquid fuel systems for natural hazards.
- **Develop consistent policy and standards on accessing information and databases about critical infrastructure systems.** There is currently a gap between the need to identify locations and functions of critical infrastructure to support safety and resilience planning and the actual access to information about these factors from lifeline system operators. As discussed above, the Pipeline

Information Management Mapping Application developed by PHMSA may provide a framework for sharing information about potentially sensitive hazardous pipelines and facilities, including information about combined systems and collocated facilities.

### *4.7.3 Research and Modeling Needs*

Following are key recommendations pertaining to research and modeling needs**:**

- **Study how the standards and community planning programs that have been developed for gas and liquid fuel systems compare to those for other lifelines, such as electric power systems as well as multiple, interdependent systems and collocated facilities.** Standards, such as API Recommended Practice 1162 (API, 2010), and PHMSA-supported stakeholder groups, such as PIPA provide a model for developing community resilience programs as applied to other lifelines and their interdependent behavior. Research and development of best practices and advanced methods, based on gas and liquid fuel community engagement standards and stakeholder groups, could be advantageous for other lifeline systems.
- **Improve knowledge, databases and modeling on the impacts of widespread flooding and storm damage on regional fuel supplies.** Fuel supplies involve multi-modal transportation systems including pipelines, shipping, port facilities, and truck transport on the upstream side and gasoline stations, jet fuel delivery, airport operation, train service, and automobile usage on the downstream side. Research is needed to understand these complex transportation interactions and to account better for the restoration of crucial services that depend on fuel as well as on regional economic recovery. Analytical models that simulate these systems would provide the means for reliability-based analyses of the most effective protective measures and operational improvements.
- **Improve knowledge, databases, and modeling of refineries and their impact on regional recovery.** As discussed in this chapter, refineries are an important part of the regional fuel supply chain and their disruption by flooding and their strong dependence on electric power have a major impact on the intermediate and long term phases of recovery (NIST, 2015).

### *4.7.4 Lifeline System Operational Needs*

Following are key recommendations pertaining to system operational needs**:**

- **Develop a process for major utilities to conduct self-assessments of their preparedness for various natural hazard events.** Guidance should be provided with support for assessments to provide some consistency of approach among lifelines. Each utility should have reasonable knowledge of their customer base and relative importance and priority for continuity of service. The results of self-assessments could then be used to prioritize improvements to system robustness and post-event response. Improvements to community resilience can be best accomplished by taking immediate steps to get the utilities to develop an understanding of the problem, assess vulnerability of their systems, and undertake an action plan.

- **Develop local plans for fuel delivery to emergency responders and critical infrastructure.** As recent hurricanes demonstrate, there is a serious gap between expectations for the availability of fuel and the threat to fuel supplies from hurricanes, floods, and earthquakes. Guidance for local planning to close these gaps is needed, with emphasis on securing fuel for emergency responders and critical infrastructure, such as telecommunication hubs, compressor stations, and pump stations for liquid fuel and water supplies.

# Chapter 5
# Telecommunications

## 5.1 System Overview

Communication infrastructure differs from other infrastructure in three crucial aspects: (1) it has multiple layers of functionality; (2) it has more dependencies than other infrastructure; and (3) infrastructure and services are often provided competitively, rather than by a public utility, and may not be regulated. All of these aspects impact available performance criteria and societal expectations. Just as transportation systems rely on a diverse set of modalities and technologies, communication systems encompass a large set of diverse modes of interaction and technologies, with these systems operating in many cases largely independently. However, previously distinct systems are now converging on using technologies based on Internet Protocols (IP). Thus, this chapter focuses on IP-based and cellular networks and, to a lesser extent, on legacy circuit-switched landline voice networks. It also refers to other types of communication infrastructure, such as broadcast and land mobile radio, where they differ significantly.

### *5.1.1 Use of Communication Infrastructure after Hazard Events*

Communication networks affect other lifelines in profound ways. Figure 5-1 illustrates some of the dependencies involved in maintaining or restoring communication capabilities after natural disasters. One can view communication after natural disasters as involving the public, civic authorities, dispatch (typically, but not necessarily, co-located with a public safety answering point) and first responders, as illustrated below.

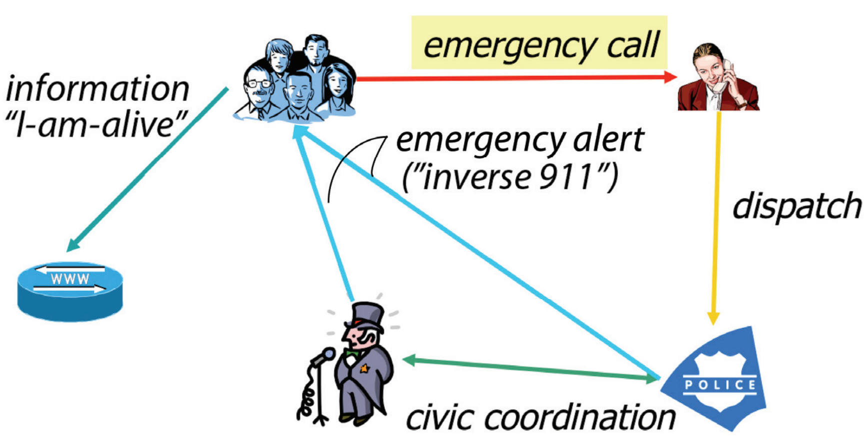


Figure 5-1 Key communication relationships after disasters.

The public reaches first responders primarily using the 911 system, but may also obtain emergency-related information via 211 (social services) and 311 (general municipal services) that are implemented in some metropolitan areas. Traditionally, the 911 system only supports voice calls, but since about 2013, an increasing number of cell carriers and public safety answering points (PSAPs) can receive Short Message Service (SMS) text messages sent to 911 ("text-to-911"). Public safety authorities primarily use three means to alert residents: Wireless Emergency Alerts (WEA) to cell phones, the Emergency Alert System (EAS) via radio and television, and, in some locations, automated phone calls, emails and text messages via alerting systems[11]. After a disaster, maps (e.g., Google crisis maps), web sites and television/cable scrolls and announcements update the public about available resources such as shelters, and school and road closings.

WEA "is a public safety system that allows customers who own certain wireless phone models and other enabled mobile devices to receive geographically-targeted, text-like messages alerting them of imminent threats to safety in their area" as defined by the Federal Communications Commission (FCC) website. It can rapidly disseminate short text messages, via cell broadcast, to subscribers. It complements EAS, which distributes audio alerts using radio and TV, regardless of whether the TV signal reaches the home over the air, via CATV (cable) or direct broadcast satellite. EAS relies partially on distributing alerts via a chain of radio transmitters and thus can continue to function even after terrestrial communication links have been disrupted.

As one example, after Hurricane Sandy, Internet services like town mailing lists and Twitter played major roles in disseminating information, not just from civic authorities or public safety to the public, but also between residents in the affected area. Residents shared information about grocery stores that were open, gas stations that had fuel or neighbors willing to share generators. Network tools, like those available from the Sahana Software Foundation, are used to maintain situational awareness for non-government organizations and public authorities.

In addition, communication systems are increasingly needed to keep other crucial community services operational. For example, gas stations monitor the fuel level in their tanks remotely, and cannot safely pump gas if they cannot determine the fill level in their underground tanks. Automated teller machines (ATMs) and credit card machines require communication links to validate account credentials.

Maintaining or quickly restoring communication services to homes and businesses can also avert or reduce secondary economic impacts from disasters as employees in many service-oriented occupations can continue to work from home or alternate

[11] A popular name for such systems is "reverse 911," a trademark of Cassidian Communications.

remote locations, either provided by emergency response providers, or through temporary locations. For example, libraries were used as impromptu remote "telework" sites after Hurricane Sandy. Employees of financial services companies in the New York City metro area doubled up in other offices after the September 11, 2001 terrorist attacks. Telework can significantly reduce the pressure on both public transportation and road networks, and can allow families to deal better with disruptions that are common after disasters, such as school closings.

Amateur and short-wave radio have limited commercial use, but can play a crucial role after disasters, particularly extreme ones that disrupt a substantial part of the infrastructure or affect a large area. According to Townsend and Moss (2005, p. 16):

> "Amateur high-frequency and short-wave radio are generally the first communications services to be restored, and the last to be destroyed, in any disaster scenario. Amateur radio is particularly important in isolated, under-developed disaster areas. Following the 2004 Indian Ocean tsunami, a handful of 'hams' provided the only communications link between the Andaman and Nicobar islands in the Indian Ocean. However, hams play a vital role in developed nations as well. When hurricanes strike in the Caribbean and southeastern United States, hams routinely step in to provide lifeline communications."

Also, in the first days after the Northridge earthquake, the only link the Granada Hills Community Hospital had with the outside world and city government was through amateur radio maintained and operated by a group of volunteers, known as the Los Angeles County Disaster Communications Services whose equipment is co-located at sheriff's offices throughout the county (Townsend and Moss, 2005).

### *5.1.2 Multiple Systems, Layers, and Diversity*

Traditionally, communication infrastructure is largely thought of as copper wires providing plain old (voice and voice data) telephone service, including trunk lines connecting telephone switches. However, that model does not describe the complexity of modern communication systems, and has not been an appropriate model for at least two decades, even as that legacy infrastructure continues to exist and serve important societal functions.

Unlike the electric grid or the natural gas grid, which delivers essentially the same service at different power/voltage or gas pressure levels to all end users, the U.S. communication public infrastructure consists of several intertwined infrastructures, each with their own history, regulatory environment, and impact on public safety. These include[12]:

- Broadband (high-speed) consumer Internet access, possibly with facilities-based voice services (VoIP) and entertainment video, using fiber, hybrid fiber-coax, copper (DSL), fixed wireless or satellite;
- Ethernet-based business data services, either for Internet access or interconnecting branch offices;
- Dark fiber[13] connectivity for businesses;
- TDM[14]-based voice services, either single lines or trunks of 24 (T1) or 720 (T3) voice circuits, or data;
- Cellular networks delivering voice, text and data services;
- Consumer cable TV delivery using hybrid fiber-coax (HFC) plant;
- Trunked land mobile radio (LMR), primarily for public safety and dispatch;
- Specialized low-rate data networks for machine-to-machine (Internet of Things) communications; and
- AM, FM and TV broadcast networks.[15]

Some of these networks share the same layer-0 and layer-1 infrastructure (see Table 5-1). For example, both cable TV and consumer broadband may use the same hybrid fiber-coax infrastructure. Similarly, DSL, some Ethernet and TDM services may all rely on the same copper loops. All data networks that provided Internet connectivity share the same small set of nationwide backbone networks; these, in turn, may share the same conduit or run along the same right-of-ways such as along pipelines, highways or railway tracks (Durairajan et al., 2015). For example, collocation led to widespread outages after the 2001 Baltimore train tunnel fire (DOT, 2002) as well as multi-network disruptions in Los Angeles after fiber cables sharing the same manhole were cut (LA Times, 2015b). Increasingly, even “traditional” networks rely on IP connectivity. For example, many radio and TV stations now use data circuits to connect smaller studios in smaller broadcast markets to their production facilities or

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[12] Only services that are available, for a fee or for free, to the public or local governments, rather than all the specialized closed networks that are operated for smaller closed user communities, such as military communications networks, are covered here.
[13] Dark fiber refers to optical fiber where the opto-electronics is provided by the end user (customer), typically a large business, rather than the telecommunication provider.
[14] TDM (time-division multiplexing) provides digital voice and data circuits over copper or fiber, dividing the overall channel capacity into time slots assigned to different calls or connections.
[15] Approximately 10% of households use a TV antenna to receive local stations; about 46% cable TV service, 12% video services provided by the local telecommunications provider, 30% by satellite, and 2% are broadband only (Nielsen, 2014b).

may use such circuits to connect their studios to their antenna plant. Thus, outages of IP connectivity may affect services that are not viewed as Internet-related.

Communication infrastructure also combines both public and private networks, with various combinations of the two. For example, the U.S. military, some U.S. states and municipalities and large corporations may buy or lease "dark fibers" or may be assigned radio spectrum that they then use to build their own private, closed networks. Well-known examples include LMR for public safety and gas, water and electric utilities and private fiber networks for large Internet and industrial companies, or U.S. higher education (Internet2). Recently, the public safety community has been planning FirstNet, a cellular (LTE) network operating on its own set of radio frequencies. FirstNet, once completed, will serve as a data network for first responders, but may also lease excess capacity to commercial carriers or may be used by gas, water and electric utilities. This combination of private and public services does not seem to have an equivalent for other lifelines.

**Table 5-1 Layers in Telecommunication Systems**

| Layer | Common Name | Example Hardware and Software Components | Functionality (simplified) |
|---|---|---|---|
| 0 | Infrastructure | Poles, ducts and conduits, towers, fiber, radio spectrum, satellites, data centers; power (commercial and backup) | Physical infrastructure for communication services (field and data centers) |
| 1 | Physical layer (PHY) | SONET, PON; optical cross-connects and splitters | Turn physical quantities (photons, electrons) into information bits |
| 2 | Link layer (MAC) | Ethernet; switches | Package bits into packets |
| 3 | Network layer | IPv4 and IPv6; routers | Routes packets across networks |
| 4 | Transport layer | UDP and TCP[16]; firewalls, home gateways | Address applications; provide end-to-end reliability |
| "upper" (5-7) | Application layer | HTTP, SMTP, SIP; cloud services; BGP; AAA | Supports applications such as VoIP, web and video; includes NG911 capabilities for public safety |

There are many ways to characterize the components of the overall communication infrastructure, depending on whether economic, regulatory or technical considerations drive the classification effort. Despite well-known limitations, a layered approach has been used in resiliency discussions, with different layering granularity (see Table 5-1). The layering approach separates different actors within the communication infrastructure, i.e., it defines "business interfaces," which have

[16] UDP (User Datagram Protocol) and TCP (Transmission Control Protocol) are two common network protocols that offer different services to the upper layers. UDP delivers data segments without reliability and without adjusting its transmission rate, while TCP delivers a stream of byte reliably and adjusts its sending rate to take network congestion into account.

been relatively stable over decades. Generally and traditionally, upper layers depend on lower layers; however, increasingly, network components are controlled by operations at the application layer. Thus the continued operation of a router, for example, may depend on the availability of an authentication, authorization and accounting (AAA) server located in a data center hundreds of miles away, and reached using all layers of the network stack. Recently, the communication industry has started to discuss software-defined networks (SDNs) and network function virtualization (NFV). The former, roughly speaking, separates the lower-layer transport functionality from the control functionality, allowing them to be geographically separated. NFV moves away from dedicated "boxes" that serve one purpose to a common cloud-based infrastructure that implements common network control functions in software.

Communication infrastructure differs from other lifelines in another key aspect: many residential and commercial users have more choices. For any given address, there is likely only to be one wastewater option, one electric (distribution) option and one water option. However, depending on the location, households and, in particular, larger enterprises may have access to:

- between one (typically two) and four national cellular providers with 3G or 4G data service;
- between one and two (and rarely, three) consumer high-speed broadband offerings with more than 10 Mb/s bandwidth;
- a DSL low-bandwidth Internet access provider, typically below 5 Mb/s; and
- a broadband satellite provider.

These options are not equivalent, as they may differ in available speeds, cost per month, data caps (i.e., how much data a subscriber may use), reliability, and latency.

Except for fill-in, all new construction of fixed communication lines is likely to be fiber, either aerial or buried. Coaxial cable and copper are rarely used for new construction, even in residential areas. Despite higher initial construction costs, buried fiber is often chosen by service providers that are subject to service level agreements (see below) and thus suffer economically if outages occur; almost all middle-mile and long-haul fiber is buried, with possible exceptions for permafrost areas. Last-mile fiber tends to use the same installation method as electric utilities for that area. Buried fiber has a number of advantages, which should be weighed against the increased initial cost and possible trade-offs for specific hazards:

- Internet service providers may avoid paying pole attachment fees to electric utilities.

- Buried fiber avoids failures due to flooding, wind loading and tree debris impact, and is sufficiently flexible to survive earthquakes. Buried fiber deployments may be substantially more reliable than aerial routes, especially where poor weather and the potential for wind or ice damage is common. However, repair may be more difficult, particularly with direct burial methods, rather than methods that place the fiber in ducts, so that in some cases, temporary aerial bypass routes may be built (NTT East, 2011). There does not appear to be any direct evidence, either way, whether buried fiber better survives earthquakes than aerial installations.
- Separating electric utilities and fiber communication cables simplifies the restoration process after disruptive events since work can more likely proceed in parallel. Often, with shared poles, the electric utility has to restore the poles and may destroy surviving communication cables in the process.
- Since it carries no current, it is largely impervious to water, even when ducts are flooded.
- It is better protected against copper thieves who mistake fiber communication cables, which are worthless as scrap, for copper lines.

There appears to be limited data comparing the reliability and time-to-repair of buried and aerial fiber installations. Verbrugge et al. (2005) compared the mean time between failures for 1 kilometer (km) of fiber as 175,000 hours for aerial versus 2.63 million hours for buried installations, without specifying the location of the installation and the nature of hazards encountered. Hart et al. (1991) analyzed a cable affected by the 1989 Loma Prieta earthquake and found that the armored cable survived a bridge collapse. Yamazaki et al. (2008) describe how to improve the resilience of underground fiber facilities and identify common failure modes. Sakaki et al. (2014) compared the damage rates of various types of conduit, finding that old-standard conduit subjected to peak ground velocity (PGV) of 90 cm/s and above suffered failure rates of 3%, while conduit conforming to the newer standards suffered failures rates of 0.5%, despite higher peak ground acceleration. Conduit buried in reclaimed land, subject to liquefaction, was shown to be particularly vulnerable. In general, many aerial fiber routes use ducts to traverse bodies of water, complicating the overall design trade-off analysis.

Corning, a major manufacturer of fiber optic cables, indicates that there is no "earthquake-proof" fiber, and recommends planning on "10% slack, concentrating on critical junctures, such as bridge and river crossings, aerial to underground transitions, and ends of long runs", and including "fail-over" links (Hintz, 2011).

The ITU-T, an international telecommunication standards body, describes hazards and their impact on fiber optic lines, identifying natural and man-made causes of failure for both aerial, buried and ducted fiber (ITU-T, 2009, p.28).

NTT East used temporary aerial fiber after the 2011 Great East Japan Earthquake damaged, among other facilities, 90 trunk line routes, 2,700 km of aerial cables and 28,000 telephone poles (NTT East, 2011). "The Sanriku Railway line took a trunk line with it when it was swept away by the tsunami. We erected 11 telephone poles alongside the railway and strung cables to restore the trunk line" (p. 23). "Kesen Bridge was swept away by the tsunami, taking a trunk line with it. We rerouted the line upstream to string a cable across the river where it was narrower" (p. 24).

Large institutions may also be able to leverage point-to-point wireless and optical links to recover from local "last-mile" (access circuit) outages. For example, a public safety answering point (PSAP) might be able to maintain a point-to-point link to a nearby government or university building that can offer fallback Internet access. Optical links can typically traverse distances of about 750 meters to 6 km at single-link speeds of 250 Megabytes/second (Mb/sec)[17], while directional wireless transmission may cover distances of up to 100 km and speeds of 1.2 Gigabytes/second (Gb/s) (5 Giga-hertz (GHz) unlicensed band).

Note that the diversity of choices differs greatly between locations. For example, high-speed cable is available to approximately 93% of households (Rodriguez, 2010), but many small businesses in more rural areas still only have low-speed DSL or even satellite as an option. Also, these services are typically offered on a monthly subscription basis, so that maintaining a primary and backup Internet service provider incurs significant recurring costs. In many cases, tethering[18] to a cellular device is likely the only economically-viable secondary Internet access option for private households and small businesses. Many carriers serve smaller population centers with only one fiber, so that a single middle-mile fiber cut may disconnect a whole town.

Larger enterprises and office buildings with multiple tenants may have access to commercial fiber offerings by companies like Cogent, Level 3 or Zayo, or, increasingly, the business-oriented offerings of cable providers. They may also be able to bundle multiple copper loops to achieve total access speeds of up to 80 Mb/s.

Thus, in some cases, enterprises and, to a lesser extent, residential users can create physically diverse access solutions, e.g., subscribe to a cable broadband provider for

[17] A tutorial on free-space optics (as of 2002) can be found at https://www.fcc.gov/events/tutorial-free-space-optical-communications.
[18] Tethering for mobile devices makes cellular Internet connectivity available to nearby laptops or other smartphones, typically via USB, Wi-Fi or Bluetooth. Not all cellular devices support tethering and some cellular providers may charge extra for tethering.

day-to-day needs and use 4G tethering as a backup to maintain the ability to accept credit cards.

Public safety agencies relying on LMR for voice and low-speed data communications typically self-provision, i.e., they operate the infrastructure such as radio towers and transmitters, and thus have limited physical diversity since they cannot switch to alternate, equivalent networks. In the past few years, many public safety agencies seem to have started using commercial cellular service as a supplement or back-stop to LMR, in some cases using the wireless priority service (WPS) described in Section 5.2.3 to ensure that calls are completed even when the commercial cellular network is congested.

### *5.1.3 System Elements and Hazards*

Despite the differences between the communication infrastructures summarized above, key elements are common, whether physically shared or just similar in engineering and construction.

- **Last mile (access).** Last mile wired connections are primarily copper twisted pairs (for voice, DSL and legacy data services), coax (for cable TV) and fiber (for cable TV, business data services, cellular backhaul and Internet access). In addition to natural hazards, copper communication cables have been subject to theft, particularly since the risk of electrocution is much lower. Recently, however, even buried fiber optic cable has been subject to human-caused hazards, such as theft of cables (Greenberg, 2015).
- **Middle mile.** Middle mile is a term most often referring to the network connection between the last mile and the Internet. For instance, in a rural area, the middle mile would likely connect a town's network to a larger metropolitan area where it then links in with major carriers.
- **Core (backbone) network.** Backbone networks connect major points-of-presence, typical in larger cities, by long-distance fiber, often deployed along existing rights of way such as railroads, pipelines or major highways.
- **Transoceanic fiber cables.** All operational transoceanic links are fiber cables. Such fibers and their landing sites are subject to multiple risks: ship anchors, sharks, earthquakes, other near-shore use such as pipelines and oil and gas exploration (CSRIC, 2014a).
- **Data centers and central offices (COs).** In the telephone era, central offices were the end point for local copper loops and housed switching equipment as well as long-distance loops. More recently, data center-like buildings are used both for hosting telecommunication facilities such as optical switches and network routers, either of a single carrier or multiple carriers ("carrier hotel"), or servers used for IT operations, such as public and private cloud services.

Regardless of their use, their physical structure and susceptibility to hazards is similar, although free-standing data centers located in more rural areas[19] are likely to be subject to somewhat different risks than urban ones.

- **Towers.** Four tower types are in common use for communication services: monopoles of 100-200 feet for cellular services, lattice towers of 200 to 400 feet height for cellular services and LMR, guyed towers reaching between 200 and 2,000 feet primarily for television and radio broadcasting and, less commonly, cellular services and, lastly, "stealth" towers integrated into church steeples, clock towers or other tall structures. A single tower is often shared between communication services, such as cellular, LMR and FM radio, while AM and TV towers tend to be single-purpose. Typical cell towers have heights of 50 to 200 feet, while radio and TV powers can exceed 1,500 feet, such as the mast for the TV station with call sign KVLY (FCC, 2015a). Towers often house transmission, switching and power backup equipment at ground level and thus may be subject to inundation. The transmission equipment may require air conditioning.
- **Rooftop antennas.** In urban areas, television and radio stations often use a small number of tall buildings to host their transmission antennas. For example, most broadcasters in New York City now use the Empire State Building and may move back to One World Trade Center. Thus, the failure of a single building may disrupt over-the-air broadcast services for a metropolitan area, as happened after the September 11, 2001 attacks. According to Townsend and Moss (2005): "Following the collapse of the north tower of the World Trade Center, some 1500 rooftop antennas were destroyed, many of which served the region's television and radio broadcasters. The roof of the towers was an ideal broadcast platform, with clear line of sight 100 miles in every direction. Of the seven primary broadcast television networks serving the New York metropolitan area, only one network (WNYW-5) whose primary broadcast facility was on the Empire State Building, was unaffected."
- **Building cell sites.** Increasingly, commercial buildings in urban and suburban areas host cellular antennas, typically near their roofline. For example, about 60% of all cell base station antennas in Los Angeles are attached to buildings (LA Times, 2015a). Recently, concerns have been voiced that many cell sites are attached to aging structures that may not meet the seismic requirements of modern building codes.
- **Satellite earth stations.** Satellite earth stations send and receive data to satellites.
- **Software.** Communication systems rely on specialized software for routing, management, access control and many other functions, located either in routing

[19] For example, a large part of the Internet traffic of the eastern United States traverses a set of data center facilities operated by Equinix near Ashburn, Virginia.

or switching equipment or separate servers. Software functionality is distributed throughout the network, including customer premises equipment. Large-scale software failures (examples as of late 1998 are documented in Schneider et al., 1998) or configuration errors (Hunter, 2008) are recurring events, with malicious (cybersecurity) attacks as a more recent concern, e.g., to redirect Internet traffic.

The Department of Homeland Security (DHS) designates certain communication assets as part of critical infrastructure (DHS, 2010). In particular, it identifies "high capacity assets" such as "major switching centers, major underwater cable landings, telecommunication hotels that are deemed to provide critical mission support on a regional or national scale." They are divided into Level 1 and Level 2 lists.

All wired networks are subject to hazards that affect their hosting rights-of-ways. For example, the Baltimore Howard Street Tunnel Fire (July 18, 2001) affected fiber bundles strung along the tunnel walls. According to the U.S. Department of Transportation (2002):

> "The Howard Street Tunnel houses an Internet pipe serving seven of the biggest U.S. Internet Information Service Providers (ISPs), which were identified as those ISPs experiencing backbone slowdowns. The fire burned through the pipe and severed fiber optic cable used for voice and data transmission, causing backbone slowdowns for ISPs such as Metromedia Fiber Network, Inc.; WorldCom, Inc.; and PSINet, Inc. Reports were received from up and down the East Coast about service disruptions and delays (for example, the Hearst Corporation lost e-mail and its main links to its Web pages on the Internet), and even the U.S. embassy in Lusaka, Zambia, in Africa experienced problems with sending and receiving e-mail.
>
> In addition to the more severe Internet problems, the flood resulting from the water main break disrupted phone service to two downtown office towers in Baltimore City and caused other temporary communication problems within the City."

The hazard event levels of routine, design and extreme events defined by NIST (2015) are not commonly used in assessing the resiliency of communication systems. This may be due in part to the impact of different hazards on different parts of the communication infrastructure, as discussed below. Also, this classification does not readily account for the geographic impact of a particular hazard. As an example, a tornado may be ranked as "extreme" in its impact and probability of occurrence, but may have very limited impact on the overall communication infrastructure in a county or state. (Indeed, cellular infrastructure may not be affected at all or can be restored within hours with mobile cell towers, such as cells-on-wheels (COWs) as long as the number of cell sites affected remains small.) Thus, for telecommunications, the most challenging disaster events, with the longest recovery period, are likely ones that affect key shared infrastructure components such as carrier hotels, submarine cables or a large geographic area.

Similarly, given the distributed and diverse nature of communication systems, dividing the recovery periods into short, intermediate and long term does not appear to figure prominently in the telecommunications resilience literature. As an approximation, carriers may informally divide recovery into restoring priority telecommunication services for first responders and other critical national security/emergency preparedness (NS/EP) infrastructure ("short term")[20], restoring operational capacity that may involve temporary solutions such as truck-based mobile switching centers (MSC), alternate broadcast antenna sites and backup data centers ("intermediate"), and longer-term restoration of sustainable and economically efficient system capacity. As noted in Section 5.3, Townsend and Moss (2005) distinguishes four key phases of post-event recovery: emergency response, restoration and repair, reconstruction, and redevelopment.

Table 5-2 summarizes the impact of common hazards on key elements of communication networks. Impact levels are characterized as low (L) or high (H), where "low" indicates that most elements will continue to function after the hazard, while "high" impact hazards are likely to render a large fraction of the network

**Table 5-2 Major Telecommunication Infrastructure Components and Impact of Hazards**

| | Wind | Earthquake | Inundation | Fire | Snow/Rain | Human-Caused |
|---|---|---|---|---|---|---|
| Submarine fiber cables | May affect landing sites | H | - | - | - | Landing sites; ship anchors |
| Last mile, copper aerial | H | H | L | H | H | H (copper theft) |
| Last mile, buried copper | L | H | H (shorting) | L | - | L |
| Backbone, middle & last mile, buried fiber | L | unknown | L | - | - | H (manholes) |
| Data centers and COs | L | P | P | P | - | P |
| Towers | P | P | L | L | L | P |
| Software | - | - | - | - | - | Cyber risks |

Note: Impact levels are characterized as low (L) or high (H); P denotes "preventable" (i.e., no impact, when design follows appropriate code and standards).

[20] An example is the telecommunications service priority (TSP) program.

element inoperative, even if the mechanical destruction of the element is locally-contained. For example, an earthquake is likely to cause only a few submarine fiber cable breaks along its whole length, but a single break is sufficient to take the whole cable out of service. The notation "P" denotes "preventable" when design follows appropriate code and standards (i.e., the elements are likely to remain unaffected by these hazards as long as the codes and standards reflect the actual severity of the potential hazard). The impact of earthquakes on buried fiber is unknown and may strongly depend on the ground displacement (e.g., whether a fiber crosses a fault line, or is in a liquefaction zone).

The restoration of submarine fiber cables after a cut may take seven to ten days for each fault (LaPerrière, 2007). For example, it took ten days to restore service to the San Juan Islands, Washington (Washington UTC, 2014).

## 5.2 Summary of Codes, Standards, Guidelines, and Performance Requirements

### *5.2.1 Measuring Reliability and Performance*

Measuring reliability for communication services has traditionally relied on outage probabilities, expressed as uptime percentages or availability. As discussed later, the referenced time frame may or may not include hazard impacts, depending on how the metric is used, and the level of hazard included or excluded may differ. Thus, they may not directly measure resilience to hazards, but, given the infrequent occurrence, offer an indicator function. The developers of this report are not aware of any studies that establish a clear correlation between general uptime percentages, packet loss and other metrics discussed in this section on the one hand and hazard resilience on the other. However, the engineering measures used to ensure high uptime values, such as redundancy and fast recovery from faults, are also likely to be helpful during hazard events. Similarly, a network that suffers from high packet loss during normal loads is unlikely to perform well when parts of the infrastructure are destroyed. While rather imperfect, these indicators seem to be the only ones available at the moment, except retrospective analyses of specific hazard events, which may or may not have predictive power for future hazards that are likely to differ in cause, location and magnitude. Attempting to correlate pre-event uptime metrics with post-event performance appears to be a promising avenue for research.

These percentages are used in two ways: as a measure of historical performance, and as a threshold that triggers contractual penalties for the provider ("service level agreement" or SLA). For example, many commercial ISPs offer an SLA availability of 100%, which simply implies that the provider owes a partial refund to the customer for any outages. SLAs are described in more detail in Section 5.2.2. Commonly used reliability grades are identified in Table 5-3.

**Table 5-3 Reliability and Unavailability Grades**

| Uptime % | Unavailability per Year | Example |
|---|---|---|
| 99% | 3.65 days | Consumer-grade (implied) |
| 99.5% | 1.82 days | Web hosting |
| 99.9% | 8.8 hours | Azure web services, Google applications |
| 99.999% ("5 nines") | 5 minutes | Classical telecommunications goal |

For packet networks, computing reliability is more complex since the network behavior cannot always be cleanly divided into "up" and "down" states, but the network may suffer from periods of degraded performance. This performance is commonly measured through packet loss and latency (delay), commonly averaged over a month. Typical SLAs for backbone networks are 0.1% packet loss and latency similar to speed-of-light propagation speed[21]. Some providers also specify an average and maximum jitter, i.e., packet delay variation. For some real-time applications, such monthly metrics may not predict the "quality of experience" (QoE) (i.e., the quality experienced by the human or service end user). For example, a delay spike of 1,000 milliseconds (ms) over a 240-minute interval in a month, with the remainder of the month at a more typical 50 ms, only yields an average delay of 55.3 ms for the month, but drops the service usability to 0.994 for those applications (i.e., below the 100% availability SLA advertised). While rare for core networks, such delay spikes can occur in access networks, partially due to large buffers in access routers.

For traditional voice networks, service reliability is measured by call-oriented metrics such as answer seizure ratio, the fraction of answered calls compared to the total call volume.

Typically, the service providers measure reliability for their own networks. However, increasingly, third parties can crowd-source network performance and outage data. For example, Heidemann et al. (2012) used network probe packets to track the impact of Hurricane Sandy, while Renesys (2012) used Internet routing table data. The FCC maintains a network of approximately 8,000 home routers as part of its *Measuring Broadband America* project and makes the measurement data publicly available. Its primary use is to measure residential Internet throughput and delay performance during normal conditions, but it can also provide reliability indicators. Bajpai and Schonwalder (2015) survey network measurement platforms. Efforts at crowdsourcing cellular performance are starting to emerge (e.g., CrisisSignal mentioned in the OpenSignal Blog on December 17, 2014).

There does not appear to be architectural metrics that characterize the resilience of local networks, for example by enumerating single points of failure, such as a fiber

[21] In fiber, this is roughly 0.66 times the free-space speed of light of 300,000 km/s.

access link to a community without a backup (KHON, 2015), or elements that are likely to suffer correlated failures.

### *5.2.2 Service Level Agreements*

For services offered to commercial entities, carriers may offer SLAs that stipulate reliability targets. Most SLAs, however, are likely to exclude events due to force majeure. There is no uniform definition of force majeure, but elements of the principles and rules of international law[22] are commonly used in contracts. A key concept is that "neither the impediment nor its consequences could have been avoided or overcome by the non-performing party." Typical lists include "war, whether declared or not, civil war or any other armed conflict, military or non-military interference by any third party state or states, acts of terrorism or serious threats of terrorist attacks, sabotage or piracy, strike or boycott, acts of governments or any other acts of authority whether lawful or unlawful, blockade, siege or sanctions, or accidents, fires, explosions, plagues, or natural disasters such as but not limited to storm, cyclone, hurricane, earthquake, landslide, flood, drought" (TransLex, 2016). In other words, almost all hazard events discussed here are likely to meet the force majeure definition. Thus, customers generally have no recourse, either monetary or contractual, to force restoration within a given time interval after such events. As noted earlier for uptime metrics, whether networks that offer any SLA at all, or more stringent SLAs, also do better after hazard events remains an open research question. Given that many of the engineering and operations approaches that improve everyday service levels are likely to also be helpful after hazards, such a correlation is plausible.

With that limitation in mind, as an example, Palo Alto Networks (2015) defines the typical components of an SLA as:

- **A description of the service being provided.** This describes the maintenance of areas such as network connectivity, domain name servers, and dynamic host configuration protocol servers.
- **Reliability.** This indicates when the service is available (percentage uptime) and the limits outages can be expected to stay within.
- **Responsiveness.** This refers to the punctuality of services to be performed in response to requests and scheduled service dates.

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[22] "*TransLex-Principles* are a systematic online-collection of principles and rules of transnational commercial law, the New Lex Mercatoria. They are being used by counsel and arbitrators in international arbitrations as well as contract drafters, academics and participants of moot court competitions in international arbitration across the globe." (http://trans-lex.org/purpose-concept)

- **Procedure for reporting problems.** This includes who can be contacted, how problems will be reported, procedure for escalation, and what other steps are taken to resolve the problem efficiently.
- **Monitoring and reporting service level.** This includes who will monitor performance, what data will be collected and how often, as well as how much access the customer is given to performance statistics.
- **Consequences for not meeting service obligations.** This may include credit or reimbursement to customers, or enabling the customer to terminate the relationship.
- **Escape clauses or constraints.** These indicate circumstances under which the level of service promised does not apply. An example could be an exemption from meeting uptime requirements in circumstance that floods, fires, or other hazardous situations damage the ISP's equipment.

Missing the reliability targets may entitle the customer to a reduction in their payment. For example, the Cogent SLA (2013) for reliability reads:

> "If Customer experiences Network Unavailability for an On-Net Service for more than 15 consecutive minutes, Customer will receive, at Customer's request, one (1) day Service Credit for each cumulative hour of Network Unavailability in any calendar month. Provided the COGENT Network experiences at least one (1) hour of Network Unavailability in any given calendar month, additional Network Unavailability of less than one (1) hour will result in a proportional Service Credit. (Example: 2 hours, 15 minutes of Network Unavailability will result in 2.25 days Service Credits.) Customer may obtain no more than one (1) month Service Credit for any given month."

### *5.2.3 Regulatory Environment*

For voice services, states have regulated telecommunication service quality for many years (Davis et al., 1996; Holloway, 2015), but with the transition to IP and local competition, many state legislatures have removed the power of their public utilities commission to regulate telecommunication services. Thus, broadly speaking, while there has been a long tradition of regulating price, service quality and entry/exit for voice telephony, the performance and reliability of IP-based communication services is not regulated at the federal, state or local level. In a small number of states, public utility commissions may continue to regulate repair times and other characteristics for classical voice services.

Federal regulations for telecommunication services are based on Title II of the Telecommunications Act, last substantially modified in 1996 (Public Law 104-104). However, the Act does not specify any particular resilience or restoration obligations of telecommunication carriers, except in the general context of “just and reasonable” practices called out in Section 201(b). The Act also generally sets out the purpose of the Act as “For the purpose of regulating interstate and foreign commerce in communications by wire and radio so as to make available, …, a rapid, efficient, Nation-wide, and world-wide wire and radio communication service with adequate facilities at reasonable charges, for the purpose of the national defense, for the purpose of promoting safety of life and property through the use of wire and radio communications, …, there is hereby created a commission to be known as the “Federal Communications Commission,” which provides the FCC with authority related to emergency communications.” Recently, the 2015 Open Internet Order classifies so-called broadband Internet access services as telecommunication services under Title II of the Act, but the descriptions in 47 CFR 8, *Protecting and Promoting the Open Internet* (FCC, 2015c), do not address reliability, resilience or restoration.

Franchise agreements may regulate certain aspects related to reliability, such as the right of customers to obtain a refund when cable TV service is disrupted. However, as far as the authors can tell, none of the local, state and federal regulations refer to any specific standards for quantitative performance, acceptable damage levels, and service restoration or recovery timeframes for general telecommunication services. For 911 services, the FCC has recently codified (see 47 CFR Part 12.4, *Resiliency, Redundancy and Reliability of Communications Systems, Reliability of Covered 911 Service Providers*, Office of the Federal Register, 2015a) key recommendations with “respect to critical 911 circuit diversity, central office backup power, and diverse network monitoring” to improve the reliability of 911 systems (Office of the Federal Register, 2015a), requiring providers of 911 service to certify annually that they follow these best practices or have taken alternative measures (FCC, 2013c; FCC, 2015b).

Even in the absence of performance standards, telecommunication providers are obligated (see 47 CFR Part 4, *Disruptions to Communications*, Office of the Federal Register, 2015b) to report major outages to the FCC (Office of the Federal Register, 2015b), where major outages are defined, for example, as 900,000 user minutes of telephony service, e.g., an outage of 30 minutes affecting 30,000 customers (see 47 CFR Part 4.9, *Disruptions to Communications*, *Outage Reporting Requirements—Threshold Criteria*, Office of the Federal Register, 2015b). Currently, an initial outage report has to be filed within 120 minutes, with a final report explaining the cause of the outage within 30 days. All reports are confidential. During major outages, carriers can voluntarily report outages via the FCC Disaster Information Reporting System (DIRS) instead. DIRS information is disseminated to other Federal agencies that are authorized participants on the Emergency Support Function-2 team (FCC, 2007).

The Telecommunications Service Priority (TSP) program is meant to facilitate restoration of key communication lifelines. According to the Department of Homeland Security (2015):

> "Telecommunications Service Priority (TSP) is a program that authorizes national security and emergency preparedness (NS/EP) organizations to receive priority treatment for vital voice and data circuits or other telecommunications services. The TSP program provides service vendors a Federal Communications Commission mandate to prioritize requests by identifying those services critical to NS/EP. A TSP assignment ensures that it will receive priority attention by the service vendor before any non-TSP service. … Eligible services must meet at least one of the following criteria: serves our national security leadership; supports the national security posture and U.S. population attack warning systems; supports public health, safety, and maintenance of law and order activities; maintains the public welfare and the national economic system; or is critical to the protection of life and property or to NS/EP activities during an emergency."

In addition, the Government Emergency Telecommunications Service (GETS) and Wireless Priority Service (WPS) provide priority access to landline and cellular communications services if these networks are congested after a disaster. As of October 21, 2015, the Department of Homeland Security website states, "WPS supports Federal, State, local, tribal and territorial governments; critical infrastructure sectors in industry; and non-governmental organizations in performing their national security and emergency preparedness (NS/EP) missions."

### *5.2.4 Codes, Standards, and Guidelines*

Codes, standards, and guidelines cover a variety of telecommunication-related components, from central offices and data centers to switching equipment and cell towers. Design standards are not mandated by law, but may be incorporated by reference into building codes, siting permits for towers or commercial contracts. In some cases, financial auditing obligations may invoke technical standards, e.g., for data center reliability. There does not appear to be any data on whether resiliency-related standards and best practices are widely followed by the communication industry. In particular, it is unclear to what extent outside plant, including fiber communication facilities, and central offices follow resiliency-related standards.

Many of these originated with the Bellcore (later Telcordia) recommendations for the Bell Operating Companies and which led to the Network Equipment Building System

(NEBS) levels of performance[23]. These are sometimes supplemented by carrier-specific requirements. For example, GR-63 (Telcordia, 2012) and GR-1089 (Telcordia, 2011) codify, inter alia, vibration resistance during earthquakes, fire resistance and thermal margin testing, while ATIS 0600329 ("Network Equipment – Earthquake Resistance") (ATIS, 2014) describes test methods and performance requirements for earthquake resistance. These standards appear to be voluntary, with no code enforcement.

TIA-222-G (TIA, 2012) contains cell tower design standards, including wind and ice loading, with many older towers built according to TIA-222-F (TIA, 1996; NIST, 2015, Vol II). Recently, the City of Los Angeles recommends upgrading the requirements for new free-standing cell towers (City of Los Angeles, 2014). TIA-222-G divides tower structures into three classes, depending on whether they may present a hazard to human life and whether the services provided are optional or essential. For example, a Class III tower is based on a 100-year return period of peak wind speeds. Cell siting commissions or local building codes may require following TIA-222-G.

For fire alarms, NFPA 72 (NFPA, 2016) mandates in Section 10.6.7.2, that alarm systems, including communication components, can maintain operation on secondary power for 24 hours. NFPA fire codes are often included, by reference, in local building codes.

As noted earlier, data centers now play a critical role in operating communication networks and services. The resilience of data center construction is divided into four tiers, and data centers typically advertise their tier level. For example, "Tier IV provides site infrastructure capacity and capability to permit any planned activity without disruption to the critical load. Fault-tolerant functionality also provides the ability of the site infrastructure to sustain at least one worst-case unplanned failure or event with no critical load impact" (TIA, 2014, Section G.2.9.1). Audit and contractual requirements, such as those in SSAE16 (AICPA, 2011) may require companies to contract with third parties, such as data centers, meeting resiliency criteria.

In addition to these construction and equipment recommendations, the Communications Security, Reliability and Interoperability Council (CSRIC) advises the FCC and provides general operational guidelines that affect reliability. CSRIC is re-chartered every two years; working groups write reports on specific topics and maintain a list of recommended best practices that are posted on the FCC website. As noted in CSRIC (2014b): "This report reinforces previous guidance that industry Best

[23] NEBS is the most common set of safety, spatial, and environmental design guidelines applied to telecommunications equipment in the United States. It is an industry requirement, but not a legal requirement.

Practices are voluntary in nature and may not apply in every situation due to the need for flexibility, innovation, and control in the management of different carriers' unique business models, cost, feasibility, resource limitations, or other factors."

To illustrate the style and nature of the recommendation, Best Practice 9-6-1006 (CSRIC, 2014c) recommends: "Network Operators, Service Providers and Equipment Suppliers should consider establishing a designated Emergency Operations Center. This center should contain tools for coordination of service restoral including UPS, alternate means of communication, maps, and documented procedures to manage business interruptions and/or disasters."

In some cases, CSRIC recommendations have become the foundation for obligations codified in Federal regulations, e.g., if failure to follow the best practices causes high-impact outages of safety-critical systems. For example, CSRIC best practices related to 911 circuit diversity, backup power and network monitoring (FCC, 2013c) were codified into 47 CFR 12.4, requiring covered 911 service providers to certify compliance annually.

Some state laws such as Act 12-148 (Connecticut, 2012) mandate closer cooperation between electric and telecommunication utilities.

As noted in Section 5.3, backup power for residential and small business network equipment is crucial to maintain and restore communication capabilities at scale. Currently, the power consumption of such devices (e.g., 17 watts for a common optical network termination unit) makes battery backup logistically challenging and costly. The EnergyStar specification (EPA, 2014) provides power allowances for broadband modems (e.g., 5.7 watts for a cable modem) that allow powering such devices by rechargeable batteries that could be re-charged in public charging stations or vehicles. For example, a 20,000 milliampere hour (mAh) USB power bank could sustain such an EnergyStar-compliant modem for approximately 17 hours. However, EnergyStar is a voluntary program only.

Recent work by Zorn and Shamseldin (2015) provides estimates of recovery times for various lifelines, including telecommunications, based on observations of disruptive hazard events that took place from 1978 to 2012. The paper shows that telecommunication infrastructure is typically restored first, with 90% functional restoration as the benchmark, followed by electricity and water, while gas takes significantly longer. For a hypothetical major earthquake in Wellington, New Zealand, that destroys 75% of the telecommunication capacity, the model predicts 90% restoration for telecommunications within ten days, while restoring electricity would take 45 days. The paper does not, however, distinguish between different parts of the communication infrastructure, such as cellular and residential access, and does not consider the impact on broadcast and specialized communication systems such as land mobile radio.

## 5.3 Societal Considerations

The societal impact of full or partial loss of communication depends on the recovery phase, the severity of the disruption, the area affected and the availability of alternatives. Townsend and Moss (2005) summarize the impacts in four phases: emergency response, restoration and repair, reconstruction, and redevelopment[24]:

> "The emergency phase occurs when the integrity of communications is at the greatest risk. Physical damage is difficult to accurately assess and repair, electrical power is likely to be disrupted, and congestion overwhelms systems optimized for more predictable usage patterns. With lives at risk, it is also the phase where the consequences of failure are the greatest. We can identify three main consequences of telecommunications breakdowns in disaster: paralyzing official responses, challenging containment, and delaying mobilization of broader relief efforts."

As noted in NIST (2015) and depicted in Figure 5-1, telecommunication needs in the short term recovery phase (zero to three days) relate to communication to coordinate emergency response. For example, emergency management agencies at the local, state and federal level need to inform the public how to avoid imminent danger to life and property (alerting and warning) and to provide post-incident information about resources such as food, shelter and medical care as well as restrictions and advisories such as road closures, health alerts or boil-water advisories. These are traditionally provided by the Emergency Alert System (EAS) and Wireless Emergency Alerts (WEA), as well as broadcast stations. Increasingly, Internet-based mechanisms, described below, supplement these traditional mechanisms.

First responders and emergency management agencies rely on communication systems to coordinate their response, typically via land mobile radio within the immediate affected area as well as Internet-based systems for intra- and inter-agency coordination beyond the immediate affected area. This includes all 15 emergency support functions enumerated by FEMA, spanning both the private and public sector, including transportation, public works and engineering, firefighting, emergency management, mass care, emergency assistance, housing, and human services, logistics management and resource support, public health and medical services (including hospitals), search and rescue, oil and hazardous material response, agriculture and natural resources, energy, public safety and security, long-term community recovery, and external affairs (e.g., public information, media and

[24] As noted earlier, other authors combine the third and fourth phase to distinguish short, medium and long term.

community relations, congressional and international affairs, tribal and insular affairs). Naturally, the importance of each of the emergency support functions changes, depending on the nature of the incident and the time after the incident.

The public relies on communication systems to coordinate within families and other close-knit communities, as well as to check on the safety and whereabouts of immediate family, relatives, friends and work colleagues. The public also uses emergency calls (911) to request emergency assistance.

Merchant et al. (2011) describe how social media have become part of the disaster response effort. After Hurricane Sandy, Burger et al. (2013) investigated information sources used by residents in New Jersey:

> "Both [Jersey Shore and Central New Jersey] groups obtained most of their information regarding safety from television, radio, friends and web/email. Information sources on health varied by location, with central Jersey respondents using mainly TV and the web, and Jersey shore respondents obtaining health information from the radio, and TV (before the storm). For information on evacuation routes, Jersey shore respondents obtained information from many sources, while central Jersey respondents obtained it from TV. Information on mold was largely obtained from friends and the web, since mold issues were dealt with several weeks after Sandy. The reliance on traditional sources of information (TV, radio, friends) found in this study suggests that the extreme power outages rendered web, cell phones, and social media on cell phones less usable, and suggests the need for an integrated communication strategy with redundancies that takes into account prolonged power outages over large geographical areas."

During power outages, TVs are largely useless, and, anecdotally, fewer people maintain battery powered transistor radios for emergencies as most home radios are now line-powered. However, in 2014, about 92% of U.S. residents 12 years and older still listened to radio at least once a week (Nielsen, 2014a). The number of households having a battery-powered radio is unknown. Some cell phones include FM radio capabilities. Also, many radio stations are now mostly airing syndicated national content, with no local reporting or announcer resources. Spence et al. (2011) found that "larger stations had more training and resources to cover a crisis event, but were less likely to have actually provided coverage once a crisis took place; these results are similar to the findings in the previous study. In the original study, results indicated that stations in larger markets were less likely to have a plan to respond to a localized crisis." Solymossy (2013) describes the usage of "high-tech, low-tech, no-tech" solutions after major hazard events, including Twitter, AM and FM radio, amateur radio, and message runners.

Communication outages may also directly cause loss of life or other health threats. Disruptions to 911 services may delay or prevent emergency response. Athey and Stern (2000) investigated the impact of 911 technology changes on survival rates for patients with cardiac diagnoses. O'Reilly et al. (2005) estimate the impact of sustained outages on health outcomes: "For a blackout lasting approximately 30 hours, for metropolitan area of 5 million people, the incremental economic cost is estimated at $36M. Note that the comprehensive costs to society will be greater, probably by a factor of 3 … The additional scenario with both blackout and telecom disruption to the whole network lasting from 8 am to 10 pm of day 1 of our two day period, knocking out 75% of the network capacity costs are increased to $63M over baseline, almost double that of the blackout only scenario."

As immediate health and safety concerns are addressed, in the intermediate time frame of one to twelve weeks, economic considerations and a restoral of normal everyday activities such as education and work assume greater importance. At least so far, communication outages have not extended beyond this time horizon, with the exception of islands, as for the case of Fire Island discussed in the context of Hurricane Sandy (see Section 5.5.5).

There appear to be no systematic studies of the impact of sustained communication outages, beyond the after-event reports described in Section 5.5. Given the changes in technology and technology use, systematic studies may also have a limited useful life. For example, if somebody had performed such a study a decade ago, it would have likely focused on voice services and ignored emerging cellular data networks. As the Internet connects more of our infrastructure to networks, the impact of communication outages are likely to increase. Many critical services that may have been able to function effectively with only minimal communication now rely on external information resources. For example, medical facilities may store electronic medical records in cloud services off-site. Patients may rely on remote monitoring of chronic conditions.

Any impact assessment would need to consider at least three facets: economic impacts on individuals and enterprises, impact on the restoration of other lifeline services, and health and safety concerns. Interdependencies with other lifelines are covered in detail in Section 5.4, while the other facets are covered in this section.

Just as the increasing number of household devices and business operations that depend on electric power has likely decreased the tolerance for disruption of commercial power, it seems plausible that the reliance on cell phones and Internet services has made sustained communication outages less tolerable. For example, many IT services that used to run on computers located in a computer room in the same building, or on a desktop personal computer, now depend on cloud services. Thus, an office building is likely to be essentially useless until communication services have been restored. (On the positive side, the use of cloud services—located in geographically diverse and generally well-protected facilities—also enables companies to resume their operations by moving people to other facilities.) For example, after Hurricane Sandy "at JPMorgan Chase, about 25,000 employees worked remotely on Monday... On a typical day, about 2,000 to 3,000 employees work through the bank's remote computer system" (Schwartz, 2012). Working from home may also reduce the pressure on disrupted local ground transportation systems.

Approximately 44% of U.S. households now rely exclusively on wireless telephone service[25] (Center for Disease Control, 2014). This likely has increased the expectation of reliable service under all circumstances particularly since alternatives such as home (wired) or payphone service are no longer available and since there is now the expectation of anytime, anywhere reachability. For example, Hoffner et al. (2015) surveyed young adults to determine their reaction to being involuntarily without their mobile phone. "Overall, more than two thirds of the sample (69.5%) reported experiencing negative emotional responses to the loss of their phone."

Sustained communication outages are likely to cause significant economic harm to individuals and enterprises. For example, freelancers may not be able to work at all and thus suffer a loss of income, while many businesses will have to either shut down (e.g., banks and other financial institutions) or reduce their services even if electric power is restored. For example, many merchants may have to operate on a cash-only basis since their credit card terminals rely on Internet or telephone service (Isaacson, 2012; Daugherty, 2012). Indirectly, the ability of employees to work remotely relies on restoring home Internet service or at least high-quality mobile data services. A report by the Ponemon Institute (2013) estimates the cost of data center outages: "On average, the cost of an unplanned outage per minute is likely to exceed almost $8,000 per incident."

With the transition to wireless and IP-based communication services, one of the long-lasting societal expectations for communication services is being upended, namely that the telephone network provides essentially a second, special-purpose electric grid, operating at 48 volts (20 to 50 milliamp current) and backed up by lead-acid batteries and diesel generators in the phone company central office. Most providers of IP-based communication solutions offer their customers the option to purchase a battery for their cable or DSL modem or optical network termination (ONT) that can power telephone voice services, but not Internet access, for up to eight hours, typically using small lead-acid batteries. A recent FCC decision codified in 47 CFR Part 12.5 (Office of the Federal Register, 2015a) mandates that carriers make eight-

[25] The U.S. Center for Disease Control releases semi-annual statistics on the use of wired and wireless telephony service; see http://www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201506.pdf.

hour backup power solutions available for all new installations, and provides a 24-hour solution within three years. The mandate has a sunset date of ten years. It is hoped that the 24-hour solution allows backup power for residential landline voice that remains particularly important for areas with spotty cell phone coverage, for households without cell phones (approximately 8% (Center for Disease Control, 2014)) or where the cell phone service itself is interrupted after a disaster.

Communication service providers have limited economic incentives to improve resilience and post-disaster recovery. Due to interdependence with electric power, such efforts may in some cases appear to be wasted since their customers may not be able to use landline services until power has been restored. Similarly, since consumers have no good way of predicting which mobile operator infrastructure will best survive a hazard event like a hurricane, they cannot factor post-disaster performance into their purchase decision for mobile services. In addition, extrapolating results from Hartman et al. (1991) pertaining to residential electric service[26], reliability might not be able to properly priced. Different carriers have different policies for supplying backup power to cell sites, for example, but it is likely impossible for consumers to know about the different network architecture decisions or to predict the impact during a storm. FCC Disaster Information Reporting System (DIRS) outage data provides an approximate measure of survivability and recovery across carriers, but the data are not available to the public. (Carriers report cell tower outages on a daily basis; due to overlapping coverage and coverage regions that differ in size, cell tower outages can only approximate the number of customers affected.)

In addition, residential ISP and cable TV providers already suffer from weak consumer satisfaction, placing last among 43 industries. “Sixty-one percent of U.S. households have just one or no high-speed Internet provider servicing their region and the lack of customer choice contributes to weak customer satisfaction. Even as Internet usage grows, customer satisfaction with ISPs remains unchanged at an American Customer Satisfaction Index (ACSI) score of 63 and tied with subscription TV for last place among 43 industries. Customers are frustrated with unreliable service, slow broadband Internet speeds and rising subscription prices – and they resent being locked into service contracts” (American Customer Satisfaction Index, 2015). It is unclear whether this provides an incentive to rapidly recover from outages.

Recent large-scale storms have yielded a significant number of articles that were critical of the service provider preparedness (as an example, see Smith, 2013), but

[26] Hartman et al (1991) noted “More importantly, customers do not seem to be willing to pay for marginal reliability increases; rather, they require compensation for reliability increases that involve movements from the status quo” when discussing residential electric service.

even within the same service territory, experiences can vary significantly across providers and by geography. For example, if a local cell tower exhausts its backup fuel supply or did not have a backup generator, customers served by that tower may experience service disruptions while others a mile away may not.

## 5.4 Interdependencies

The overall communication infrastructure depends on commercial power, but also less directly on road transportation following a disruptive event.[27] For example, during outages of commercial power, switching facilities, data centers, TV/radio transmitters and cell towers rely on the delivery of diesel fuel by truck to sustain backup generators. After Hurricane Sandy, Verizon used up to 1,500 generators, consuming 100,000 gallons of fuel each day (Cheng, 2012). Typical cell sites are equipped with a 20-60 kWatt generator (Balshe, 2011). Use of multiple fuel sources, such as solar, diesel, and natural gas fuel cells (Kuwata et al., 1996), may reduce the dependency on the transportation system or liquid fuel supplies.

Figure 5-2 shows a simplified set of dependencies, distinguishing three key physical components of communication systems, namely, the outside plant such as fiber and copper loops, central offices and data centers and, finally, towers and antenna systems for cellular, broadcast, and land mobile radio applications. Transportation systems are necessary to supply fuel and spare parts to cell towers and radio and TV antennas. Pipelines may share rights-of-ways with outside plant, in particular fiber. Electric power is likely to share poles with the outside plant of telecommunication systems.

Conversely, almost all other lifelines depend on communication services for control and monitoring. Electric generation and transmission facilities need to be monitored using supervisory control and data acquisition (SCADA) systems. Smart meters monitor residential and commercial electric energy consumption and initiate load control. Pipelines require remote operation of leak detectors and valves. Railroads, whether they carry passengers or freight, increasingly rely on automatic train control, operating over a fiber-connected wireless transmitter network, to ensure their safe operation. Commercial air transportation would not be possible without a nationwide voice and data network that connects air-to-ground radio transmitters, air traffic control facilities, and radar sites.

[27] Most terrestrial-wide area communication facilities are typically located near major transportation arteries, such as along railroad rights-of-ways, highways, and pipelines. Thus, disruptions of these lifelines may also physically affect the fiber buried next to the railroad tracks, highway, or pipeline.

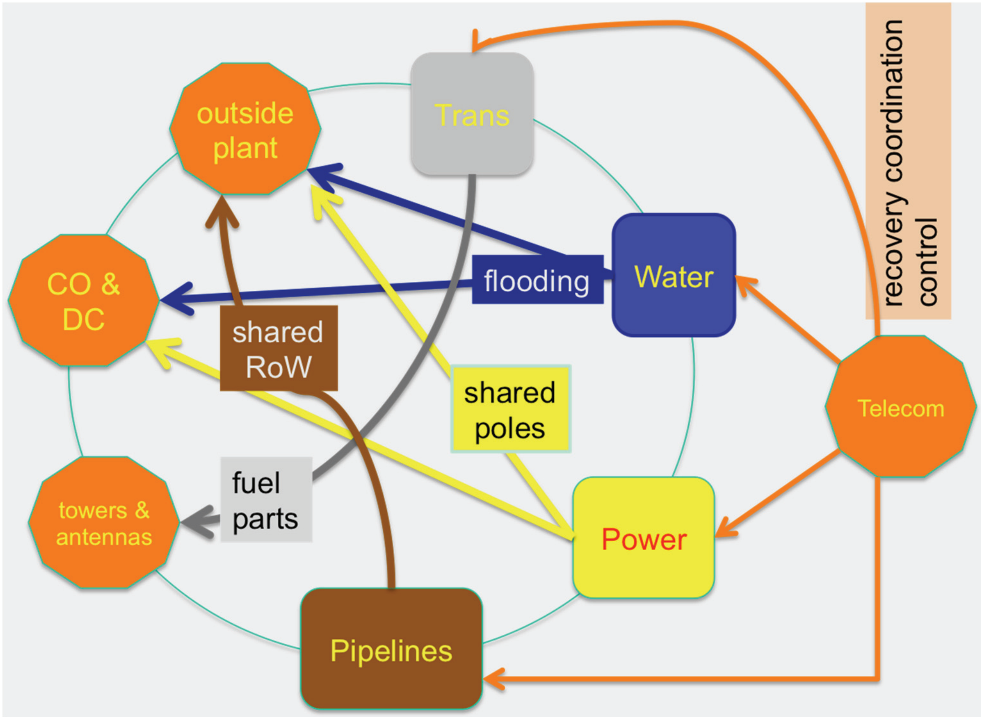



Figure 5-2 Simplified illustration of telecommunication interdependencies. CO denotes central offices, DC denotes data centers, RoW indicates Right of Way; orange decagon indicates telecom-related components; rounded rectangles refer to other critical infrastructures and how they can impact aspects of telecommunication systems (for example, water main breaks may flood central offices (CO) and data centers (DC).

In the past, road transportation could function without an extensive communication infrastructure. As telematics and intelligent transportation systems rely on vehicle-to-infrastructure communication for everything from collecting road tolls to alerting vehicles to road hazards, even road transportation could be severely disrupted if communication services fail.

Beyond the direct technical dependencies in managing and controlling the operation of lifelines, communication networks are also vital to coordinate the work of public safety and utility personnel. This is pointed out in a Long-Term Power Outage tabletop exercise report (Wisconsin Emergency Management, 2010):

> "Communication challenges were a key barrier identified during the TTXs [Long-Term Power Outage tabletop exercise reports]. The extent of the impacts on communication systems during a LTPO [Long-Term Power Outage] event was not fully known or explored in the limited time available. Additional communication planning and training for Public Information Officers is needed, including pre-established messages for use during such an event."

Since electric and communication utilities share the same poles and, to a lesser extent, duct space, restoration needs to be closely coordinated.

While all lifeline infrastructures have geographic dependencies (i.e., disruptions in one location may affect users of that infrastructure far beyond the locus of the physical disruption itself), these dependencies are particularly pronounced for communication networks, and not always obvious and predictable. For example, the U.S. Internet is connected via transoceanic fiber links to other continents, and traffic from these other continents may pass through North American fiber links, e.g., from Europe to South America. Many higher-layer services are housed in a small number of data centers so that the temporary unavailability of a data center in Virginia may prevent users in California, Canada or the Czech Republic from sending email or conducting electronic commerce transactions. Communication services for traditional public safety functions such as 911 are being centralized in a small number of physical locations, so that a single outage can affect multiple states (Public Safety and Homeland Security Bureau, 2014). Often, telecommunication carriers and their customers may not be aware of the interdependencies within their own networks or other networks. For example, due to "circuit grooming," carriers may inadvertently route circuits that were meant to be geographically diverse through the same physical cable or fiber. O'Rourke (2007) provides several additional examples of how other lifelines affect telecommunication services.

## 5.5 Disaster Lessons

Telecommunications impacts and lessons resulting from the following recent large-scale disasters within the United States are briefly summarized: Hurricane Katrina in 2005, Hurricane Irene in 2011, the June 2012 derecho, and Hurricane Sandy in 2012. Disasters that occurred earlier than about 2005 are likely to be less informative given the significant changes in technology, interdependencies, industry structure, and consumer behavior. The Public Safety and Homeland Security Bureau (2014) report that covers the April 2014 multistate 911 telecommunication outage caused by a software failure may also be of interest, but outside the scope of this study.

In general, there does not appear to have been any systematic follow-up whether and to what extent the recommendations of the reports cited below have been translated into practice. Where known, the current implementation status is described. For example, there do not appear to be regular government-industry exercises that focus on communication resilience and restoration.

### *5.5.1 2005 Hurricane Katrina*

The Independent Panel Reviewing the Impact of Hurricane Katrina on Communication Networks (2006) noted a number of lifeline interdependencies for communication networks, in particular with electric power and transportation. It noted that generators for cellular base stations were designed to operate for 24 to 48 hours, and portable first-responder radios and backup batteries for eight to ten hours. In some cases, the flooding impacted transportation options and prevented fuel transport and thus the refueling of generators.

The Panel (2006) noted a bimodal distribution of service restoration:

> "Nevertheless, ten days after Katrina, nearly 90 percent of wireline customers in the Gulf region who had lost service had their service restored. However, the vast majority of these customers were in the less impacted regions of the Gulf; regions that were harder hit sustained more infrastructure damage and continued to have difficulty in restoring service. … However, within one week after Katrina, approximately 80% of wireless cell sites were up and running. Consistent with other systems, the 20 percent of base stations still affected were in the areas most impacted by Katrina. … Approximately 28 percent of television stations experienced downtime in the storm zone; approximately 35 percent of radio stations failed in one fashion or other. In addition, in New Orleans and the surrounding area, only 4 of the 41 broadcast radio stations remained on the air in the wake of the hurricane. … Nevertheless, within three weeks after Katrina, more than 90 percent of the broadcasters were up and running in the affected region. However, in the areas most affected by the storm, the vast majority of stations remained down much longer."

The Panel's (2006) report made the following key recommendations related to lifelines:

- The communications industry should develop business continuity plans that include power reserves, cache of essential replacement equipment, adequate sparing levels, credentialing, emergency center operation coordination, training and disaster drills, and appropriate disaster preparedness checklists. It should conduct exercises to evaluate these plans and train personnel, develop and practicing a communication plan to identify "key players" and multiple means of contacting them, and routinely archive critical system backups and providing for their storage in a secure off-site facility.
- Public safety should be educated on the availability and capabilities of non-traditional technologies that might provide effective back-up solutions.
- The FCC should automatically grant certain types of waivers or special temporary authority for affected areas.
- The FCC should collect outage data once a day and share it with appropriate government entities. (This led to the Disaster Information Reporting System (DIRS) described earlier.)

- Repair staff for all communication infrastructure providers should be credentialed and be afforded emergency responder status so that they can gain access to the affected areas.
- States should designate post-disaster coordination areas for communication infrastructure providers where credentialing, security, escorts and further coordination can be achieved.
- States should include communication facilities on the priority list for commercial power restoration and electric utilities should coordinate power restoration activities with communication restoration.
- The FCC should work with the National Communications System (NCS) to promote GETS, WPS, and TSP to all eligible government, public safety, and critical industry groups.
- The FCC should encourage state and local jurisdictions to retain and maintain, including through arrangements with the private sector, a cache of equipment components that would be needed to immediately restore existing public safety communications. The FCC should also work with the NCC to develop inventories of alternative communication assets.
- The FCC should take several steps to facilitate interoperability among first responder communications.
- PSAPs should maintain diverse facility routes and 911 selective routers. (This led to the FCC 2013 Report and Order (FCC, 2013c)).

### *5.5.2 2011 Hurricane Irene*

Hurricane Irene caused significant telecommunication impacts, primarily to cellular systems. According to Plumb (2011): "On Sunday [August 28], … Irene had brought down around 1,400 cell sites in North Carolina and Virginia. After the storm moved northward through Connecticut, Rhode Island, and Vermont, an updated report stated that 6,500 cell sites were down along the East Coast. Recent updates show Vermont with 44 percent of its cell sites down… FCC reported Monday that only 11 percent of cell sites in North Carolina are down, an improvement of 14 percent from Sunday's numbers. The FCC's Sunday afternoon report also said 130,000 wirelines were down and 500,000 cable subscribers were without service. A day later, those numbers rose to 210,000 and 1 million, respectively."

Irene illustrated the relationship of bridges and fiber lines, in the report by Plumb (2011): "Our redundant fiber rings were cut on both the western and eastern sides of Vermont, and also en route to Boston, and also west-to-east connecting Springfield to Wallingford, and also north-to-south connecting Springfield to Hartland, Chester to Grafton, and Wallingford to Killington. In cases where our fiber is (or was) on bridges that washed away, or under roads that eroded, the repairs require coordination. By far, the most-isolated of our service area is Killington, where our fiber ring follows Route 4 and Route 100, and both roads washed out."

#### *5.5.3 2011 Great East Japan Earthquake*

NTT East (NTT East, 2011) summarizes the damage caused by the Great East Japan Earthquake: "This infrastructure suffered unprecedented damage as a result of the Great East Japan Earthquake. The tsunami in particular caused enormous damage that far surpassed the impacts of the Great Hanshin-Awaji (Kobe) Earthquake of 1995. The widespread and prolonged power outages prompted by the earthquake also affected 990 exchange buildings at the peak of the crisis, incapacitating many of them. As a result, approximately 1.5 million lines in the Tohoku region and adjacent areas were affected." The earthquake and tsunami incapacitated 385 buildings, disrupted 90 trunk routes, completely destroyed 16 exchange buildings and flooded 12 more, and as noted earlier, damaged 28,000 telephone poles in the coastal areas and took down approximately 2,700 km of aerial cables in the coastal areas. Restoration took approximately 50 days (NTT East, 2011, p. 7).

"Trunk lines that connect exchange buildings to each other also suffered unprecedented damage, some being severed when the bridge under which they ran collapsed, and others being swept away with the railway lines alongside which they were laid." "The access lines that connect the customer premises to NTT East exchange buildings suffered widespread damage. A great many telephone poles were swept away by the tsunami, while liquefaction and land subsidence caused others to lean or topple over. Underground ducts also suffered from submergence and mudslides caused by the tsunami" (NTT East, 2011).

NTT East has drawn a number of lessons from the 2011 earthquake, including strengthening trunk line backup systems by subdividing network loops, creating a ladder-like structure; creating new inland routes in tsunami areas; and laying ducts under riverbeds in locations where cables strung along bridges were swept away or severed (NTT East, 2011, p. 35).

#### *5.5.4 2012 Midwest and Mid-Atlantic Derecho*

The derecho that hit portions of the Midwest and Mid-Atlantic regions of the United States on June 29 and 30, 2012 affected both wireline and cellular communications, and, in particular, 911 systems. Unlike other major storms, it hit with relatively little warning. The FCC published a report (Public Safety and Homeland Security Bureau, 2013) summarizing the impact and lessons:

> "The 2012 derecho severely disrupted 911-related communications. Seventy-seven 911 call centers (also known as PSAPs) serving more than 3.6 million

> people in six states lost some degree of connectivity, including vital information on the location of 911 calls, mostly due to service provider network problems. From isolated breakdowns in Ohio, New Jersey, Maryland, and Indiana, to systemic failures in northern Virginia and West Virginia, 911 systems and services were partially or completely down for up to several days. Seventeen PSAPs in three states lost service completely, affecting the ability of more than 2 million people to reach 911 at all. … In total, more than 1.2 million wireline communications customers in twelve states experienced outages (not counting other residents affected by the inability to reach 911 on all platforms). In addition more than 30,000 high capacity transport lines ("DS3s") were affected… The bulk of those outages occurred in Ohio, with more than 170,000 wireline customers affected for periods ranging from one hour to more than five days, and in Maryland, where roughly 100,000 wireline customers lost service for as long as six days."

The derecho illustrated an interdependency between power and communication lifelines, namely power quality: "A significant amount of transport equipment failed, according to Verizon, because of power surges and low voltages in central offices. For example, more than 200 circuit boards in one of Verizon's digital cross-connect systems failed and had to be replaced" (Public Safety and Homeland Security Bureau, 2013).

According to the Public Safety and Homeland Security Bureau (2013) report, initially, "just about 11 percent of all cell sites in the affected area (were) down at the peak and (there was) a rapid restoration of service from July 2 through July 4… The two main reasons reported for cell site outages were loss of power and the disabling of transport facilities that carry calls from cell sites to mobile switching centers. Cell sites were as likely to fail because of disruptions to landline backhaul communications as due to backup power exhaustion in the first days following the derecho." Verizon reported that about 7% of its generators in central offices did not function properly; similarly, Frontier reported generator failures. The Public Safety and Homeland Security Bureau (2013) report states that "Although Frontier deployed mobile generators in some locations, as many as twenty were stolen from Frontier facilities in the storm's aftermath, causing additional backup power failures."

Figure 5-3 shows how cell sites recovered; Figure 5-4 illustrates the causes for cell site outages, illustrating how power issues may become increasingly prevalent as easier-to-restore cell sites recover. The report notes several failures to implement Communications Security, Reliability and Interoperability Council best practices as likely contributing to the scope, severity, and duration of outages. Just as in the Katrina report, the Derecho report recommends that PSAPs maintain multiple alternate means of communication. In 2013, the FCC required providers of 911

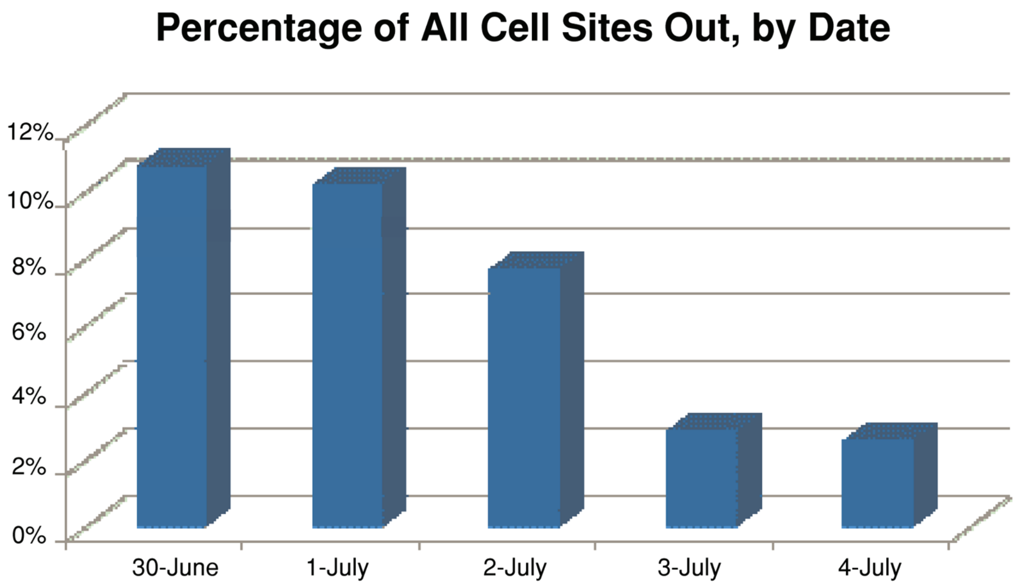



Figure 5-3 Cell site recovery following the 2012 Midwest and Mid-Atlantic Derecho (Public Safety and Homeland Security Bureau, 2013).

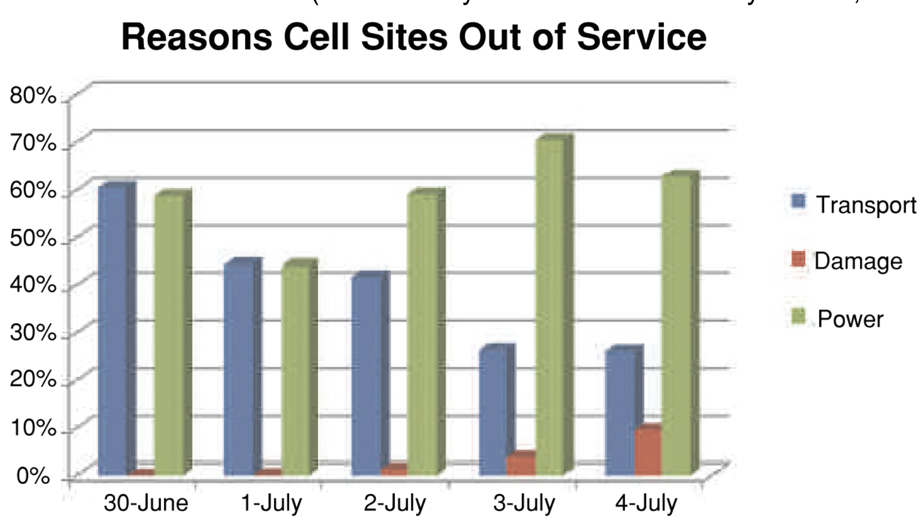



Figure 5-4 Causes of cell site disruption following the 2012 Midwest and Mid-Atlantic Derecho (Public Safety and Homeland Security Bureau, 2013).

services to implement best practices related to circuit diversity, circuit monitoring and backup power (FCC, 2013c).

### 5.5.5 2012 Hurricane Sandy

Hurricane Sandy also caused widespread cell tower outages, with up to 25% of cell sites across the ten states affected out of service, with up to half in the hardest hit counties, according to the Chief of the Public Safety and Homeland Security Bureau (Turetsky, 2013). A workshop report by NYU Polytechnic (2013) analyzes some of the lessons for wireless and other communication networks, such as better coordination between electric utilities and telecommunication providers through a common geographic information system, undergrounding of utilities, and low-power consumer and small business network elements that can operate on battery power for extended periods of time. Recently, the White House Broadband Opportunity Council (Broadband Opportunity Council, 2015) recommended that "Federal Agencies that fund significant infrastructure investments should work together to further promote 'Dig Once' policies." Two FCC workshops (FCC, 2013a, 2013b) reflected on experience and lessons learned, as well as longer-term technology options, but there appears to have been no systematic follow-up. A report by the Hurricane Sandy Rebuilding Task Force (2013) recommends developing "a resilient power strategy for wireless and data communication infrastructure and consumer equipment." The City of New York (2013a) *Hurricane Sandy After Action Report* makes similar recommendations:

- "Work with telecommunication providers to get accurate, regular data on the status of phone, internet, and data availability throughout the City.
- Carrier reporting, pursuant to FCC DIRS, should be a requirement and not voluntary. The FCC should ensure any relevant information collected that affects a severely-impacted community be shared immediately with first responders responsible for serving those communities.
- Develop a plan along with carriers to pre-stage COWs (cells on wheels) and other critical telecommunication assets where they could be needed following a coastal storm.
- Work with carriers to extend backup power time at cell sites in flood-prone areas.
- Work with the FCC to establish minimum performance standards for carriers for voice and text messaging services during high-volume call times."

In each of the four large-scale disasters described above, large-scale disasters seemed to be followed by two different types of recovery: the "routine" recovery, where replacement of facilities and equipment followed a well-known operational pattern, yielding 80 to 97% cell site recovery within roughly three days after Hurricane Sandy (Albanesius, 2012). Some disruptions, however, such as the flooding of the Verizon central office on Broad Street in lower Manhattan took much longer to repair. In that case, the carrier chose to replace copper loops with fiber, rather than simply replacing like-with-like. On Fire Island, the copper loop infrastructure was almost completely destroyed and it took six months to restore service using a replacement network.

## 5.6 Gaps and Deficits: Codes, Standards, Performance Requirements, and Societal Considerations

As described in Section 5.3, there are estimates of the economic and health and safety impact of prolonged communication outages, but the increasing complexity of communication networks and applications make a more precise prediction difficult.

For example, a complete loss of all non-satellite and non-high frequency radio is likely going to have a very different impact than, say, the outage of residential broadband service or a single mobile carrier. Similarly, restoring a small number of fiber circuits to a data center is likely faster and easier than restoring service to millions of homes.

While there are performance standards (as summarized in Section 5.2) for individual components of communication systems up to the level of a data center, there appear to be no simulation tools that estimate the influence of design choices and recovery strategies, provide resources for overall lifeline performance, or predict the likely recovery timeline. For example, the number of technician teams working in parallel and the difficulty of resourcing spare parts or replacements may influence recovery times. Besides mostly manual tabletop exercises, protocols do not appear to be available for practicing emergency operations with all entities likely to be affected by a major disaster. A Monte-Carlo simulation approach to the whole system may allow the carrier as well as possibly third parties to estimate the likely lifeline resilience.

Currently, the collection of data about communication system outages is best characterized as anecdotal. There does not appear to be a systematic approach to recording outage information over time so that researchers can, for example, compare the effectiveness of different approaches or determine whether organizations learned from previous incidents. Similarly, data exchange during an outage is largely manual, presumably in spreadsheets, rather than standardized data feeds that allow communication providers to track recovery of related services or the deployment of repair resources.

The various after-action reports make helpful recommendations, but there does not appear to be a systematic effort to track whether these recommendations have been translated into action, particularly where this requires action by widely distributed entities such as 911 PSAPs, telecommunication providers or localities. Data centers appear to be the only communication-related entities that have a comprehensive, verifiable set of standards, with auditing, such as SSAE16 SOC 2 (AICPA, 2010). For other entities, self-assessment or third-party audit checklists, like the Payment Card Industry Data Security Standard tools for entities that accept credit cards, may facilitate validating that all current best practices are being followed or that compensating alternatives are in place.

Several of the “lessons learned” reports cited indicated that backup plans did not work as anticipated or that assumed redundancy either never did exist or had disappeared due to engineering changes, leading to a false sense of resiliency. Thus, rather than waiting for a real disaster to test resiliency, it may be prudent to follow the “Chaos Monkey” approach pioneered by Netflix to test the resilience and recoverability of their cloud computing services. According to the Netflix Tech Blog

(2012), “(t)he service has a configurable schedule that, by default, runs on non-holiday weekdays between 9 am and 3 pm. In most cases, we have designed our applications to continue working when an instance goes offline, but in those special cases that they don’t, we want to make sure there are people around to resolve and learn from any problems.” This approach may ferret out problems within a single service provider, but is less likely to be applicable to failures that occur due to the interaction of multiple interdependent organizations. If the risk of affecting customers is seen as too high, it may be possible to simulate systems in table top exercises that span multiple organizations, including local, state and federal governments.

As noted earlier for Verizon’s lower Manhattan central office, the best recovery strategy may well involve replacing a legacy infrastructure with current technology, particularly since older components may not be manufactured anymore and spare parts may be difficult to procure quickly. (For example, all major manufacturers of telephone circuit switches have either ceased manufacturing these systems or are no longer in business.)

Since the old model of regulating telecommunication carriers via state public utility commissions is unlikely to be revived, there is a need to identify incentives and penalties, whether contractual, through insurance mechanisms, franchise agreements or Federal regulatory, that appropriately capture the externalities of communication system outages after disasters.

## 5.7 Conclusions and Recommendations

The recommendations below extend and summarize those mentioned in Sections 5.5 and 5.6.

### *5.7.1 Review of Key Points*

Unlike traditional utilities, telecommunications consists of multiple overlapping systems that have evolved independently over decades, but are slowly converging on an Internet Protocol (IP) platform. Unlike electricity, water, and gas, Internet-based services can often be delivered by several different providers, using diverse technologies ranging from fiber and copper loops to cellular wireless and satellite. The number of competitive offerings differs greatly between geographic areas, with typical urban areas having more offerings than rural areas. Similarly, households can receive over-the-air radio and television signals from dozens of stations (at least in densely-populated areas) that are operated independently.

Unlike other lifeline systems, communication systems exhibit a layered architecture, where multiple higher-layer services share a single underlying infrastructure or, conversely, where an application-layer service such as email or telephone may use multiple different network and physical-layer technologies.

Specialized networks such as land mobile radio and broadcast networks offer services that are more restricted in functionality (e.g., voice-only or one-way transmission) or are limited to smaller user groups (e.g., amateur radio or government-only systems).

Despite their diversity in technology and infrastructure, these communication systems may share points of failure, both well-known and hidden, that are likely to cause widespread outages during and after hazard events.

Compared to other lifelines, Internet-based communication systems are lightly regulated in terms of their performance requirements. There are component-level design guidelines and standards for some telecommunication system components such as cell towers, central offices or data centers, but law or regulation does generally not mandate adherence to these standards and the degree of adherence is unknown to outside observers, probably including customers of the carriers. Organizations such as the FCC's Communications Security, Reliability and Interoperability Council provide best-practice guidance, but emphasize their voluntary nature. Large commercial customers may be able to obtain binding service level agreements, but these do not cover performance during disasters. Widespread outages of residential voice and Internet service have to be reported to the FCC.

Experience from past disasters has shown that communication systems are restored relatively quickly compared to other lifelines, but lack of communication systems can severely disrupt not just economic activities and everyday life, but also make it much more difficult for first and second responders to be effective and efficient. Thus, society expects communication systems, at least with partial functionality or reduced capacity, to remain operational during and after the disaster. Many economic activities cannot effectively resume until businesses, medical facilities and public buildings have access to voice and Internet services. In particular, 911 emergency systems are crucial during disasters as a way for the public to reach first responders and request assistance. Emergency alerting systems, whether using traditional broadcast or cellular technology, can help inform the public of imminent threats to life safety. First and second responders rely on land mobile radio to coordinate activities within each organization, between services and with incident command systems (ICS).

Telecommunication systems depend strongly on other lifelines, in particular electric power and road transportation. Increasingly, these other lifelines also rely on either dedicated or commercial (public) telecommunication services for operation, fault diagnosis and coordinating restoration activities.

### *5.7.2 Lifeline Standards Development Needs*

There are three broad areas that could benefit from additional lifeline-related standards and performance metrics: for telecommunication systems in general, for specific communities and to ensure interoperability among first responders. First, as noted in Section 5.2.3, there are no general hazard-related guidelines, standards, and performance criteria for many key elements of telecommunication systems, nor are there metrics characterizing the resilience after hazard events. (For example, there is no common metric to estimate the impact of cell tower outages or fiber loops, e.g., in terms of area, capacity or population affected.) This leads to the second gap—communities and enterprises often make plans using anecdotal past experience, i.e., predicting the future based on the last storm, flood, earthquake or wildfire, even though the technology and infrastructure are changing rapidly, rather than on probabilistic predictions based on possible hazards. Communities would benefit from knowing, for example, whether they depend on one fiber route or one cell tower for their commercial services. Finally, common standards for first responders at the local, state and federal level would ensure that the available communication channels can be used effectively after a hazard event.

Specific recommendations are:

- **Develop metrics that allow customers, communities and regulatory bodies to assess the resiliency of communication systems**, e.g., in their ability to withstand a particular set of hazard intensities or to provide (capacity-reduced) functionality after loss of physical assets.
- **Develop quantitative metrics that capture the impact of hazard events and the speed of recovery in communication systems**, e.g., by measuring the impact on network reach (coverage) and capacity.
- **Develop standards or guidance to help facilitate interoperability among first responder communication systems.**

### *5.7.3 Research Needs*

Following are key research needs:

- **Conduct research to better understand the economic impact of sustained communication outages.** Except for anecdotal information from recent disasters, little is known about the economic impact of outages. Improved insights into the likely economic impact will allow communities and enterprises to better plan and allocate resources, e.g., for backup systems or more resilient communication system elements. Such research will be possible only if system performance metrics both for the initial impact and the recovery are recorded with sufficient granularity during and after disasters and if such data are made available to researchers.

  While the Federal Communications Commission gathers data about large-scale network outages both during normal operation and after hazard events, the data are currently not available for root-cause analysis or to estimate recovery times, nor to compare the effects of different design choices. Recommendations from after-action reports also do not appear to be systematically studied to know if they are implemented or whether they were indeed effective.

- **Develop protocols and systems that allow large-scale monitoring to improve the ability of carriers to diagnose and correct faults.** Network systems, particularly for small businesses and homes, typically have limited remote monitoring and diagnostics capability.
- **Conduct studies to compare mean time between failure and mean time to repair buried fiber versus aerial installations.** While industry practice and limited published data appear to suggest that burying fiber is likely to yield higher reliability and resilience than aerial installation (Verbrugge et al., 2005), particularly for weather-related hazards, there do not appear to be any recent peer-reviewed studies comparing mean time between failure and mean time to repair (MTTR) of the two options. Such studies should be based on field experience both during regular operation and after disasters.
- **Conduct research to identify a potential range and effectiveness of incentives and penalties for key "systemically important" actors, whether contractual, through insurance mechanisms, franchise agreements or federal regulations.** Such measures should appropriately capture the externalities of communication system outages after disasters.

### *5.7.4 Modeling Needs*

One key modeling need is as follows:

- **Develop computational models and tools for simulating the impact of disruptive hazard events on telecommunication systems.** Combined with realistic recovery assumptions, such simulations can help quantify the trade-offs between cost, survivability and recovery for different parts of the communication lifeline infrastructure.

### *5.7.5 Lifeline System Operational Needs*

The following are considerations for addressing lifeline system operational needs:

- **Critical services such as hospitals, utility emergency management centers and public safety facilities (including PSAPs) should maintain as many diverse communication facilities as possible, including multiple wireline and cellular data services, free-space optical, point-to-point wireless and satellite connections**.
- **Fiber lines, particularly to critical services such as PSAPs and hospitals, should be buried to reduce the impact of wind and ice events, although this does typically increase the cost**. Undergrounding can be made more affordable

by routinely burying shared PVC conduit when building or resurfacing roads, water and sewer pipes or rail tracks ("dig once").

- **Consider replacing copper with fiber optic communications lines to increase system resilience.** Fiber optic communication lines are more likely to survive submersion than copper loops, including coaxial cable, and are not susceptible to corrosion at connection point. Since they are non-conducting, they can also be lashed to distribution and transmission power lines. While such replacement is costly, some telecommunication providers are systematically replacing copper with fiber, even for voice-only customers (Sanderson, 2014).
- **Consider adding resilient communications capabilities to gas, water and electric systems, both for distribution and end users.** This may allow operators of these other lifelines to obtain a better situational awareness of outages, recovery and post-event performance.
- **Develop resilience metrics and requirements for the communications industry**. Data centers often advertise their conformance to industry standards that include in-depth resiliency provisions, allowing their customers to have some confidence that their critical computational needs will be met even during disasters. The communications industry similarly needs metrics and requirements, possibly reinforced by appropriate state or federal regulation for system components constituting and affecting other critical infrastructures, on developing business continuity plans that include power reserves, cache of essential replacement equipment, adequate sparing levels, credentialing, emergency center operation coordination, training/event drills, and appropriate disaster preparedness checklists. It should include requirements on conducting self-assessments as well as exercises to evaluate these plans and train personnel, develop and practice a communication plan to identify "key players," and multiple means of contacting them, and routinely archiving critical system backups and providing for their storage in a secure off-site facility. Some elements of such planning may require interaction with local and state emergency planners to pre-plan credentialing, access and designated post-disaster coordination areas, pre-plan the staging of COWs (cells on wheels) and other telecommunication assets and priority listing all key communication facilities for power restoration.
- **Communication system operators should work with the communities they serve to improve community resilience in the face of communication system disruptions.**
- **Consider using multi-fuel and hybrid backup power systems to provide additional resiliency for smaller cell sites if natural gas pipelines remain operational after hazard events, even if liquid fuels cannot be delivered**.

- **Carriers should work to extend the backup power time at cell sites in hazard-prone areas where post-disaster access may be particularly challenging, such as floodplain and coastal locations**.
- **Consider ways to reduce power consumption of consumer customer premises equipment, such as DSL and cable modems.** If the power consumption of consumer customer premises equipment can be reduced to no more than 5 watts, it becomes feasible to power such equipment indefinitely by rechargeable lithium-ion batteries, possibly combined with small solar panels.
- **Deploying text-to-911 allows individuals to reach 911 even when the voice or data telecommunication networks are overloaded due to increased call volume or reduced capacity**.
- **Regularly exercise the impact of component failures, with appropriate safeguards and coordination, both in isolation and in combination (e.g., via "Chaos Monkey" or realistic simulation exercises), to improve the resiliency of individual operators of communication systems as well as entities that interconnect and depend on them.**
- **Promote better coordination between electric utilities and telecommunication providers in response and restoration planning.** If they agree in advance to share data about the status of distribution facilities, they can better coordinate repair efforts and avoid tearing down communication lines when repairing power lines on the same utility poles. They could also develop mutual strategies for undergrounding of utilities. Federal agencies that fund infrastructure investment could also further promote "dig once" policies.
- **Plan for restoration of road access and commercial power to key communication resources such as central offices, cell towers and data centers in an effort to accelerate recovery.**
- **Promote the automated and continuous measurement of landline and communication and data services, as well as PSAPs, before and during major disasters.** Such measurements can provide communities, emergency operations centers and researchers with up-to-date and consistent information about the impact and recovery of key communication services.

### *5.7.6 Future Considerations and Trends*

It appears likely that the different communication modalities such as broadcast, private two-way radio services, private data services, circuit-switched telephony, cable TV and Internet will converge onto a single platform based on Internet protocols within the next decade, at least in densely populated areas of the country.

# Chapter 6
# Transportation

## 6.1 System Overview

Transportation systems provide the means by which people and goods move around the country and the world. They are essential for the maintenance and growth of modern commerce and standards of living. Multiple modes of transportation often serve complementary functions, which create redundancy and enhance inherent resilience in the overall transportation network. The performance of transportation systems during a natural hazard event will depend on both the intensity of the event and the condition of the system at the time of the event. Older and poorly maintained transportation infrastructure will generally perform worse than newer well-maintained infrastructure when subjected to the same intensity event.

During a routine or design hazard event, failure of a few individual components of the overall transportation network will result in inconvenience, delays, and economic losses, but alternative routes are generally available to maintain an adequate flow of people and goods. However, during extreme hazard events, more substantial damage to the transportation systems can threaten life safety and result in major economic consequences.

Transportation system recovery time after a natural hazard event will also depend on the intensity of the event and the condition of the system at the time of the event. Alternative modes of transportation can often be utilized in the short-term recovery phase (lasting days); however, repairs and reconstruction of damaged components of the transportation network are typically intermediate- to long-term recovery activities (lasting weeks to months and even years). Because of the greater extent of damage anticipated after an extreme event, a shortage of available contractors to repair or rebuild the transportation infrastructure may extend the recovery time.

Community resilience to natural hazards can be improved by strategies such as hardening existing transportation systems through mitigation or retrofit projects, performance-based design of new transportation components, and enhancement of transportation system redundancy.

### *6.1.1 Transportation Infrastructure*

Transportation infrastructure is generally considered to include highway, rail, airport, shipping, and intermodal systems, each of which is discussed under a subheading that follows.

#### 6.1.1.1 Highway Transportation Systems

These systems consist of roadways ranging from local residential streets to interstate freeways, and everything in between. Most roads are built on grade, but rely on bridges to cross rivers, railway lines and other highways. Road tunnels are used to pass below central business districts or through mountainous terrain and below waterways. The highway system is used to transport both people and goods locally, regionally and nationally. A majority of vehicles currently rely on petroleum or diesel fuel, so well-supplied fuel stations are critical to maintaining a functioning vehicular transportation system.

The weak links in the highway transportation system are often the bridge structures, including the approach embankments at each end of the bridge. During earthquakes, bridge structures are particularly susceptible to damage or collapse (Cooper et al., 2015). Coastal inundation and wave loading during past tropical storms and tsunamis has also resulted in numerous bridge failures (Douglass and Krolak, 2008; Saatcioglu et al., 2005; Chock et al., 2013). Damage to tunnels and on-grade roadways can also occur during various hazard events (Chock et al., 2013). Generally in urban areas there is sufficient redundancy in the highway network to accommodate closure of some roadways, but loss of major arterial freeways can lead to severe traffic gridlock. Rural areas may be serviced by only one or a limited number of highways, making these routes more critical for emergency responders after a damaging hazard event.

Community-based planning is required to identify critical roadways that need to meet transportation requirements during and after all possible hazards to improve highway transport resilience for future hazard events.

#### 6.1.1.2 Railway Transportation Systems

Railway systems consist of both heavy and light rail, each made up of roadbeds and tracks, associated bridges and tunnels, and railway system facilities (e.g., control buildings, switching gear, electrical power supply lines, and fuel facilities). Heavy rail lines are predominantly used to transport cargo, though some passenger traffic also uses rail. Amtrak reported more than 31.2 million passengers in 2012, while freight railroads transport almost half the nation’s intercity freight and approximately a third of its exports (NIST, 2015). Freight rail systems also contribute to the intermodal transportation of containerized cargo and imported automobiles from ports on both east and west coasts to the interior of the U.S. (NIST, 2015).

Mass transit systems such as light rail, commuter rail and subways provide essential commuter transportation from suburban communities to the city core. Disruption of these rail-based mass transit systems after the Loma Prieta earthquake (Penzien et al., 2003) and Hurricane Sandy (New York City, 2013a) led to significant disruptions in economic activity in the affected metropolitan areas. However, the lack of damage to the Bay Area Rapid Transit (BART) system during the Loma Prieta earthquake meant that it was available to satisfy some of the excess demand resulting from the closure of the Bay Bridge connecting San Francisco to the East Bay communities (Penzien et al., 2003).

The roadbeds, bridges and tunnels making up the rail network are susceptible to similar damage as those in the highway system. However, the rail network generally has significantly less redundancy than the highway system, so failure of only a few components can cause major disruption and delays (NIST, 2015; City of New York, 2013).

#### 6.1.1.3 Airport Transportation Systems

Air travel allows for rapid transport of people and goods over long distances, but at considerable cost compared with alternative ground transportation systems. The air transport network is based on various size airports, each of which consists of runways, terminal buildings, control tower(s) and associated radar and lighting systems, fuel facilities, maintenance and hanger facilities, and parking structures. Runways are exposed to similar damage as highways and roadbeds, but are more difficult to repair because of the lower tolerance for imperfections to provide adequate safety during takeoff and landing (FAA, 2009). Terminal buildings, control towers, parking structures and other buildings are exposed to damage during most hazard events. Earthquake damage to ceilings and other non-structural components led to closure of the Santiago International Airport for five days after the February 27, 2010 earthquake (Resnicoff, 2010). Earthquake and tsunami damage caused by the March 11, 2011 earthquake in Japan resulted in closure of the Sendai Airport for over a month (Chock et al., 2013). Only limited military and relief aid flights were possible during this closure due to lack of power and damage to the terminal building. Loss of power to operate radar and lighting systems makes an airport virtually unusable until power is restored. Loss of a major airport hub can result in ripple effects of delayed and cancelled flights throughout the country as demonstrated by the closure of all three major airports in New York City during Hurricane Sandy (City of New York, 2013).

#### 6.1.1.4 Shipping Transportation Systems

Shipping transportation systems consist of ocean-going cargo and cruise vessels, barge traffic on inland and intracoastal waterways, and ferry transport on coastal or inland waterways. These systems rely on ports equipped with waterfront structures (e.g., wharves, piers, and seawalls), port control centers, cranes and bulk cargo handling equipment, fuel facilities, shipping container storage areas and warehouses.

The vast majority of import and export trade in the United States relies on ocean shipping, which is dependent on ports around the coastline. U.S. seaports are responsible for moving more than 99 % of the country's overseas cargo by volume and 65 % by value (AAPA, 2015). Closure of a single port due to a natural disaster can lead to major economic consequences for the immediate community around the port, as occurred in Kobe, Japan, after the 1995 earthquake. Ships can often use alternate ports, but this may still lead to delays and loss of perishable cargo.

A significant amount of internal cargo transport is performed by barges traveling on inland riverine and great lake waterways and the Gulf and Atlantic Intracoastal waterways. Shallow draft navigation (e.g., barges) serves 87 % of all major U.S. cities, and accounts for 79 % of all domestic waterborne freight. The U.S. Maritime Administration estimates that if inland waterways became unavailable for transport, truck traffic on rural highways would increase by approximately 33% (58 million truck trips annually) and rail transport, by tonnage, would increase by 25%. Increases of these magnitudes would put tremendous stress on land-based infrastructure (NIST, 2015). This system of natural and manmade waterways, canals and locks allows for cargo shipping throughout the Central and Eastern United States. There is a distinct lack of redundancy in this waterway network. Damage to a single lock or collapse of a bridge spanning one of these waterways can disrupt traffic for months. Because much of this cargo is transported in bulk form, requiring specialized equipment for rapid loading and unloading, it is often very difficult to use alternate port facilities to transfer the cargo to other forms of transportation.

Table 6-1 provides a rough comparison of the cargo capacities of the various forms of shipping and other transport systems. The standard measure is a 20-foot-long equivalent shipping container, or TEU. Clearly replacement of a single river barge with road transportation would require a considerable number of vehicles.

**Table 6-1 Cargo Shipping Equivalencies**

| Cargo Shipping Mode | Twenty-foot-long Equivalent Unit (TEU) |
|---|---|
| Ocean Container Ships | 1,500 – 12,000* |
| River Barge | 116** |
| 15-Barge Tow | 1740** |
| 100-Car Train | 870** |
| Highway Truck | 2 |

*World Shipping Council, 2016

**NIST, 2015

### *6.1.2 Multimodal Transportation*

Large metropolitan areas generally maintain extensive and complex transportation systems that often rely on multimodal transport of both people and goods. People often use multiple modes of transportation on a daily basis, particularly in large urban centers (NIST, 2015). For example, individuals may use a car, bus, taxi, or bicycle to get to and from subway or commuter train stations during their daily commute to and from work. Similarly, transport of cargo often involves multiple modes of transportation. Such multimodal transportation is dependent on all components of the network functioning correctly. Loss of a single transportation mode could delay or potentially terminate the trip.

At the same time, the presence of multiple modes of transport adds resilience by enabling modal replacement during and after a damaging event. Interruption to one mode of transport will lead to increased reliance on the other available modes, often straining or exceeding their capacity. For example, after the Loma Prieta earthquake in the San Francisco Bay area in 1989, closure of the Bay Bridge due to collapse of one deck span presented a major interruption to the normal flow of people and cargo across San Francisco Bay. Traffic that diverted to alternate routes to the North and South of San Francisco Bay experienced significant delays due to increased traffic on already busy thoroughfares. However, increased frequency of BART rail traffic and increased harbor ferry schedules helped to relieve some of this demand (SPUR, 2010). Understanding the interdependencies of the overall transportation system is crucial for effective planning to increase transportation resilience.

## 6.2 Summary of Codes, Standards, Guidelines, and Performance Requirements

Table 6-2 summarizes the design codes, structural standards and guidelines governing transportation systems in the United States. It does not include a number of guidelines that deal with the capacity and flow side of transportation design. Typically these design provisions focus on individual components rather than on the transportation system as a whole. Designs for earthquake and high wind hazards generally focus on low-probability/high-consequence events (ASCE, 2010), while designs for riverine flooding, coastal storm inundation, and storm wave loading often consider shorter return period events, typically 100 years (e.g., ASCE, 2014a).

## 6.3 Societal Considerations

Major failures of transportation structures are not anticipated under normal conditions, so the sudden collapse in 2007 of the I-35W bridge over the Mississippi River in Minneapolis was unexpected.

The loss of the I35W Mississippi Bridge in 2007, Minnesota's second busiest bridge carrying 140,000 vehicles daily, had significant consequences for the local traffic network. The Minnesota Department of Transportation estimated the economic impact to Minnesota's economy due to the loss of this important river crossing at about $17 million in 2007 and $43 million in 2008 (Minnesota DOT, 2008). These

**Table 6-2 U.S. Codes, Standards, and Guidelines Governing Transportation Systems**

| Category | Title | General Description |
|---|---|---|
| Standard | American Association of State Highway and Transportation Officials (AASHTO) *Load and Resistance Factor Design (LRFD) Bridge Design Specifications*, 7th Edition with 2015 Supplement (AASHTO, 2014) | Intended for use in the design, evaluation, and rehabilitation of highway bridges, and mandated by the Federal Highway Administration (FHWA) for use on all bridges using federal funding. |
| Standard | AASHTO *Guide Specifications for LRFD Seismic Bridge Design, 2nd Edition*, with 2012, 2014 and 2015 Interim Revisions (AASHTO, 2011) | Guidelines for use of displacement-based design procedures for design of typical non-critical and non-essential bridges. Approved as an alternative to the AASHTO LRFD Bridge Design Specifications. |
| Standard | AASHTO LRFD *Bridge Construction Specifications, 3rd Edition*, with 2010, 2011, 2012, 2014 and 2015 Interim Revisions (AASHTO, 2010) | A companion to the AASHTO LRFD Bridge Design Specifications with specifications for material testing and acceptance criteria, material references, and recommended guidelines for construction loads. |
| Code | American Railway Engineering and Maintenance of Way Association (AREMA) *2015 Manual for Railway Engineering* (AREMA, 2015a) | Contains principles, data, specifications, plans and economics information pertaining to the engineering, design and construction of the fixed plant of railways (except signals and communications), and allied services and facilities. |
| Code | AREMA *Communications and Signals Manual*, 2015 (AREMA, 2015b) | Contains recommended practices for railway communications and signaling. Required by the Federal Railroad Administration for all U.S. railroads. |
| Guidelines | *Advisory Circular (AC) 150/5300-13A - Airport Design* (FAA, 2012) | Contains Federal Aviation Administration (FAA) standards and recommendations for the geometric layout and engineering design of runways, taxiways, aprons, and other facilities at civil airports. |
| Standard | AC 150/5320-6, *Airport Pavement Design and Evaluation* (FAA, 2009) | FAA pavement standard provides guidance on the design and evaluation of pavements at civil airports. |
| Standard | AC 150/5370-10, *Standards for Specifying Construction of Airports* (FAA, 2014) | The standards contained in this document relate to materials and methods used for airport construction. Items covered include general provisions, earthwork, flexible base courses, rigid base courses, flexible surface courses, rigid pavement, fencing, drainage, turfing, and lighting installation. |
| Code | *Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS)* (CSLC, 2010) | This document was developed by the California State Lands Commission (CSLC) and is incorporated in the *California Building Code* (CBSC, 2013). The provisions apply to all existing and new marine oil terminals in California. |
| Guidelines | *Seismic Design Guidelines for Port Structures*, World Association for Waterborne Transport Infrastructure (PIANC, 2001) | International design guidelines for seismic design of port structures. Non-mandatory guidelines developed by The World Association for Waterborne Transport Infrastructure (PIANC). |
| Standard | American Society of Civil Engineers (ASCE) 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010) | ASCE Standard for loads and design procedures. Referenced by the *International Building Code* (ICC, 2012), and therefore in force wherever the *International Building Code* is adopted by local communities. |

**Table 6-2 U.S. Codes, Standards, and Guidelines Governing Transportation Systems (continued)**

| Category | Title | General Description |
|---|---|---|
| Standard | American Concrete Institute *ACI 318-11 Building Code Requirements for Structural Concrete, and Commentary* (ACI, 2011) | ACI building code for concrete structures. Referenced by the *International Building Code* (ICC, 2012) for design of all concrete structures. Includes comprehensive seismic design requirements. |
| Standard | American Institute of Steel Construction (AISC) *Steel Construction Manual, 14th Edition* (AISC, 2010a) and *Seismic Design Manual* (AISC, 2010b) | AISC manual for design of steel structures, with companion manual for seismic design of steel structures. Referenced by the *International Building Code* (ICC, 2012) for all steel construction. |
| Standard | ASCE 24-14, *Flood Resistant Design and Construction* (ASCE, 2014a) | ASCE Standard for design loading due to riverine flooding and coastal inundation due to storm surge and wave action. Does not address tsunami loading. |

estimates were developed by assigning monetary values to business auto travel time and heavy commercial truck travel time, as well as to variable operating costs for both. The daily loss of an estimated $247,000 through longer commutes for individuals represents a significant burden for members of the community who previously relied on the bridge. Construction of a replacement bridge was completed as quickly as feasible, but still took over a year, at a cost of $140 million (Minnesota DOT, 2008).

Effects on commuter behavior were surveyed and reported by Zhu et al. (2010). They found that immediately after the collapse, individual travel times for commuters who previously used the I-35W bridge increased 13 %, and 32 % of commuters adjusted their departure time to avoid anticipated congestion.

The bridge collapse also blocked river traffic along the Mississippi River and rail traffic on a line parallel to the river that passed under the bridge for about a month until the bridge could be demolished and removed. While rail traffic could be diverted to other lines, river traffic was halted by the collapse. Delays in barge traffic resulted in layoffs for workers at an aggregate supply company (Wyant, 2007).

Although not the result of a natural hazard, this collapse of a single bridge illustrates the significant effect on the transportation network and local economy. At the same time, the transportation agency response illustrated how design and operations strategies can adapt and overcome (at least to some extent) loss of function in transportation systems/networks.

Public expectations of the performance of transportation systems during natural hazard events are likely to be based in large part on observations of performance during past events. Given this basis for expectations, the high wind events would not be perceived to cause structural damage to transportation infrastructure, although loss of power could result in down time for rail systems and traffic control systems for highway traffic. Recovery after high wind events depends upon reinstatement of power and clearing of debris from rail lines and roadways.

Coastal inundation due to storm surge and wave action during tropical cyclones and other storms can cause localized damage to transportation systems. During routine and design coastal storms and hurricanes the level of damage to transportation infrastructure is generally limited to downed power poles and trees, and limited damage to roadways and rail lines. Typically the debris can be removed and damage repaired within days. However, after extreme coastal flooding events such as during Hurricane Katrina, failure of a number of coastal bridges, both road and rail, hampered transport of people and goods along the Gulf Coast in Louisiana, Mississippi and Alabama for many months (Robertson et al., 2007). The availability of alternate inland routes alleviated this disruption. During Hurricane Sandy, another coastal flooding event, people in New York City experienced significant commuter transportation disruption due primarily to flooding of road, rail and subway tunnels (NYS, 2013). Alternative bus and ferry transport was able to alleviate some of this congestion. It took one to several weeks for all tunnels to be pumped dry and reopened to rail and road traffic.

During past minor (routine) earthquakes, minimal structural damage has occurred to transportation networks. Localized bridge, road or rail failures have generally been repaired, at least temporarily, within days of the event. During design and extreme earthquakes, however, past performance has shown that bridge and port structures may be severely damaged (see Section 6.5). Public expectations of the performance of transportation infrastructure may, nevertheless, be somewhat optimistic, not understanding that current code approaches to seismic design anticipate a significant percentage (on the order of 5% to 10%) of code compliant structures will be severely damaged or destroyed during a design level or larger event (ASCE, 2010). The probability of collapse or severe damage for heritage structures that do not meet current codes and standards would likely be even higher. Recovery from these more damaging events can be expected to extend into the intermediate- to long-term phases of recovery. Structures that survive the event with less serious damage will still need to be closed during structural evaluations and implementation of any repairs required to reinstate their structural integrity, thereby reducing their functionality for some time after the event.

During tsunami events that cause only minor inundation, coastal transportation systems are expected to experience damage similar to that during hurricane storm surge, though scour and debris accumulation may be more severe (Robertson et al., 2010). Damage to commercial ports will also be limited, though recreational harbors may experience more severe effects (UH SeaGrant, 2013). During extreme tsunami events, public perception may anticipate that very little of the built environment will survive. In the case of transportation infrastructure, this is a fairly pessimistic view based on the relatively good performance of many transportation structures during the 2011 Tohoku, Japan tsunami (Chock et al., 2013). Based on field surveys performed after the earthquake and tsunami, a California Department of Transportation (Caltrans) team concluded that "most bridges suffered little or no damage from the tsunami that accompanied the Tohoku earthquake. This was despite bridges not being specifically designed for tsunami" (Yashinsky, 2011). However, it would be expected that coastal roads and railways will be interrupted by failure of individual components, and ports and harbors will sustain considerable debris damage due to shipping container and boats carried by water flow (Chock et al., 2013).

Subsequent to damaging natural hazard events, affected communities commonly focus on lessons learned and developing plans for improved resilience for similar future events. After the 1989 Loma Prieta earthquake, the State of California made considerable efforts to remove, replace or retrofit older critical bridges that were seismically vulnerable. This effort included removal of the elevated Embarcadero Freeway in San Francisco because of the collapse of the similar vintage Cypress Street Viaduct in Oakland. Many critical bridges were retrofitted to improve seismic performance, most notably the Golden Gate Bridge and the western span of the Bay Bridge. Other critical bridges were replaced with modern seismically designed structures, such as the new eastern span of the Bay Bridge and the South Approach Viaduct to the Golden Gate Bridge, both of which were opened in 2015. Although it took over 25 years to complete these and many other seismic upgrades, it is anticipated that the transportation system in the San Francisco Bay Area will perform significantly better during future earthquakes. Similarly, New York City and surrounding communities have learned from Hurricane Sandy. Considerable effort has been focused on improving resilience to future inundation events, for example by undertaking measures to prevent flooding of subway, road and rail tunnels (City of New York, 2013b; NYS, 2013).

These community-based efforts have led to a number of recommendations to improve resilience of infrastructure systems, including a transportation study for San Francisco (SPUR, 2010) and several studies of facilities in New York City following Hurricane Sandy (City of New York, 2013b; NYS, 2013). These recommendations generally include a comprehensive community-based risk assessment, strengthening of existing critical transportation networks, increasing system redundancies, and implementation of enhanced guidelines, standards, policies, and procedures to build more resilient facilities.

## 6.4 Interdependencies

All transportation systems rely on other components of the civil infrastructure for their operation. Power and communication systems are required for operation of electric trains, rail and roadway signals, airport control systems, harbor cranes, and other transportation-related electrical equipment. Until power and telecommunication services are restored to an area, transportation systems will have limited functionality.

Fuel supply is also essential for operation of airplanes, ships and most vehicles. Damage to refineries, fuel storage tanks, pump stations, and transmission pipelines will limit the fuel supply, and damage to road and rail networks will hamper alternate fuel deliveries. As highlighted in Section 4.5, Hurricanes Katrina and Sandy demonstrated the vulnerability of the fuel production and distribution systems and the consequences for recovery of the transportation system.

A port has limited function if there is no road or rail connection leading inland from the port. The same applies to airports. Damage to rail or road network connections to airports or harbors could result in significant downtime following an extreme earthquake or tsunami, with repair and recovery time on the order of months. Pipelines are also a critical link for bulk cargo transportation between harbors and storage facilities or supply networks (see Chapter 4). At the same time, these systems are often complementary, making the overall transportation infrastructure more resilient. For example, loss of rail service can be augmented by truck and barge transport, while loss of air traffic to a particular location can be replaced by surface transport. Damage to a single port can generally be offset by redirecting traffic to adjacent ports. Damage to a bulk material pipeline can be replaced by road or rail transport. These substitutions will seldom be as efficient as the original system, and may become overwhelmed if the alternate means of transport themselves suffer damage or were initially near maximum capacity and do not have the ability to accommodate the increased traffic.

If local rail or road networks are already near capacity, then dealing with emergencies that limit the available network is particularly difficult. For example, road networks that are already near capacity with frequent extended traffic jams will become inoperable with the loss of only a few bridges or roadways. Alternative routes or modes of transportation should be available to bypass anticipated failures in the existing transportation networks. For example, after the 1989 Loma Prieta earthquake, BART and harbor ferries were able to increase service during the closures of the Bay Bridge and San Mateo Bridge (SPUR, 2010).

The ability of a local transportation network to function effectively after damage to some of its components will depend on the level of redundancy in the network. Shiraki et al. (2007) studied the effect of 47 scenario earthquakes on the state highway and freeway network in Los Angeles and Orange Counties, which they note is highly redundant. They observed that for all but the largest scenario events, the average effect on travel times due to bridge damage is less than five minutes per passenger car unit in the Greater Los Angeles area. This average suppresses the large variation in travel times for individual vehicles on different routes, but confirms that transportation system redundancy is a critical component of community resilience.

In contrast, after the Maule earthquake in Chile in 2010 the lack of alternate transportation corridors to bypass the earthquake damage to bridges along North-South Highway 5 resulted in delays in the flow of goods and people. Road connectivity was reestablished using Bailey bridges and alternate routes, where available (Dueñas-Osorio and Kwasinski, 2012).

## 6.5 Disaster Lessons

All transportation systems are susceptible to damage or disruption during natural hazard events. Earthquakes can damage almost all components of transportation systems except boats and ships that are either at sea or docked in a port (that is not impacted by a tsunami), airplanes in flight or on an open taxiway, and trucks and cars on grade level roadways. Tsunamis and coastal storm surge with associated wave action can damage or destroy bridges, coastal roadways, port facilities including ships and boats, and coastal airports. Potentially the least threatening hazards for transportation systems are high-wind hazard events, such as hurricanes and tornados. In these events, damage is likely to be limited to transportation-associated buildings, fuel facilities and electrical power supply for railroads, though some historical failures of bridges have resulted from wind loading.

### *6.5.1 Performance during Past Earthquakes*

The occurrence of a design or extreme earthquake near a major city may be a rare event but its societal and economic impacts can be so devastating that it is a matter of national interest. Recent examples of earthquake disasters, and associated fatalities and damage and loss estimates, include: Northridge, California in 1994 (60 fatalities and $40 billion in losses); Kobe, Japan, in 1995 (over 5,500 fatalities and $100 billion in losses); Kocaeli, Turkey, in 1999 (over 17,000 fatalities and $20 billion in losses); Taiwan in 1999 (over 2,300 fatalities and $14 billion in losses); Gujarat, India in 2001 (over 20,000 fatalities); Southeastern Iran in 2003 (over 31,000 fatalities and $32 billion in losses); Pakistan in 2005 (over 86,000 fatalities and $5 billion in losses); Sichuan, China, in 2008 (over 87,000 fatalities and more than $86 billion in losses); Haiti in 2010 (over 300,000 fatalities and $8 billion in losses); Christchurch, New Zealand, in 2011 (181 fatalities and more than $15 billion in losses); and Nepal in 2015 (over 9,000 fatalities and approximately $5 billion in losses) (Earthquake Report, 2014).

The 1971 San Fernando earthquake in California provided numerous lessons for structural and geotechnical engineers regarding the performance of bridge and roadway structures when subjected to severe ground shaking. It led to significant improvement of new design codes for almost all components of the transportation infrastructure. The impacts of that earthquake also led to the initiation of a state-wide seismic retrofit program by Caltrans that focused on the improvement of bridge expansion joints (Penzien et al., 2003).

Following the 1989 Loma Prieta earthquake, which caused bridge failures on major routes in the San Francisco Bay area, Caltrans expanded their seismic retrofit program to address other seismic deficiencies revealed during that earthquake. The Caltrans *Bridge Design Specification Manual* (Caltrans, 1986) was also revised and improved, based on new knowledge and lessons learned (ATC, 1996). The collapse of the elevated Cypress Viaduct section of Interstate 880 in Oakland and closure of the Bay Bridge led to significant delays due to increased traffic on alternate thoroughfares (Penzien et al., 2003).

During the Northridge earthquake in 1994, only nine bridges suffered major damage or collapse, out of an estimated 1,600 bridges that experienced ground shaking exceeding 0.25g (Mitchell et al., 1995). Much of this improved performance was attributed to past seismic retrofits. As noted by Cooper et al. (2015), "These failures did, however, create severe hardships for the traveling public, involving as it did some of the busiest freeways in the world, including the Santa Monica Freeway (Interstate Highway 10) and the Antelope Valley Freeway (state Route 14)-Golden State Freeway (I-5) interchange" in the Los Angeles area.

Railway bridges are also susceptible to collapse as occurred during the 1995 Kobe earthquake. The Shinkansen (Bullet Train) service on the Hankyu line was disrupted for six months. Alternate service via a major detour resulted in a two-hour trip from Osaka to Kobe compared with the half hour trip by Shinkansen (Endstation, 1998). Highways and rail lines adjacent to steep slopes or passing through canyons are also susceptible to damage or blockage due to rock falls or landslides triggered by the earthquake.

Earthquake damage to airports is typically associated with structural and nonstructural damage to the terminal and hanger buildings. However, runways can also suffer from liquefaction and shaking induced settlement of subgrade soils, which can be difficult to repair in order for planes to use the runways safely. During the Loma Prieta earthquake, approximately 900 meters of the western end of Runway 11-29 of the Metropolitan Oakland International Airport (MOIA) was damaged due to liquefaction (Grogan and Vallerga, 2000). Fortunately the North runway was undamaged so air traffic could still be accommodated while repairs, which took two months, were made to the damaged runway. However, air-cargo carriers were required to reduce their loads because of the limited take-off distance (Grogan and Vallerga, 2000).

Seaports are also susceptible to damage due to ground shaking, often related to liquefaction of loose granular fill behind wharves and under slab-on-grade aprons. Cargo cranes have sustained damage during past earthquakes either due to liquefaction induced distortion of the track supports, or structural damage to the crane itself. The Port of Kobe was essentially shut down due to severe damage caused by the 1995 Great Hanshin earthquake, requiring two years of repairs before the port was again fully operational. Prior to the disaster, Kobe ranked sixth among container ports worldwide. This ranking dropped to 17th by 1997 due primarily to diversion of foreign transshipment cargo to competing Asian ports (Chang, 2000).

Harbor entry channels and riverine waterways that require dredging to maintain sufficient draft in the channel may be impacted by landslides or slips that reduce the draft and prevent vessels from entering or leaving the port, or using the waterway. Locks and associated mechanical systems may suffer damage during earthquakes that make them inoperable, resulting in closure of inland waterways. The riverine waterways and the Gulf and Atlantic intracoastal waterways are at risk of blockage due to collapse of bridges crossing these waterways. Water traffic would only be able to resume once the resulting debris has been cleared from the shipping channel (Wyant, 2007).

### *6.5.2 Performance during Past Tsunamis*

Recent damaging tsunamis have highlighted the exposure of coastal communities around the world to high velocity inundation associated with tsunamis. In particular, the Indian Ocean tsunami caused by a 9.1-magnitude earthquake off the West Coast of Northern Sumatra in 2004 resulted in over 225,000 deaths in countries bordering the Indian Ocean (IOC, 2013). This was a wake-up call that led to development of tsunami warning systems throughout the Pacific and Indian oceans, as well as the Caribbean and other tsunami-prone coastlines. Subsequent damaging tsunamis affecting Samoa in 2009 (192 fatalities), Chile in 2010 (156 fatalities), and Tohoku Japan in 2011 (over 18,700 fatalities and approximately $235 billion in losses) (IOC, 2013; Economist, 2011) reinforced the need for improved tsunami preparedness both in terms of warning systems and evacuation planning, but also in the form of enhanced resilience of coastal communities. While Chile has largely recovered from the 2010 tsunami, much of the damage in Samoa has not been repaired, and many communities in Japan are still struggling to recover from the devastating effects of the Tohoku tsunami four years afterwards.

During the 2011 Tohoku tsunami, numerous road and rail bridges were damaged or destroyed by the high velocity flow, while others survived structurally with damage only to non-structural components. Damage to airport and port buildings in the inundation zone was also extensive, though piers and wharfs performed surprisingly well, probably as a result of their design for large live loads, including ship impact during berthing, and earthquake lateral loading. Pore pressure softening of soil due to inundation followed by rapid drawdown of water resulted in extensive scour and sediment transport around port structures, below concrete aprons and behind wharves (Chock et al., 2013).

### *6.5.3 Performance during Past High Wind Events*

Transportation infrastructure is generally immune to damage during high wind events. However, there are some notable exceptions. In 1879, the Tay Bridge in Scotland collapsed during a winter storm with wind gusts estimated at 80 miles per hour (mph), partly attributed to underestimation during the design of design wind pressures. In 1940, the first Tacoma Narrows Bridge collapsed as a result of vortex shedding vibrations induced by a steady 40 mph wind. Subsequent bridge designs benefitted from these and similar lessons, and current bridge design requirements include adequate consideration of wind loading effects to avoid similar failures in the future.

Other components of transportation systems are more susceptible to wind induced damage, such as power lines over electric rail lines, traffic lights at road intersections, airport and port buildings, particularly large volume warehouses and hangers. High wind damage to power distribution systems can cut power to transportation systems, degrading their functionality.

### *6.5.4 Recovery and Reconstruction*

The rate of recovery and reconstruction in Japan after the 2011 Tohoku earthquake and tsunami may provide a good indication of how an industrialized nation with good preparation for earthquake and tsunami disasters might respond after a design level or greater event. These observations can be applied to similar coastal communities in the five western U.S. states of Alaska, Washington, Oregon, California, and Hawaii, which all have seismic design requirements and an appreciable tsunami threat. They can also be compared to water inundation impacts resulting from hurricanes and major flooding in the United States and elsewhere. It must be noted that seismic design in Japan is somewhat more conservative than that applied in the United States, with less reliance on post-yielding ductility in the Japan designs.

#### 6.5.4.1 Re-Opening of Roadways

Immediately after the 2011 Tohoku tsunami, emergency responders in Japan found it difficult to access the damaged areas because of debris on the roadways. Tunnels and subway systems can become flooded during coastal inundation due to either tsunamis or storm surge and wave action. Flooding during Hurricane Sandy resulted in considerable disruption to the heavily used transportation network in New York City, resulting in significant economic losses (City of New York, 2013b). Debris obstructions on road and rail systems also occur during earthquakes and high wind events.

Priority is normally given to clearing debris from major and then secondary roadways throughout the hazard zone. In Japan, this process took from days to weeks, depending on the size of the affected community, but was predominantly complete within the first month after the tsunami (Chock et al., 2013). After Hurricane Sandy, it took two weeks for the transportation system in New York to recover to pre-event capacity and travel times (City of New York, 2013b).

#### 6.5.4.2 Reconstruction of Highway Bridges

The road network is critical for accessing damaged areas for emergency response and recovery after a tsunami. Rapid repair of critical bridges is an essential component of recovery efforts. At numerous locations in Japan where critical bridges failed, temporary bridge structures were installed within the first month after the tsunami (see Figures 6-1 and 6-2). Although generally only providing one lane of traffic, these temporary structures were able to re-connect critical coastal highways, allowing for the resumption of road transportation in and out of the coastal region. These temporary bridge options work for shorter span bridges, but are not always possible when multiple spans of a longer bridge have failed. More permanent structures were constructed at longer bridge crossings of the Kitakami River and a river mouth in Rikuzenkoizumi (see Figure 6-3). This construction takes significantly longer than the temporary bridges, but they provide the same traffic lanes as the original bridge, and will provide many years of service until permanent replacement bridges can be constructed.

Figure 6-1 Temporary bridge restoring coastal highway in Minamisanriku, Japan (N 38.673519, E 141.443135) (left) (one month after March 11, 2011 tsunami); and more substantial replacement bridge built 4 months later (right). (Photos courtesy of Ian Robertson).

Figure 6-2 Temporary bridge restoring coastal highway in Rikuzentakata, Japan (N 39.009206, E 141.630195) (left) (one month after March 11, 2011 tsunami), and bridge repaired within one year (right). (Photos courtesy of Ian Robertson).

Figure 6-3 Temporary steel girder bridge over river in Koizumi, Japan (N: 38.67933, E: 141.50787), just North of Utatsu, Japan, completed 107 days after the March 11, 2011 tsunami. (Photos courtesy of Ian Robertson).

#### 6.5.4.3 Reconstruction of Railway Systems

Railway lines are most commonly used for commuter rail and freight trains. Railway lines located on grade or on embankments generally consist of tracks supported by sleepers resting in a gravel bed. The tracks are rigidly connected to the sleepers to maintain the correct gage, but the sleepers are not fixed to the ground, except possibly at level crossings. Earthquake shaking can distort the alignment, and if the rails are inundated by fast moving water during storm surge or a tsunami, the rails and sleepers are often washed away with the gravel bed. Rail lines may also become covered with debris making them impassable immediately after the event. This debris is relatively easy to clear, and new tracks can be laid within days, if necessary.

In Japan, because of extensive damage to the coastal Japan Rail (JR) rail line during the 2011 tsunami, freight traffic was diverted to inland rail lines and highway truck transport once these systems were inspected for earthquake damage. Railway bus routes were established to provide temporary commuter transport along some portions of the impacted coast. Many of the coastal rail lines may not be restored because of the extensive damage to bridges and embankments (Chock et al., 2013). In some locations in Japan, the idea of a coastal railway has been abandoned and replaced by Bus Rapid Transit (BRT) systems located in the previous rail alignment. After Hurricane Sandy, New York City implemented emergency bus transport to bypass flooded subway tunnels (City of New York, 2013b). Recommendations were also made to add or enhance bus rapid transit systems to improve resilience after future hazard events.

Damage to components of the railway network may prevent rapid restoration of rail service. As with road bridges, railway bridges are susceptible to damage or collapse during strong ground shaking. Railway tunnels may also be damaged during earthquakes, but are unlikely to be damaged during a tsunami or high wind event. Soil embankments can suffer geotechnical failures during an earthquake or can be eroded by the high velocity flow during a tsunami, leading to a loss of the rail line even though the tunnels and bridges remain structurally intact. If the deck of a railway bridge is elevated above the flow depth during storm surge or a tsunami, it will likely survive without damage. However, when the flow depth exceeds the level of the bridge deck, severe damage to the bridge superstructure can occur, as observed during Hurricane Katrina (Robertson et al., 2007) and the Tohoku tsunami (Chock et al., 2013).

Reconstruction of railway systems is more difficult than highway systems. Replacing track that has been disturbed by ground shaking or water inundation is relatively easy, as is clearing debris from tracks and tunnels. However, most bridge failures have to be replaced with new structures since temporary structures are not commonly available to support heavy train loads. This reconstruction can take from months to years.

#### 6.5.4.4 Reconstruction of Harbor and Port Facilities

Commercial ports are essential for both national and international trade, while fishing ports and yacht marinas support important industries for many coastal communities. Most port facilities are, by necessity, constructed at or near sea level. During earthquakes, soil failures due to liquefaction and lateral spreading can damage pavements, piers, and wharves. Cargo handling cranes can suffer damage or jump from their tracks.

During storm surge or tsunami inundation, ships, barges and other floating vessels that were not able to evacuate from the harbor may break free from their moorings and potentially cause substantial damage to the port infrastructure. Shipping containers will also float and become fast moving debris that can damage nearby structures. Fuel storage tanks adjacent to ports may float if they are not full, and are easily ruptured by impacts with other structures or floating debris, resulting in fuel spills and increased potential for fires.

Incoming tsunami and storm surge flows can also cause large uplift pressures below wharfs and piers. During the Tohoku tsunami, this uplift caused damage to the panels that connect the pile-supported wharf and the adjacent grade-supported apron. Once these panels failed, the uplift pressure on the adjacent pile supported wharf was reduced, possibly protecting the wharf from further damage.

Scour around structures and under slab-on-grade aprons can also be significant during inundation events. If this scour results in structural collapse then repair could take considerable time. However, if the scour only results in soil removal around structural elements, it can generally be repaired relatively quickly.

Before shipping operations can resume at a damaged port, it is important to survey the harbor basin and access channels for submarine slope failures, sunken ships, containers and other debris that may impede harbor traffic. Unmanned Autonomous Vehicles (UAVs) can be used for this purpose, as well as sonar scans from small boats. Damaged piers and wharfs may take some time to repair, while damaged cranes can be replaced at least temporarily using mobile cranes or cargo handling equipment.

## 6.6 Gaps and Deficits: Codes, Standards, Performance Requirements, and Societal Considerations

There is a lack of information on societal expectations of transportation system performance during routine, design and extreme events and the anticipated time for recovery of their function after the event. More research is needed to fill this gap in knowledge. The NIST *Guide* (NIST, 2015) provides a methodology for individual communities to develop short- and long-term plans to enhance their resilience to future disasters. This process includes the development of a community-based expectation of damage levels and recovery times for various components of the built environment, including transportation systems. This will also require input from transportation system operators and owners to develop an informed assessment of expected damage and recovery. The outcomes of early application of such a methodology would be helpful as indicators of typical community perception of the likely performance of the built environment, and their anticipation of the recovery time required to restore systems to their pre-disaster functionality. It is anticipated that public perceptions will vary, based on the location and size of the community, but these data are not yet available.

Until more reliable data are available relating to societal perceptions of transportation infrastructure performance and recovery times, the opinions of experts in the fields of transportation infrastructure engineering and disaster recovery planning provide an initial estimate of the gaps between societal expectations and engineering reality. Table 6-3 has been populated using expert opinions from two studies of infrastructure fragility and recovery estimates. The first of these studies assembled a group of transportation experts from Caltrans, academia and other organizations to estimate both the extent of damage and recovery time for transportation infrastructure during the November 13, 2008 ShakeOut Scenario developed for Los Angeles and neighboring communities (Jones et al., 2008). The second set of expert opinions was generated by tsunami researchers during the development of a Tsunami Module for the federally-funded and publicly-available disaster scenario loss estimation software, HAZUS-MH (FEMA, 2012). Because these studies each had a particular purpose and geographical focus in mind, their findings do not necessarily translate directly to estimates of damage and down time for future events. Nevertheless, they have been

**Table 6-3 Expert Opinion on Public Expectations of Transportation System Recovery Times after an Extreme Event, Compared with Engineering Estimates of Recovery Time**

| Transportation System Component | Short-term (days) | | | Intermediate (weeks) | | | Long-term (months) | | |
|---|---|---|---|---|---|---|---|---|---|
| | *1* | *2-4* | *5-7* | *1-4* | *4-8* | *8-12* | *3-6* | *6-24* | *24+* |
| **Extreme Wind Event**** | | | | | | | | | |
| Highways* | Public Expectation | Engineering Estimate | | | | | | | |
| Railways* | Public Expectation | Engineering Estimate | | | | | | | |
| Commercial Airports | Public Expectation | | Engineering Estimate | | | | | | |
| Commercial Ports | | Public Expectation | Engineering Estimate | | | | | | |
| **Extreme Earthquake Event***** | | | | | | | | | |
| Highways* | | | | | Public Expectation | | Engineering Estimate | | |
| Railways* | | | | | Public Expectation | Engineering Estimate | | | |
| Commercial Airports | | | | Public Expectation | Engineering Estimate | | | | |
| Commercial Ports | | | | Public Expectation | | | Engineering Estimate | | |
| **Extreme Tsunami Event****** | | | | | | | | | |
| Highways* | | | | | | | Engineering Estimate | Public Expectation | |
| Railways* | | | | | | | Public Expectation | Engineering Estimate | |
| Commercial Airports | | | | | Engineering Estimate | Public Expectation | | | |
| Commercial Ports | | | | | | | Engineering Estimate | Public Expectation | |

Public Expectation (light blue) Engineering Estimate (dark blue)

* Including bridges and tunnels

** Wind estimates are those of the authors of this report.

*** Earthquake estimates based on Jones et al. (2008).

**** Tsunami estimates based on FEMA (2012).

used here to provide a rough estimate of recovery time for a typical urban transportation system after an extreme hazard event. More detailed information is provided in Section C.2 and Table C-1 in Appendix C.

The estimates in Table 6-3 are offered as a starting point to assess societal expectations of transportation system performance. They are based on years of post-disaster observation and engineering judgment. No surveys or systematic research data were available to inform these estimates.

Additional research is required to establish a more comprehensive understanding of societal expectations of the performance of transportation infrastructure systems during future routine, design and extreme hazard events, and also to assess their expectations of the associated recovery times. Targeted scenario studies and public education can then be used to raise awareness of the likely consequences of various level hazards, and close the gaps between societal expectations and likely infrastructure performance and recovery times.

## 6.7 Conclusions and Recommendations

### *6.7.1 Review of Key Points*

Resilient transportation networks are an essential component to ensure rapid recovery of communities affected by natural hazards. Following a disaster, transportation networks provide the means to import resources, equipment and labor to assist in recovery efforts. They also facilitate the movement of people and goods within the affected community and to and from neighboring communities unaffected by the disaster. Resilience of transportation systems can be enhanced by various strategies, such as improved design of components of existing transportation systems through mitigation and retrofit projects, improving performance based design of future components, expanding design considerations to the entire system, and increasing both single-mode and multimodal redundancy.

Community-based planning is required to identify critical components of local transportation networks. These planning efforts must be performed in collaboration with the respective transportation system owners and operators, and take into account all redundancies and potential alternate modes of transportation. Critical components identified through this process should be designed to meet community goals to minimize the possibility of loss of function after an extreme event.

### *6.7.2 Lifeline Standards Development Needs*

Following is the study team's key recommendation:

- **Expand design standards and procedures for transportation systems to consider the performance of the entire transportation network in addition to**

**individual components of the network.** Current design standards relating to transportation systems focus almost exclusively on the individual components that make up each system. Although these design standards provide high reliability of good performance during routine and design natural hazard events, system performance needs to be addressed. There is a lack of guidance on planning and designing an entire transportation network to maintain its function of transporting people and goods immediately after a natural hazard event.

### *6.7.3 Research Needs*

The following key study is recommended:

- **Conduct focused research to determine societal considerations and expectations pertaining to the performance of transportation infrastructure during future routine, design and extreme hazard events**. Relatively little is known about public perception of transportation system resilience and recovery expectations. Apart from some localized community planning efforts, little research has been performed to determine societal expectations of the transportation infrastructure performance during future hazard events. Accurately quantifying the gaps that occur between societal expectations and engineering reality will help to improve public education and planning for recovery and reconstruction after future hazard events. Better understanding of these gaps will help the community prioritize mitigation and retrofit projects, and also encourage them to identify alternative solutions that can satisfy the community's transportation needs immediately after a disaster.

### *6.7.4 Lifeline System Operational Needs*

The following key transportation network operational activity is recommended:

- **Enhance network resilience through improved maintenance of the existing transportation infrastructure**. Aging of the transportation infrastructure presents states and local communities with significant challenges, both with respect to regular maintenance of existing infrastructure, as well as the need to enhance resilience for future hazard events. Difficult decisions will need to be made to prioritize and fund these efforts so that the transportation system can continue to serve its intended function.

### *6.7.5 Future Considerations and Trends*

Climate change over the coming decades is likely to place greater demands on coastal transportation infrastructure. Global warming with the associated sea level rise, and increased tropical storm frequency and intensity will adversely affect coastal transportation systems including ports, harbors, coastal bridges, highways, rail lines, and airports.

Future trends in distributed power generation and alternate fuel development may increase transportation system resilience. Increased use of alternative fuel transportation systems and the likelihood of driverless vehicles in the near future may alter road transportation significantly. The potential for dispersed power generation for charging electric vehicles or producing hydrogen for fuel cell engines could improve resilience when power and fuel distribution systems are interrupted.

# Chapter 7

# Water and Wastewater

## 7.1 Systems Overview

The water systems described in this document provide domestic and industrial potable water service. The wastewater systems described provide sanitary and storm water sewer collection services. Where referenced, service connections for storm water drainage systems are essentially catch basins and other locations where storm water can enter the collection system. In the context of lifeline engineering, conventional treatment of storm water does not include all the facilities needed to protect communities against floods and inundation. However, flood control systems may be affected by storm water management. Water, wastewater, and storm water systems range from relatively small simple local networks to large complex geographically distributed networks. This section summarizes the main points related to societal expectations of acceptable system performance levels and restoration timeframes. Appendix D—Supplement to Water and Wastewater Analysis—provides additional supporting documentation referenced in this chapter.

### *7.1.1 Water Systems*

The main purpose of establishing and maintaining a water system is to ensure a safe and reliable water supply. Water systems generally serve the following functions (Davis and Giovinazzi, 2015):

1. Providing potable water supply for domestic, commercial, and industrial uses, including critical services (e.g., firefighting), emergency operations and evacuation centers, and for other lifeline systems; and
2. Providing potable or non-potable water supply for cleaning, flushing, cooling, firefighting, irrigation, recreation, and environmental quality.

This document addresses potable systems providing the above services. Water systems consist of several subsystems, including raw water supply, treatment, transmission, and distribution systems as described in Table 7-1. The division between the subsystems shown in Table 7-1 is not always clear. However, in general more advanced water systems have more distinct subsystems. System division into subsystems helps in the understanding and definition of the functions of planning, design, and operations. A hierarchical view of the subsystem structure allows for an assessment of major functions, their relative importance, and operational procedures, as well as overall water system serviceability and resiliency. Table 7-1 also identifies

**Table 7-1 Major Potable Water Subsystems (Modified from Davis and O'Rourke, 2011; Davis and Giovinazzi, 2015)**

| 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. | Reservoirs, pump stations, wells, bar screens, head works, intakes, pipelines, canals, 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, ultra violet processes, chlorination stations, chloramination stations, and other chemical stations (e.g., fluoridation, hypo-chlorination, chloramine). |
| 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. 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, tanks and reservoirs, valves, and piping that are not defined as part of another system and form a network from connections at the transmission systems to points of service. Includes service laterals, hydrant laterals and fire hydrants, and meters. |

Notes:

(1) Pump stations and treatment systems have their own site-specific subsystems made up of mechanical, electrical, and civil engineered subsystems and components.

(2) Supervisory Control and Data Acquisition systems are used to monitor and operate water systems.

(3) 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 a water system and each subsystem.

typical facilities or components comprising the different subsystems. The structuring described here allows for many types of water systems with many different attributes to be addressed within a common framework.

### *7.1.2 Wastewater Systems*

The main purpose of establishing and maintaining a wastewater system is to ensure reliable removal of fluid waste to promote public health and safety. Wastewater systems generally involve the removal of both sanitary waste and storm water and serve the following functions:

1. Removing wastewater from domestic, commercial, and industrial buildings and facilities.
2. Providing alternative reclaimed water supply sources for cleaning, flushing, cooling, firefighting, irrigation, recreation, environmental quality, direct potable reuse, groundwater recharge, and other uses.
3. Providing surface or subsurface water drainage to protect people and infrastructure against flooding from storms and prevent water from ponding and causing public health problems. These functions include separate storm water drainage systems or combined storm and sanitation wastewater systems.
4. Storm water capture for drainage systems (separate from or preceding its combination with sanitary sewer systems). This operation is also sometimes called rainwater harvesting.

Wastewater systems consist of several subsystems, including collection, conveyance, treatment, and disposal systems as described in Table 7-2. The division between the subsystems shown in Table 7-2 is not always clear. However, in general more advanced wastewater systems have more distinct subsystems. As in the case of water systems (above), the division of wastewater systems into subsystems helps to define planning, design, and operational functions, their relative importance, and contributions to system serviceability and resiliency. Table 7-2 also identifies typical facilities and components comprising the different subsystems. The structuring allows for many types of wastewater systems, having many different attributes, to be addressed within a common framework.

### *7.1.3 Storm Water and Flood Control Systems*

Drainage for beneficial land use and the management of storm water are important functions of water and wastewater management and an integral part of local and regional flood control systems. The collection, diversion, storage, and release of storm and drainage water involves a wide range of options. Under extreme conditions, storm water control may require substantial pumping capacity, as exemplified by the largest pump station in the world in New Orleans that is capable

Table 7-2 **Major Wastewater Subsystems (Davis, 2014b)**

| Subsystems | Description | Typical Facilities/Components |
|---|---|---|
| Collection Systems | 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 laterals.<br>Specific storm drainage facilities: laterals, drains, catch basins, channels, curb and gutter, streets. |
| Conveyance Systems | Systems for conveying raw sewage or storm water. Raw water conveyance systems, sometimes referred to as trunk systems, convey sewage and storm water 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.<br>Specific storm drainage facilities: catch basins, drains, culverts, channels, curb and gutter, streets. |
| Treatment Systems | Systems for treating and disinfecting sewage and storm water to make it safe for disposal or for recycling/ reclaiming water for alternate safe use by customers as part of a water system. | Treatment plants, screens, grit chambers, sedimentation basins and tanks, bio-treatment, clarifiers, filtration systems, galleries, ponds and lagoons, levees, chlorine or other chemical disinfectant facilities, chlorination stations, pump stations not related to conveyance and discharge systems, digesters, solids processing, centrifuge. |
| Discharge/ Disposal Systems | Systems for discharging or disposing of treated sewage and storm water 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 storm water. | Outfalls (ocean, sea, lake), river and creek outlets, levees, diffusers, gates and valves, flaps, disposal pumping stations, weirs, channels, recharge basins (for reuse), and septic systems.<br>Transmission lines to customers or storage locations that provide an interface with water systems where recycled water is used from wastewater treatment plants and storm water collection sources). |

Notes:

(1) Pump stations and treatment systems have their own site-specific subsystems made up of mechanical, electrical, and civil engineered subsystems and components.

(2) Supervisory Control and Data Acquisition systems are used to monitor and operate wastewater systems.

(3) Buildings and facilities, including central headquarters, operation and maintenance yards, pump station housings, treatment and disinfection system housings are also a part of a wastewater system and each subsystem.

of pumping 150,000 gallons/sec. (Reid, 2013). Wastewater management may also involve modifications in traditional land use to reduce the impact of new construction on natural hydrologic features (e.g., Williams and Wise, 2009).

Davis (2014b) refers to inundation protection systems as the combination of storm water and drainage operations with regional flood management systems. Land use expansion into flood-vulnerable areas is often coupled with the construction of flood control systems that provide barriers to inundation, and collect, divert, store or detain water and debris. Although flood control systems are not regarded as part of water, wastewater, and storm water systems, the two are often closely linked.

The increasing threats from climate change may be addressed by the development and improvement of flood protection systems, including a better understanding of the role provided by water, wastewater, and storm water management in preventing or reducing inundation. This role is frequently overlooked and thus represents an opportunity for broader, more integrative planning to promote community resilience.

## 7.2 Summary of Codes, Standards, Guidelines, and Performance Requirements

This section first reviews existing performance requirements for water and wastewater systems and methods for evaluating system performance levels. This is followed by discussion of recent efforts to define system performance requirements.

### *7.2.1 Existing Standards and Performance Objectives*

Appendix D, Section D.1 tabulates and summarizes 59 documents reviewed for this project. They include one code, 15 standards, 19 guidelines, and 24 manuals. Table 7-3 summarizes water and wastewater system design performance requirements for hazard events drawing on the more detailed information provided in Appendix D. While the analysis focused on water and wastewater systems, many of these documents also apply to flood control systems.

There is a wide range of existing performance requirements for various hazards related to water and wastewater systems. Table 7-3 includes, where information is available, many different components of water and wastewater systems listed in Tables 7-1 and 7-2. Table 7-3 summarizes the performance levels for different types of facilities or subsystems. Specialized structures including dams, levees, and tunnels, are also included in Table 7-3.

As Table 7-3 shows, existing performance objectives are focused on life safety, public health, and fire protection. Life safety is addressed for buildings and structures, tanks and reservoirs, dams, tunnels, and mechanical and electrical equipment. Public health is addressed for the overall water and wastewater systems. Fire protection is addressed for water systems.

Table 7-3 Summary of Design Performance Requirements for Hazard Events

| Component(s) or Subsystem | Performance Level | Jurisdictional Authority | Existing Codes and Standards (Yes or No) | Guidelines and Manuals (Yes or No) | Hazards Associated with Performance Criteria |
|---|---|---|---|---|---|
| Buildings and Other Structures | Life Safety | Building Code/Building authority | Yes | Yes, many but not presented herein. | IBC, American Society of Civil Engineers (ASCE) 7: flood, wind, snow, rain, ice, and seismic. |
| Tanks and Reservoirs | Life Safety | Building code and other standards | Yes | Yes, many but not presented herein. | ASCE 7: flood, wind, snow, rain, ice, and seismic. |
| Water Retaining Dams | Life Safety | State Dam Safety organizations and Federal Energy Regulatory Commission (FERC) | Yes, but mostly state of practice. | Yes, many but not presented herein. | Flood, earthquake, and others, as needed to ensure life safety. |
| Levees | None identified | None identified, possible local authorities in some areas | None identified | Yes, mostly flood & earthquake but not presented herein. | Flood and earthquake design, but not presented herein. |
| Tunnels | Life Safety | Occupational Safety and Health Administration (OSHA) | Yes, but mostly state of practice. | Yes, many but not presented herein. | Flood and earthquake design, but not presented herein. |
| Pipelines | None identified | None identified | None in U.S. address hazard performance. International Organization for Standards (ISO) standards exist. | ASCE, ALA and MCEER for earthquake. | Earthquake for pipe design guidelines. |
| Mechanical Equipment | Life Safety | Building Code/Building authority for certain facilities only | Yes, but none addressed herein, see American Lifelines Alliance (ALA) (2004a) for listings. | Yes | Earthquake qualifications. |
| Electrical Equipment | Life Safety | Building Code/Building authority for certain facilities only | Yes, but none addressed herein, see ALA (2004a) for listings. | Yes | Earthquake qualifications, possibly others. |
| Water System | Public Health | Federal, state, local public health departments | Yes, American Water Works Association (AWWA) (2010) but concerns addressed in Appendix D. | Yes, some address hazards. | Standard (AWWA, 2010) and Guidelines cover earthquake, ground deformation, wind, tornado, icing, flooding, and human threats. |
| Wastewater System | Public Health | Federal, state, local public health departments | Yes, AWWA (2010) but concerns addressed in Appendix D. | Yes, some address hazards. | Standard (AWWA, 2010) and Guidelines cover earthquake, ground deformation, wind, tornado, icing, flooding, and human threats. |
| Water System | Fire Protection | State Health and Safety codes for fire | Yes, but does not address hazards beyond fire. | Yes, some address hazards and fire following earthquake. | Earthquake (ASCE, 2005a). |

There are no consistent hazard design criteria for components, except for buildings and structures. Pipelines have no hazard performance requirements, but some guidance is provided for earthquake hazards. Several documents provide guidance for earthquake systemic performance criteria based on the *Uniform Building Code* (UBC), which is no longer in use. Consistency is lacking on the hazards to be evaluated for the components of water and wastewater systems. Where performance goals are identified, they are set for a single hazard level. The sole exception pertains to earthquakes, for which earthquake performance goals are generally established for two or three seismic hazard levels.

For the most part, there is no recommended restoration time for water and wastewater systems included with any of the performance criteria. The NIST *Guide* (NIST, 2015) does, however, estimate recovery times implied by current codes. Appendix D, Sections D.2.1 and D.2.2, reviews performance goals/targets for four water systems and three wastewater systems located on the west coast showing how different targets are linked with restoration times.

Davis (2014a, 2014b, 2014c) identifies water, wastewater, and inundation protection system core services (drainage and flood control) and how they relate to performance categories for these systems. These performance categories are identified in Table 7-4. Essentially, all the performance categories described in AWWA (1994), ALA (2004b, 2005a, 2005b), ASCE (1999, 2002), KJC (1993), NIST (1997), WRF (2012) are grouped into the three categories shown in Table 7-4, except the accessibility services described below. There are five baseline service categories each for water and wastewater systems, which are summarized in Tables 7-5 and 7-6, respectively.

Accessibility services provide customers access to the basic water or wastewater services through alternative sources or locations that are available for the period after an event when the services identified in Tables 7-4 to 7-6 cannot be obtained conventionally (e.g., potable water from kitchen faucet) through the infrastructure networks (Davis, 2014a). An example of a water accessibility service is the provision of pre-packaged water while potable water cannot be provided through the network. An example wastewater accessibility service is the provision of portable toilets. Some of

**Table 7-4 Primary Water and Wastewater System Performance Categories Provided by Infrastructure Networks**

| Performance Category | Description |
|---|---|
| Water and Wastewater Services | Provision of water and wastewater services identified in Tables 7-5 and 7-6, respectively. |
| Life Safety | Preventing injuries and casualties from direct or indirect damage to system facilities; includes safety matters related to response and restoration activities. |
| Property Protection | Preventing property damage as a result of damage to system components; also includes preventing system damage. |

**Table 7-5 Water Service Categories Provided through Built Infrastructure Networks**

| Service Categories | Description |
|---|---|
| Water Delivery | The system is able to distribute water to customer service connections, but water delivered may not meet quality standards (requires water purification notice), pre-event volumes (requires water rationing), fire flow requirements (impacting firefighting capabilities), or pre-event functionality (inhibiting system operations). |
| Quality | The water quality at service connections meets pre-event standards. Potable water meets health standards (water 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 is able to provide pressure and flow of a suitable magnitude and duration to fight fires. |
| Functionality | The system functions perform at pre-event or improved reliability, including pressure (operational constraints resulting from the event have been removed/resolved). |

**Table 7-6 Wastewater Service Categories Provided through Built Infrastructure Networks**

| Service Categories | Description |
|---|---|
| Wastewater Collection/Removal | The system is able to collect and remove wastewater at the customer service connections without sewage overflow, but the system may not be able to treat collected wastewater to meet quality standards, properly dispose of wastewater, or meet pre-event functionality (inhibiting system operations). |
| Quality | Wastewater is treated to pre-event volumes using available processes, while meeting public health standards. |
| Disposal | Entire wastewater volume is able to be properly disposed, protecting the environment, and meeting public health standards (including containment within pipe network). |
| Reclaimed Source | Wastewater is able to be treated and used as an alternative source of water supply (Note: This does not apply to all wastewater systems). |
| Functionality | The system functions perform at pre-event or improved reliability (operational constraints resulting from the event have been removed/resolved). |

the existing performance objectives summarized in Appendix D, Section D.2 include accessibility services. The scope of this project focuses on the water and wastewater infrastructure and therefore does not include accessibility services. However, the overall performance of water and wastewater systems relies on accessibility services in the days to months following an event.

### *7.2.2 Recent Developments*

Davis (2011, 2014a, 2014b, 2014c) and Davis et al. (2012) provide guidance on how to identify and utilize core services for water, wastewater, and protection against inundation. The core services are related to system performance categories using common network components and topology. Davis et al. (2012) and Davis (2014a) show how these services are measured in existing systems using the Los Angeles Water System performance during the 1994 Northridge earthquake and the Table 7-5 service definitions. The results are graphed in Figure 7-1 as the cumulative times needed to restore the services identified in Table 7-5. Davis (2014b and 2014c) presents a methodology to calculate system functionality for the subsystems identified in Tables 7-1 and 7-2. Hirayama and Davis (2013) describe how the procedure is useful for helping to quantify resilience improvements for the Kobe Waterworks Bureau implemented since the 1995 earthquake.

Davis (2014a and 2014b) defines system operability and how important this metric is in supporting community resilience. As seen in Figure 7-1, operability is defined as the cumulative time needed to restore the services identified in Tables 7-5 and 7-6, respectively for each system, other than functionality.[28]

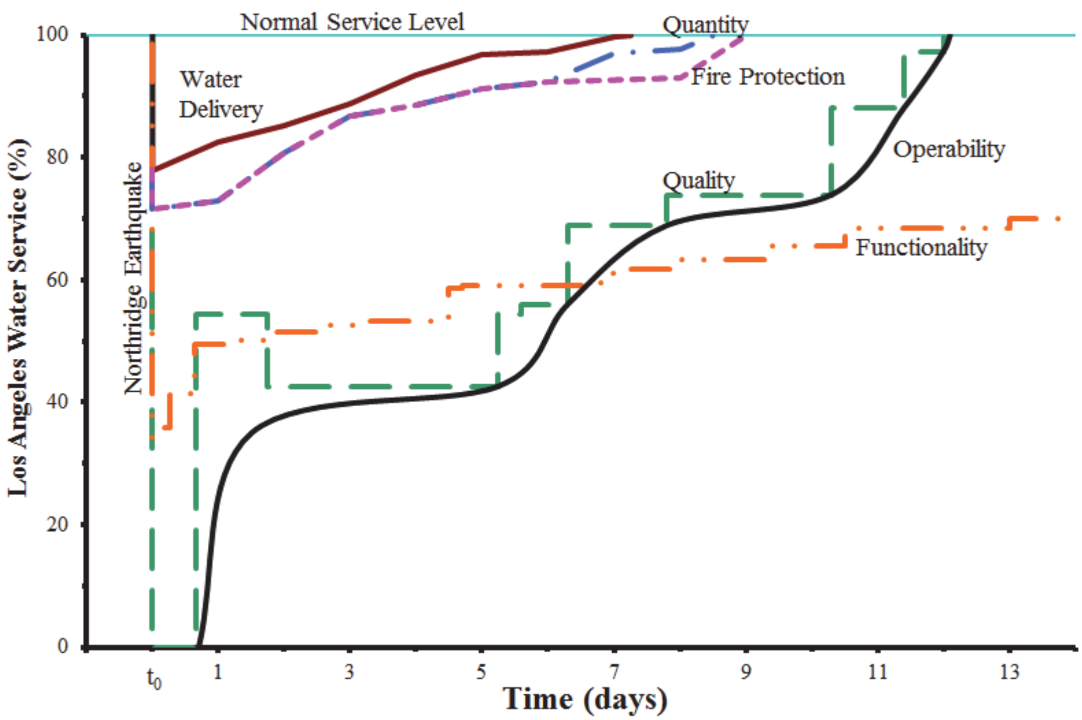



Figure 7-1 Los Angeles water system service restorations following the 1994 Northridge earthquake (Davis et al., 2012; Davis, 2014a).

[28] This project focuses on societal effects of system service losses and restoration which is more related to operability and, as a result, functionality will only be described in relation to the other services.

Davis (2014a) also describes how system operation to address one service may affect and possibly inhibit the performance needed to support another service in a disaster. Using water system quality and fire protection services as an example, a system can usually be restored more rapidly when not accounting for water quality services to meet fire protection services. However, this requires non-potable water to be placed within the network, which is generally made accessible to all customers requiring that the system get permission from public health officials or violate public health laws. Alternatively, water restoration can be delayed (sometimes significantly, as occurred after the 1995 Kobe Japan earthquake) to provide water quality meeting public health requirements once restored, but at the sacrifice of not providing firefighting water supplies for the same duration.

## 7.3 Societal Considerations

Water and wastewater systems are essential for life, public health, firefighting, and industrial processes. Chapter 2 provides information on societal considerations for water following earthquakes. It is clear society relies on water and wastewater systems to provide basic water and sanitation services for life safety, public health, and economic wellbeing. Important societal services are identified in Tables 7-4 to 7-6. In addition, some basic survival needs can be met with alternative sources to the networks through accessibility services, which may or may not be the responsibility of the utility owners and operators. The social needs must be met over time using a combination of the water and wastewater networks and alternative services; plans must include both.

### *7.3.1 Societal Service Functions for Recovery Phases*

Tables 7-7 and 7-8 present the societal service functions of water and wastewater systems for the three recovery phases (short, intermediate, and long-term) proposed in the National Disaster Recovery Framework (FEMA, 2011). The levels of restoration for each of the core services identified in Tables 7-5 and 7-6, respectively, are described in Tables 7-7 and 7-8 for each phase of recovery in terms of the systemic support for community critical and non-critical facilities and lifelines.

Hospitals, nursing homes, and emergency evacuation shelters need to remain operable, or resume operation as soon as possible after disaster occurs. While providing life safety and property protection, the restoration priorities for water and wastewater need to be established for critical community facilities as well as for other lifelines that support them. For example, water, wastewater, and electricity are needed to ensure that hospitals can operate, and thus priority should to be given to the restoration of these services. Restoration priorities will vary for each system.

**Table 7-7 Societal Serving Functions during Disaster Recovery of Core Water Services Provided through the Infrastructure Systems**

| Service | Short-term Phase (days) | | Intermediate Phase (weeks to months) | Long-term Phase (months to years) |
|---|---|---|---|---|
| | *Non-critical Facilities* | *Critical Facilities & Lifelines* | | |
| Water Delivery | Sufficient to meet fire protection services<br>Note 1 | Sufficient to meet quality, quantity, and fire protection services | Fully operable<br>Note 3 | Fully operable |
| Quality | Note 1 | Potable services to all facilities requiring human consumption and health care<br>Note 1 | Fully operable<br>Note 3 | Fully operable |
| Quantity | Note 1<br>Governed by fire protection services | Minimum volumes to meet facility purposes and fire protection services<br>Notes 1 and 2 | Fully operable<br>Note 3 | Fully operable |
| Fire Protection | Requires minimum flow rate through combination of network and alternative sources at distances to firefighting sites. Need minimum pressure where network utilized (Note 4). | | Fully operable<br>Note 3<br>Note 6 | Fully operable |
| Functionality | Sufficient to provide minimum state of operability for other services | | Minimum level to provide state of operability | Fully restore<br>Note 5 |

Note 1. Individuals should be prepared and have storage of their own supplies sufficient to survive through the short-term as recommended by emergency management.

Note 2. Minimum volumes to meet minimum health care functionality, emergency evacuation and other needs, such as those for mass care centers if alternative accessibility services are insufficient.

Note 3. There is a transition period within the intermediate-term where water delivery, quality, quantity, and fire protection services gradually improve from that identified for short-term to that identified for fully operable.

Note 4. Pressure needs to be sufficient to suppress fires in high-rise structures and to relay water to a distance no greater than the capability of existing firefighting equipment.

Note 5. Known vulnerabilities need to be removed; may require reconstruction at locations where repairs were undertaken in short-term and intermediate-term phases.

Note 6. Fire underwriters generally require minimum operating pressure of 25 psi (140 kPa) to resist hose collapse when connected to hydrants during firefighting.

### *7.3.2 System Societal Services and Interactions*

The loss of water and wastewater system services compromises basic survival, public health, personal dignity, and economic wellbeing. These two systems have interactions; Davis (2014a) identifies water service interactions that arise when the service categories described in Table 7-5 are provided by a single pipeline network. The loss of water delivery is crucial because it restricts the provision of virtually all water and wastewater services. Water service interactions between water delivery and quality as well as quality and quantity can have significant societal impacts. Declining water quality can result in health concerns that prevent water delivery

**Table 7-8 Societal Serving Functions during Disaster Recovery of Core Wastewater Services Provided through the Infrastructure Systems**

| Service | Short-term Phase (days) | | Intermediate Phase (weeks to months) | Long-term Phase (months to years) |
|---|---|---|---|---|
| | *Non-Critical Facilities* | *Critical Facilities & Lifelines* | | |
| Wastewater Collection/ Removal | Note 1 | Sufficient for public health, dignity, and operational requirements | Fully operable<br>Note 3 | Fully operable |
| Quality | Decontaminate and monitor. Partially dictated by disposal services.<br>Note 2 | | Fully operable<br>Note 3 | Fully operable |
| Disposal | Minimum volumes not able to be handled using alternative services; alternatives should not result in significant public health or environment degradation. | | Fully operable<br>Note 3 | Fully operable |
| Reclaimed Source | Generally not needed | Minimum volume and quality where providing services for essential functions (Note 4); see Table 7-7 | Fully operable for critical facilities and lifelines; partially operable for all other | Fully operable |
| Functionality | Sufficient to provide minimum state of operability for other services | | Minimum level to provide state of operability | Fully restore<br>Note 5 |

Note 1. Individuals should be prepared and able to manage personal waste for the short-term.

Note 2. Quality can be compromised during short-term.

Note 3. There is a transition period within the intermediate-term where wastewater collection, quality, and disposal services gradually improve from that identified for short-term to that identified for fully operable. In some locations storm water drainage may not require full operability at intermediate-term phase if drainage can be achieved in alternate form without threatening public health, safety, or property damage.

Note 4. Essential functions may include cooling for refineries, water for creating steam at electric power generator, firefighting, and other functions.

Note 5. Known vulnerabilities need to be removed; may require reconstruction at locations where repairs were undertaken in short-term and intermediate-term phases.

(Davis, 2014a). This, in turn, can amplify the effects of other health hazards and restrict fire-fighting capabilities, compromising emergency response essential for community resilience. If there is sufficient volume to provide some water delivery services, then delivery may be allowed in combination with public information on water purification in extreme cases (e.g., CDPH, 2003). In this way, water can still be utilized for numerous activities such as the use of home toilets (if sanitary sewer collection service is available), treating water at point of use, heating, and cooling.

Informed by numerous disasters impacting water quality, Adams (1999) points out that if "choices need to be made about increasing water quantity or improving water quality when time and resources are scarce, priority should always be given to increasing the quantity of water available, even if the water provided is contaminated," pending available water. Adams (1999) notes "in many emergencies, the most important routes for the transmission of water- and excreta-related disease are linked to hygiene problems caused by insufficient quantity of water, rather than by contaminated water supplies." Water quantity services can be partially met through reductions in customer demand. There are examples of water conservation and voluntary reductions in demand immediately after a disruptive event strikes.

On a daily basis, society relies upon water systems to provide sufficient volume and pressure for fire suppression. Fires commonly ignite following other hazard occurrences, such as earthquakes and floods. Fires can be fought in many ways, but most times water is utilized from the distribution network. Communities can tolerate water loss in a system as long as it does not prevent firefighters from controlling fires, as was the case following the 1994 Northridge earthquake in Los Angeles. Although rare, the fires can result in conflagrations causing severe property loss and casualties. In such rare instances, the absence of water can be the cause of significant property loss and mortality, as was experienced following the 1906 San Francisco earthquake, 1923 Great Kanto earthquake in Tokyo, Japan, and 1995 Kobe, Japan earthquake.

Society generally has high expectations for reliable water and wastewater services under normal conditions and in routine hazard events. There can be little tolerance for service outages after routine events. Chapter 2 explains how society can tolerate certain amounts of water and wastewater service losses for a limited time during and after extreme events, typically those exceeding routine events. This is true as long as people and property remain safe and system damage does not lead to cascading impacts (e.g., downstream inundation from dam failure following an earthquake or flood). After most relatively severe events, immediate water and basic sanitation needs can often be met using accessibility services—alternatives to the water or wastewater networks (e.g., bottled water and portable toilets). An exception to this consideration is the loss of wastewater system capability to provide drainage, leading to severe flooding.

### *7.3.3 Accessibility Services*

The duration of acceptable water and wastewater service outage is related to accessibility services. The scope of this report does not include defining and investigating the accessibility services, but some descriptive examples are provided to show how they influence the restoration of water and wastewater services. Acceptable service outage durations are a function of accessibility to alternatives in both distance and allocation. For example, people may tolerate lengthier disruptions in potable water service delivery if bottled water is delivered to their homes. By comparison, if they have to go a significant distance each way every day to retrieve an allotted gallon of water per person they may not be as tolerable, especially if they live in an upper story of a multistory complex. Similarly, a person is more likely to accept using a portable toilet right outside their single story home as compared to someone who must descend six stories to access such ground floor facilities.

The allocation of alternatives must meet basic survival needs for the duration of service outages. If the water delivery service is not restored for two weeks, but the allocation of bottled or other potable water as a supplement is exhausted in one week, then this condition would not be acceptable. This clarifies the need for establishing system performance criteria with consideration of accessibility services (i.e., available alternatives to the normal water and wastewater services).

There are also limits on the duration of alternatives because (1) demand increases over time, (2) economics, and (3) a need for returning to pre-event functionality. Demand generally lowers after an event. Personal demand for water and wastewater services increases with time due to need to bathe, clean, and cook. Households and businesses tolerance will have limits and these can vary based on individual conditions. At some point demands for a return to "normalcy" will take hold in a community. Restoration of water and wastewater services is a strong indicator of normality. Every person, household, and community will have their own tolerance for returning to "normal," making it difficult to define duration tolerances with any certainty. Information presented in Appendix D indicates that the practical time limits for restoring all service categories in Tables 7-5 and 7-6 is about 30 to 60 days for water systems and 70 days or more for some wastewater services, depending upon hazard level. However, some service reductions may be tolerable for longer durations. For example, water rationing may be tolerated for months following a very rare and extreme event severely impacting a water supply aqueduct, as long as households are able to function properly and economic wellbeing is not severely disrupted.

In summary, the tolerance for water and wastewater service losses is a function of the potential consequences resulting from the service loss. Severe consequences are generally not acceptable, even if an extreme hazard event occurs. There is a societal expectation for good performance of water and wastewater infrastructure under normal conditions and after the occurrence of a routine hazard event. Disruptions, however, may be acceptable for a limited time following a hazard event as long as sufficient accessibility services are available and able to meet the time-dependent increases in demand necessary to support community resilience.

## 7.4 Interdependencies

Water and wastewater systems depend on other infrastructure systems. These relationships generally involve single dependencies, but may also entail interdependencies in which there are reciprocal relationships. Water and wastewater utilities, for example, rely on electric power to run pumps, treatment processes, laboratory, and other operations. Roadways, bridges, and highways are needed for access, installation, maintenance, repair, and operation of all types of facilities. Railways and shipping often transport bulk goods needed for water and wastewater systems, such as chemicals, pipe and fittings, mechanical and electrical equipment. Curbs and gutters along local roadways are used as part of the collection systems for many drainage systems. Telecommunications are required for passing information between staff and management, including landlines, cellular, radio, and microwave data. Most sizable water and wastewater system operations depend on supervisory control and data acquisition networks, which are internal networks that depend on external telecommunication services.

Wastewater systems generally depend on water systems to operate because most waste can only be collected by running water. Water systems depend on wastewater systems for certain operations beyond general usage by employees, including disposal of treatment sludge in sewer systems and obtaining reclaimed water from sanitary sewer and storm facilities.

Many other lifelines depend on water and wastewater systems. For example, power plants need water for cooling and steam, both of which can be disrupted by a damaged water system that requires electric pumps to restart water distribution. Water for cooling and steam generation, however, is not always obtained from a water network, and some gravity water systems may not require power to support distribution. Therefore, interdependent relationships should not be presumed, but investigated locally.

Water is required by telecommunication systems for cooling; transportation systems for operation and maintenance; and gas and liquid fuel systems for processing, cooling, and transportation. All lifelines rely on drainage and waste disposal. In particular, highways and roads rely on wastewater systems for drainage to prevent disruption during storms and local flooding. Some utilities operate steam distributions systems for heating, cooling, restaurant and hotel service, and sterilization of medical equipment in hospitals. The Consolidated Edison Company of New York (Con Ed) uses cogeneration at fossil fuel plants to produce steam that is distributed throughout Manhattan by approximately 100 mi. (160 km) of high pressure/high temperature pipelines.

There is a strong interdependency between water and wastewater systems and the communities they serve. These systems cannot operate financially without income from the customers paying their bills. There is an overall need for a community to function at a minimum level to allow the water and wastewater systems to meet minimum functionality and vice versa. Communities also depend on water and wastewater systems to help maintain basic life support (e.g., potable water and removal of waste for a contaminant free environment) and safety (e.g., fire protection) while the systems themselves depend upon societal functioning to maintain operations, such as the provision of healthcare for employees. Buildings depend on fire protection services, which in turn depend on water supply.

The collocation of water and wastewater pipelines with other lifelines is also an interdependency concern. For example, water and wastewater pipelines are buried under roadways and attached to bridges for river and other crossings. Similarly, electric power and telecommunication conduits as well as gas and liquid fuel pipelines are collocated under roadways. Severe congestion of underground utilities frequently occurs in urban environments. As pointed out by O'Rourke (2010), congestion increases risk due to proximity. Damage to one facility, such as a cast iron water main, can cascade rapidly into damage in surrounding facilities, such as electric and telecommunication cables and gas mains, with system-wide consequences. Additional treatment of dependency relationships associated with water and wastewater systems, including colocation issues, is provided by NIST (2015), and discussed in Chapter 8.

## 7.5 Disaster Lessons

There are numerous documents describing performance of water and wastewater systems in past events. Many of these were prepared by the ASCE Technical Council on Lifeline Earthquake Engineering (TCLEE) as a result of post-earthquake investigations (e.g., ASCE, 2005a). Eight key cases are described herein providing useful information on societal expectations and lifeline dependency relationships. NIST (2015, p. 223-224) describes other events, including several flood events of importance to this analysis. These cases identify key social issues useful for assessing needed water and wastewater system performance criteria.

The NIST *Guide* recommends using three hazard levels—routine, design, and extreme—to address the range of potential damage and formulate response and recovery scenarios. The example events covered in this section were all above routine hazard levels and in general are characterized as being either extreme or some combination of design and extreme hazards.

### *7.5.1 1971 San Fernando Earthquake*

Many of the widespread effects of the 1971 San Fernando, California, earthquake were unexpected when they occurred, but would be considered design to extreme in the current state of practice. Numerous problems not only affected water and wastewater systems, but all lifeline systems. The impact of the San Fernando earthquake on utilities and geographically distributed infrastructure was one of the principal reasons for establishing lifeline earthquake engineering as an area of specialized, multi-disciplinary research and practice, supported primarily by ASCE and the National Science Foundation (NSF).

The many damaged water supply and storage facilities caused extensive service losses to customers. Key issues were damage to dams and reservoirs, storage tanks, pumping stations, chlorination stations, aqueducts, and mainline piping from a variety of geotechnical hazards, including ground shaking, landslides, liquefaction and lateral spreading, and fault rupture (NOAA, 1973). The acquisition/determination of restoration durations and total impacts on services was not possible during the development of this report and requires further effort.

One significant consequence of the 1971 earthquake was the upstream slope failure of the Lower San Fernando Dam. Within minutes after the earthquake, 30 of the 35 feet of freeboard was lost as a result of slope deformations. The remaining freeboard was cracked and started to leak, raising concerns for a potential catastrophic release of water and resulting in the evacuation of about 80,000 downstream residents. Fortunately, the dam was able to retain water until the reservoir was safely drained. The reservoir performance was unacceptably close to failure and is an example where water facilities need to be properly designed to withstand extreme events. There are a number of cases of dam failures caused by earthquake and flooding across the country and around the world that had devastating effects on downstream communities and the environment.

### *7.5.2 1983 New York City Garment District Incident*

On August 10, 1983, a 12-inch (in.) diameter cast iron water main ruptured near the intersection of 38th Street and 7th Avenue in New York City. This may be considered a routine infrastructure hazard in terms of its cause, but extreme in terms of operational planning levels and design considerations. As described by O'Rourke at al. (2003), water from the burst main flooded an underground electric substation, shorting electric circuits and touching off an immense fire. Loss of the substation caused a black out of approximately 0.5 square miles of the city, including the Garment District and neighboring areas of the city. This involved over 10,000 customers, including Macy's and Gimbel's Department Stores. The blackout affected a telephone company central office, interrupting telecommunication service to tens of thousands of customers until emergency power was switched on. Electric power was not fully restored in Midtown Manhattan for over five days. The loss of electricity interrupted track signaling and shut down all lines of the New York City subway passing through Mid-town, thereby affecting the entire system.

Fire in the substation caused heat so intense that firefighters could not approach the blaze directly, but had to attack it with more than 60,000 cubic feet ($ft^3$) of foam. The blaze flared up an air shaft, igniting the roof of a 25-story building. Burning transformers released polychlorinated biphenyls (PCBs), thereby generating hazardous emissions.

The accident occurred during Market Week in the Garment District, when most out-of-town buyers come to New York City to order next year's spring clothing lines. Direct and indirect business losses during this critical time have been estimated in the tens of millions of dollars.

### *7.5.3 1994 Northridge Earthquake*

The magnitude-6.7 Northridge, California, earthquake of January 17, 1994 was a design to extreme hazard event, based on the ground motions experienced. Water service was disrupted over a large area by the earthquake as a result of damage to pipelines and system facilities. Water delivery was restored within seven days, and potable water within 12 days after the earthquake (Davis et al., 2012). These restoration times were found reasonably acceptable by customers given the overall extent of earthquake impacts. Two issues, in particular, resulting from the earthquake are helpful in defining institutional and social expectations:

- The Federal Aviation Administration (FAA) raised concerns about non-potable water deliveries to the Los Angeles International airport (LAX) and were considering the need to shut down air traffic until potable supplies could be delivered. Aircraft need to provide potable water to passengers during flight for public health and safety. FAA concerns were raised at about two to three days after the earthquake, and four days after the earthquake water quality was confirmed to meet public health standards. LAX was not shut down due to water quality concerns.
- The Northridge Medical Center (NMC) and other critical care facilities in the north and western San Fernando Valley were out of water immediately after the earthquake. Non-potable water deliveries were restored to most in about three days and to all within seven days. NMC had potable water restored at 10 days. They were able to continue functioning throughout the emergency, but the duration for non-potable service deliveries was considered too long for assisting community resilience.

For the most part, fires were able to be fought using alternative water sources when ignitions occurred in areas where water was not available from the distribution system (ASCE, 2005a).

There were no significant wastewater system service disruptions following the 1994 Northridge earthquake. Overall, the water and wastewater service restorations fell within the range shown in Tables 7-7 and 7-8, except for a few critical facilities and fire protection that were not restored to meet the short-term needs. Accessibility services were provided using bottled water, tanker trucks, and portable toilets as alternative sources.

### *7.5.4 1995 Kobe Earthquake*

The 1995 Kobe, Japan, earthquake, was a design to extreme hazard event, based on the ground motions experienced. The event resulted in the loss of water to significant portions of the City of Kobe soon after the earthquake. It took approximately 90 days to restore water service, and for the most part, service restorations took longer than those shown in Tables 7-7 and 7-8. The loss of water soon after the earthquake allowed fires to burn significant portions of the city and caused numerous casualties. Approximately 67 blocks were severely burned primarily in the industrial parts of the city where fires were initiated by chemical reactions (Hamada et al., 1995). Although water loss was not the only factor contributing to the fires, the loss of water and inability to help suppress the fires was considered unacceptable.

The five-week duration to restore water services to the community was also considered unacceptable. Kobe Waterworks Bureau performed surveys to better understand their customers' perspective. The results are summarized in Table 7-9, which provides information about Japanese tolerance pertaining to the restoration of water services. As indicated in Table 7-9, the tolerance for loss of water service expressed by members of the Kobe community is less than five weeks.

Accessibility services were provided using bottled water, portable toilets, and portable showers as alternative sources. Water was also imported by tank trucks, trailers, and ships.

**Table 7-9 Japan Citizen Response on Lack of Water Following 1995 Kobe Earthquake (Matsushita, 1999)**

| | Week 1 | Week 2 | Weeks 3 & 4 | Week 5 |
|---|---|---|---|---|
| Response | Request for information | Irritation | Anxiety, impatience | Anger |
| Comments | Situation?<br>Tank truck?<br>Recovery date? | Want to take a bath | Water supply is insufficient | Very tired and exhausted |

### *7.5.5 2001 World Trade Center Disaster*

The World Trade Center (WTC) Disaster of September 11, 2001 was an extreme hazard event and beyond anticipated design levels. During the event, there was serious collateral damage to critical infrastructure due to flooding and water damage from ruptured water mains supplying the Twin Towers (O'Rourke et al., 2003; Bonneau et al., 2010). Ruptured mains accounted for about 55 million gallons of water loss per day, which flowed into underground sections of the WTC complex and flooded the Port Authority and Trans-Hudson (PATH) Tunnels beneath the Hudson River. Water flooded the cable vault of the Verizon Building at 140 West St., where 70,000 copper pairs and fiber optic cables were located. Nearly 11 million gallons of water had to be pumped from the vault during recovery. As a result of the damage from debris impact coupled with flooding, Verizon lost 200,000 voice lines, 100,000 private branch exchange lines, and 4.4 million data circuits. More than 14,000 business and 20,000 residential customers were affected.

The WTC disaster aftermath provides a graphic illustration of the interdependencies of infrastructure systems. The building collapses triggered water main breaks that flooded rail tunnels, a commuter station, and the vault containing all the cables for one of the largest telecommunication nodes in the world. Damage affected the Security Industry Data Network and the Security Industry Automation Corporation circuits used to execute and confirm block trades on the New York Stock Exchange (NYSE). Before trading resumed on the NYSE on Monday, September 17, 2001, the communications network had to be reconfigured. Hence, ruptured water mains were linked directly with the interruption of securities trading as well critical underground transportation facilities.

### *7.5.6 2010-2011 Canterbury, New Zealand Earthquake Sequence*

The City of Christchurch and the Canterbury region of New Zealand were struck by a series of earthquakes in 2010-2011, known as the Canterbury Earthquake Sequence (CES), which resulted in substantial damage to both the water and wastewater systems. The most significant impacts arose from the February 22, 2011 earthquake, and the severity of shaking and extent of damage caused by that event was well beyond design levels.

Water services after the February 22 event were restored in about six weeks, except to the Christchurch Central Business District, which was cordoned off to promote public safety while repairs were undertaken and damaged buildings removed. There were only a few fires, which were confined and extinguished by the fire department.

Water quality was a concern. A boil water notice was in effect for about 41 days. The sewer system was severely damaged from liquefaction (described in more detail below) and caused concerns for cross contamination into the water system through wells and broken pipes. Decontamination was required at a few locations in the water system. Seven days after the February 22 event there were some reports of gastroenteritis.

Initial water system restorations within weeks of the February 22, 2011 earthquake were able to provide winter water demand levels to all customers. However, the restoration of important reservoirs was unable to be completed for more than a year, and as a result, summertime rationing was required during 2011-2012.Summertime rationing had an impact on irrigation and domestic water use in neighborhoods heavily damaged by liquefaction and other areas served by the damaged tanks.

The Christchurch sanitary sewer system was severely damaged and is still being restored in 2016. The greatest damage came from liquefaction induced ground deformations and the infiltration of sand and silt into broken pipelines. The differential ground movement changed pipeline gradients and the ability of the gravity system to transport sewage in some areas. Liquefaction caused significant damage to the Bromley Wastewater Treatment Plant, reducing its operational capacity for a long period of time. There were four main CES earthquakes, and the successive and collective damage from these shocks led to a continuing disruption of plant operations.

As a result of the damage, raw sewage was pumped initially into local rivers and tertiary treatment lagoons, bypassing primary and secondary treatment operations in the plant. The lagoons are part of the final treatment process before the treated water enters an outfall pipeline and is conveyed offshore into the ocean. Placing the untreated sewage into the lagoons nearly depleted the oxygen required for aerobic breakdown of organics and required an emergency effort to prevent the destruction of the local ecosystem, which would have resulted in serious environmental and air quality problems.

Conveyance of raw sewage into local rivers caused environmental damage and several reported illnesses that medical officials attributed to the sewage release. Fortunately, the local authorities were able to contain these problems. The difficulties experienced with sewage collection, conveyance, treatment and disposal are not considered acceptable system performance in Christchurch.

The sand and silt that entered broken pipelines and conveyed into the wastewater treatment plant for many months following the February 22, 2011 earthquake had a negative effect on operations. The scrapers in the primary settling basins were damaged by large quantities of sand and silt. Inorganic solids entering the secondary treatment system affected the biological and chemical processes for decomposition of organics. Sand and silt abraded pumping equipment, thereby accelerating wear and tear and reducing efficiency.

The repair of wastewater pipelines was very expensive. These types of pipelines are relatively deep, on the order 10 to 15 ft not only in Christchurch but in wastewater conveyance systems generally. Given the weak, potentially unstable soils in Christchurch a high water table (about 3 to 5 ft deep in many places), excavations to replace damaged pipelines needed trench box support and dewatering by well points. The cost of such construction on a large scale was substantial and contributed to depletion of available reserves in the Local Authorities Protection Plan, which is an insurance program to provide support for local authorities in New Zealand to restore public infrastructure after natural hazards.

The storm water drainage system in Christchurch, for the most part, is separate from the sanitary sewer system. Storm water pipelines were damaged by liquefaction, with damage patterns similar to those of the sanitary sewer network. Repairs to the storm water system, however, were a lower priority than those of the sanitary sewer system. In addition, ground settlement in the relatively low-lying and flat terrain of Christchurch inhibited drainage. The storm water drainage system is part of a larger flood control system for Christchurch, which also includes local rivers and engineered channels to convey flows and runoff through the city to the ocean.

The combination of damage to levees, changes in elevation and gradient to river beds, large local total and differential settlements, and impacts on local storm water collection and conveyance pipe networks, led to flooding in portions of the city. There were significant threats to overtopping levees within weeks of the February 22, 2011 earthquake, requiring emergency construction activities. As a result of the Canterbury Earthquake Sequence, there is increased vulnerability to flooding in several areas of Christchurch. In March 2014, significant flooding occurred in relatively large areas of the city (GEER, 2014). The social impacts from earthquake damage of the local drainage network are considered unacceptable.

Water and wastewater service restoration times are complicated by the combined effects of multiple earthquakes, but fall well beyond those shown in Tables 7-7 and 7-8. Accessibility services were provided using bottled water, importing water in tank truck and trailers, rail cars, and using portable desalination plants as alternative sources. Portable toilets and portable showers were alternatives for wastewater.

### *7.5.7 2011 Great East Japan Earthquake and Tsunami*

The Great East Japan earthquake (Tohoku earthquake) of March 11, 2011 was a design to extreme hazard event, with a tsunami surge that is considered an extreme hazard event. There were numerous effects on water and wastewater systems from the earthquake, tsunami, and the subsequent disaster at the Fukushima Nuclear Power Plant. While the impacts of that earthquake are too numerous to describe in this report, a few are highlighted below.

In areas inundated by the tsunami, water system damages were extensive and significantly inhibited emergency response, recovery, and restoration activities. The effects in some areas were so extensive that even the local groundwater supply was contaminated by salt water intrusion and could not be utilized.

Sewer treatment systems were severely damaged by the tsunami. Some treatment plants were completely unusable for months and raw sewage was conveyed directly to the ocean after receiving large doses of chlorine. Ground settlements along the coast reached several meters, changing the hydraulic grade relative to sea level and increasing sea water inundation potential. Some treatment plants could not dispose of sewage at demand level during high tide. The performance of sewage treatment plants following the tsunami was found to be unacceptable, as evidenced by subsequent code changes and increasing tsunami design requirements adopted in Japan and elsewhere.

The Fukushima nuclear release had serious impacts on water and wastewater systems. Existing regulations did not ensure proper testing for contamination. The water and wastewater treatment waste was contaminated at high concentrations and unable to be disposed of in a timely manner. This resulted in a large buildup of waste materials that compounded health and air quality impacts.

Many areas along the coastal regions have increased vulnerability to flooding following the earthquake as a result of damage to local drainage and larger flood control systems. This vulnerability extends to flooding from high tides, typhoons, and tsunami. The impact of the tsunami on water and wastewater management has been found unacceptable and require extensive changes in local drainage and flood control systems. Consistent with the lessons learned from Christchurch, New Zealand, the Japanese recognize the need for improved inundation protection systems to safeguard communities against runoff and flooding after major earthquake hazards.

Accessibility services were provided using bottled water, importing water in tankers and trailers, portable toilets, portable showers, and pumping of drainage water as alternative sources.

### *7.5.8 2012 Hurricane Sandy*

The main impact of Hurricane Sandy on the New York City (NYC) water distribution system was relatively modest with respect to reservoirs, treatment plants, pipelines, and the tunnel system (City of New York, 2013b). Significant problems, however, were experienced in supplying water in high-rise buildings, which experienced loss of utility supplied electricity and/or flooding of basements containing diesel generators, pumps, and fuel. In Manhattan, the storm surge overtopped protective barriers at the Con Ed East 13th Street complex, flooding two substations and resulting in the loss of electric power to the great majority of Con Ed customers south of 34th Street (City of New York, 2013b). Many pumps for water distribution in high-rise buildings failed, either because of disrupted utility power, loss of local generators, or both. The impact of water loss affected buildings over six stories high—buildings that are taller than the maximum elevation that can be reached by normal pressure in the water pipeline system. Buildings with water towers were able to provide water by gravity flow, but those were depleted over time.

During Hurricane Sandy, ten of 14 wastewater treatment plants operated by the NYC Department of Environmental Protection were damaged or lost electric power, and released untreated or partially treated wastewater into local waterways (City of New

York, 2013b). Three of these facilities were shut down completely, including Coney Island for two hours, North River for seven hours, and Rockaway for three days. Sandy also had an adverse impact on pumping stations, with 42 of 96 such stations sustaining damage or losing power (City of New York, 2013b). Most of the damage to wastewater facilities involved electrical equipment and systems, including substations, motors, control panels junction boxes, and instrumentation. Many treatment plants and pumping stations in wastewater systems are located in areas of low elevation adjacent to water bodies, including rivers, lakes, and bays. The exposure in these areas to flooding in combination with electrical equipment located at lower levels in the facilities makes wastewater systems especially vulnerable to storms and hurricanes.

## 7.6 Gaps and Deficiencies: Codes, Standards, Performance Requirements, and Societal Considerations

There are several important gaps and deficiencies in the current approach to water and wastewater system resilience, several of which are summarized in this section.

The information reviewed for this project indicates the performance criteria established to date are driven by engineering objectives and current water and wastewater agency capabilities, and only partially informed by community and social needs. The codes, standards, and manuals have an inconsistent approach to the design of water and wastewater components making up the systems. There is no established set of performance requirements for any hazards that the water and wastewater systems are expected to meet. As a result, only a few system owners and operators have established performance objectives or targets for a limited number of hazards (mostly earthquake, but some related to climate change). The AWWA (1994) guidance document, *Minimizing Earthquake Damage: A Guide for Water Utilities*, has been used to help guide the establishment of performance criteria, at least for earthquake hazards. However, the basis for these criteria (i.e., the *Uniform Building Code*) have long been outdated and need to be revisited. Due to the inconsistent codes and standards, there is no way to assess how the system as a whole is expected to perform when piecing together the components that make up the systems. Furthermore, there is no current methodology to help develop designs for all water and wastewater components in a consistent manner that accounts for the large geographic coverage of these systems and the hazard variation from a single event, much less from multiple events. Davis (2005, 2008) and ALA (2005a, 2005b) proposed methods to address these problems for water and wastewater design and performance. The current state-of-practice for water and wastewater system design and modification requires some reworking and much more development to ensure it can properly support community resilience.

There is a gap between engineering practice for what is considered acceptable design levels, including what is defined as extreme events, and what communities find acceptable. The extreme hazard level has an implied link to maximum considered levels described in ASCE 7-10 (ASCE, 2010), which specifies ground motions having a 1% to 3% chance of exceedance in 50 years; this specification does not account for the other hazards that need to be considered by communities seeking improved resilience. For example, buildings designed using the maximum considered earthquake (MCE) ground motions in ASCE 7-10 have a 10% probability of collapse if impacted by the MCE; this translates to a 1% collapse risk in 50 years due to ground shaking. By comparison, liquefaction potential assessments, which are based on ground motions having a 2% chance of exceedance in 50 years, are concerned with consequences from a different type of hazard, with a different probability of occurrence. Similarly, the probabilities associated with liquefaction potential and building collapse risk are different from the probabilities of occurrence of landslides or fault surface rupture, which may have much lower probabilities and much greater consequences. Design criteria based on probabilities of occurrence of other natural hazards, such as extreme winds and coastal inundation, are similarly disparate, as are the consequences if a design level event occurs. Communities need to recognize that extreme design levels identified for one hazard type may cause consequences quite dissimilar to consequences for other specified extreme hazard design levels. Communities also need to understand clearly the consequences that can occur if the design level adopted by the community for a given hazard occurs, versus the consequences of a more rare event of the same hazard type or the consequences of other hazard types that could impact the community.

For criteria established to address the highest design hazard level, lifeline systems should remain at least minimally functional, have the ability to restore functionality when needed to support the response and recovery of the community, and not result in furthering foreseeable cascading hazards. Lifeline systems should be evaluated for the consequences of plausible hazards rarer than that selected for design. Designers need to consider what may happen if an event exceeding the design level occurs and mitigate consequences unacceptable to the community.

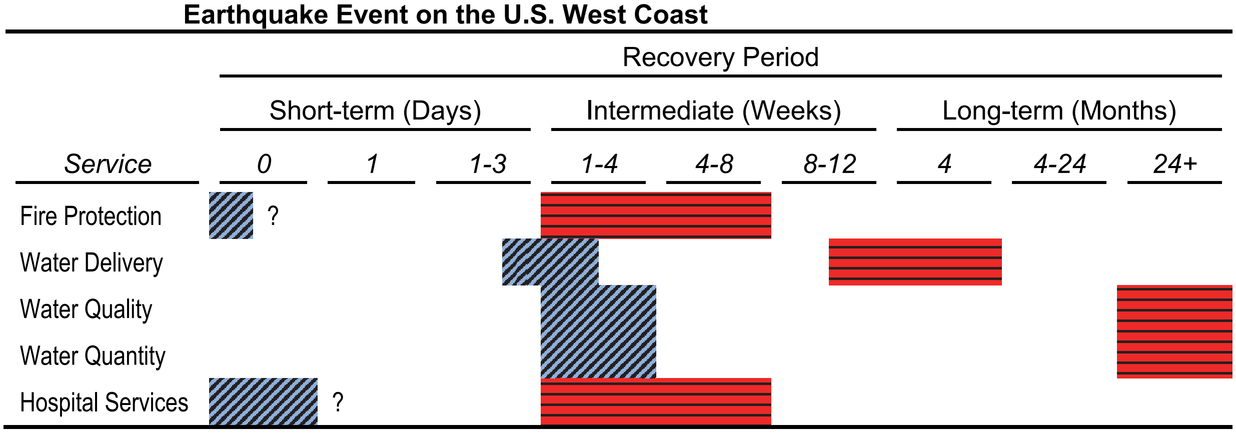
An important example of the need to design for high impact consequences is the 2011 Great East Japan earthquake and tsunami disaster. A tsunami generated by rupture along the entire Tohoku Subduction Zone was not accounted for in Japanese nuclear power plant design before the 2011 earthquake, and historical evidence for widespread tsunami inundation was not used by owners to re-assess tsunami risk (Hamada, 2014).

Some infrastructure is too big and important to fail. Examples include the hurricane protection system in New Orleans and the nuclear power plant system in Japan, both of which failed with terrible consequences to the communities they served. Under such conditions, a higher performance level needs to be identified that accounts for community consequences and impacts. A security audit can check performance beyond the hazard probability adopted in design. A similar approach, known as "defense in depth," is required by the Nuclear Regulatory Commission for U.S. nuclear power facilities (NRC, 2015). No counterpart, however, exists for other critical infrastructure systems. Guidance and protocols for such an approach are needed.

There are also important gaps between societal expectations for water and wastewater system performance and how the systems are anticipated to perform in reality. This is expressed through generalized, but informed estimates for water system restoration in Table 7-10. The societal expectations are based on information presented in this report. The anticipated water system performance levels are informed by SPUR (2009b), OSSPAC (2013), performance criteria summarized in Appendix D, and documented historic performance for similar events. The water services listed in Table 7-10 are described in previous sections of this chapter. Service provision to critical hospitals is also presented in the table. During the recovery period, communities will rely heavily on accessibility services, which are not detailed in this report. Table 7-10 identifies a significant gap between societal expectations of water services and the performance anticipated from the systems.

There are inconsistencies in industry practice with terminology and system characterization that can inhibit the ability to create a common set of performance objectives and to implement water and wastewater system improvements. Examples include terminology that is used interchangeably, such as "performance goals" versus "performance targets," and inconsistent naming of system components in various industry documents.

**Table 7-10 Water System Service Restoration Comparison Between Societal Expectations and Anticipated System Recovery for About 90% of Service Area for a Design Earthquake Event on the U.S. West Coast**




Legend:

Expected: blue diagonal hatch

Anticipated: red horizontal hatch

Current categorizations of water and wastewater lifeline systems do not include all the facilities needed to protect communities against inundation hazards. Of special significance are flood control systems, which are not currently included as lifelines, but are fundamentally important for the resilience of all communities. The current view of water and wastewater systems, from a lifeline engineering perspective, does not specifically address the links to flood protection infrastructure, such as levees, sea walls, and dams built primarily for flood control. Water and wastewater systems focus on potable water supply and wastewater removal for public health and local drainage. Wastewater systems may incorporate storm water sewers, which in many large urban areas do not typically include the large storm conveyance channels needed for flood protection. Flood control measures, such as the Mississippi River levees, New Orleans Hurricane Protection System, Sacramento Delta levees, and local projects in New York City after Hurricane Sandy are considered independently of water and wastewater systems, thereby losing the opportunity to develop a broader, more integrated approach to community protection from flooding. Furthermore, the climate change impacts discussed in Chapter 2 provide additional reasons to focus on inundation protection as a key factor for improving community resilience by placing greater emphasis on drainage and flood control systems.

Water and wastewater service restorations are coupled with accessibility services that are not part of daily operations and system hardware. The coupling of accessibility and restoration times of the core water and wastewater services, as described in Tables 7-5 and 7-6, will improve resiliency at the community level.

## 7.7 Conclusions and Recommendations

### *7.7.1 Review of Key Points*

A large number of existing codes, standards, guidelines, and manuals are applicable to water and wastewater systems. The performance objectives, where they exist, focus on life safety, public health, and fire protection; but there are no consistent hazard design criteria except for buildings and structures. No restoration times are recommended for any system in any documents reviewed. As a result, existing codes and standards tend to support the basic concepts of lifeline system resilience but fall short of creating water and wastewater systems to support community resilience. For example, there is no standard for seismic design of buried water and wastewater pipelines, although there are widely used guidelines from the gas and liquid fuels industry (ASCE, 1984; Honegger et al., 2004). Some documents provide guidance on earthquake performance criteria for lifeline systems (e.g., ALA, 2004b, 2005a, 2005b; ASCE, 1999; AWWA, 1994), but guidance is absent for other hazards. The core water and wastewater service categories discussed previously in this chapter can be used as a framework for developing performance objectives. These core services can be linked with the phases of restoration and recovery.

There is limited information on societal expectations for water and wastewater system performance. Furthermore, the performance of these systems cannot be properly established without full consideration of accessibility services (e.g., bottled water and portable toilets). System performance criteria and accessibility service targets must be planned and analyzed together to ensure there are no gaps in the provision of critical services.

Water and wastewater systems are interrelated with each other and other lifelines. These interrelationships involve both one-way dependencies and interdependencies, the importance of which cannot be underestimated as illustrated in Section 7.4.

In summary, there are a number of critical gaps and opportunities for improvement, including:

- Existing performance criteria are driven by engineering objectives and only partially informed by community and social needs;
- How society expects water and wastewater systems to perform and how the systems are actually designed to perform;
- The need to evaluate critical system performance beyond the hazard levels adopted in design; and
- Lack of wastewater system integration with regional flood control so that local drainage and storm water management become an integral part of inundation protection.

### *7.7.2 Lifeline Standards Development Needs*

Following are recommendations to address lifeline standards development needs:

- **Develop water and wastewater performance goals.** Include guidance documentation on how to develop desired community-specific system performance. Such guidance can serve multiple purposes from helping communities become more resilient to setting targets for which codes and standards can be developed with consistent performance criteria.
- **Address accessibility services in developing performance goals for water and wastewater services.** Community resilience is defined in part by the ability of residents and businesses to deal with temporary reductions, alternative methods of supply/collection, and other modifications to normal water and wastewater services. Although water and wastewater system owners and operators routinely account for this type of community response, measures that support such activities are rarely quantified or even qualified relative to system performance goals. The water service categories (i.e., water delivery, quality, quantity, fire protection, and functionality) and wastewater service categories (i.e., wastewater collection/removal, quality, disposal, reclaimed source, and functionality), as

defined in Tables 7-5 and 7-6, respectively, should be used in developing improved criteria that include accessibility (see Davis, 2014a for example). Accessibility services can fill gaps in service and thus should also be part of water and wastewater system performance goals.

- **Modify existing water and wastewater standards and guidelines to achieve resilience-based performance goals.** There currently are no consistent resilience-based performance goals in any standards or guidelines useful for implementing water and wastewater component designs. Procedures for setting local, regional, national, and international system performance goals need to be established. From these performance goals, there needs to be a methodology to ensure that individual system components can be designed to meet the system-wide performance goals.
- **Develop a methodology to determine how component design levels established by codes and standards can meet the system level performance criteria.** Currently, the design of system components based on codes and standards has no direct correlation with intended systemic performance targets. For example, designing pipelines and pumping stations to resist the effects of ground motions for design level seismic hazards does not mean the overall water or wastewater system will meet the social functions and performance goals, nor do such criteria indicate the extent to which the system is over or under designed.

### 7.7.3 Research Needs

Following are recommendations to address research needs:

- **Establish procedures to quantify hazards over spatially distributed systems.** As identified in the *Earthquake-Resilient Lifelines: NEHRP Research, Development, and Implementation Roadmap* (NIST, 2014), there is an important need to develop modeling procedures, guidance documents, and standards for hazard quantification across geographically distributed systems, including network-specific hazard maps.
- **Develop performance goals for services that water and wastewater systems provide, as defined in Tables 7-4 to 7-6.** Additionally, describe how to utilize the same services to address critical facilities and other facility clusters needing special attention within the service area.
- **Develop guidance and protocols to check performance beyond the hazard levels adopted in design.** Some infrastructure is too big and important to fail. Designers therefore need to consider what may happen if an event exceeding the design level occurs. A security audit is needed to check performance beyond the design hazard level for critical infrastructure that is essential for community security and economic stability. A similar approach is required by the NRC for

U.S. nuclear power facilities, but does not exist for other critical infrastructure systems, including water supplies essential for regional and national security.

- **Perform research to determine how to close the gap between societal expectations and anticipated performance of water and wastewater systems for both design and extreme events.** See Table 7-10 for current comparisons of the societal expectations for restoration of water service following a design earthquake versus anticipated system recovery based on recent studies and documented system performance in prior similar design earthquakes.
- **Perform research on needed service restoration times in relation to other lifelines and overall societal expectations.** Give due consideration to accessibility services.
- **Perform studies on changes in water demand considering an array of hazards as well as seasonal and longer-term climate variability, like drought.** Loss of water due to hazard-related damage may be viewed as an imposed drought. Thus, a better understanding of community response to lack of water, including rationing and use of accessibility services, can be understood better by evaluating operator and customer response to actual drought conditions. For example, public response to the current California drought, manifested in significant reduction in water use, provides a unique opportunity to evaluate regional and local effects from actual reductions in supply, most effective measures for rationing, and successful public outreach and risk communication practices.

### *7.7.4 Modeling Needs*

Following are recommendations to address modeling needs:

- **Improve numerical modeling of water and wastewater systems, with emphasis on validation of models, developing the most effective simulation procedures, and applications in real systems.** The complex performance of water and wastewater systems in response to hazards, including in particular severe earthquakes and floods, requires complex network modeling to capture the effects that pipeline leaks and breaks, as well as the structural damage to treatment, storage, and control facilities, have on network behavior. Substantial progress in modeling complex water distribution response to hazards has been made, including algorithms for quantifying flow and pressure in heavily damaged hydraulic networks based on satisfying required nodal demands (e.g., O'Rourke et al., 2008; O'Rourke, 2010). Hydraulic network analyses are currently being developed for the Auxiliary Water Supply System in San Francisco on the basis of pressure dependent demand analyses (e.g., Jun and Guoping, 2013; Abdy Sayyed et al., 2014), with the potential for providing a more refined assessment of post-hazard water available for firefighting in this smaller pipeline network. There is a continuing need to improve these models.

- **Verify pipeline performance with the assistance of large-scale testing and develop the computational models for simulating the hazard response of the new generation of pipelines.** The next generation of water supply pipelines is currently being developed in response to enhanced seismic requirements from U.S. and Canadian water system owners, operating along the West Coast. In general, these pipelines are composed of ductile iron, steel, or polyvinyl chloride with special joints that allow for enhanced expansion/contraction and rotation in response to ground deformations. High and medium density polyethylene pipelines were virtually undamaged in Christchurch, New Zealand, during the Canterbury Earthquake Sequence in 2010-2011 (O'Rourke et al., 2014). A testing program to confirm their demonstrated performance in ground deformation, and a coordinated related program to develop computational models for simulating the hazard response of such systems, has the real potential for encouraging their widespread future use.

### *7.7.5 Lifeline System Operational Needs*

Following are recommendations to address water and wastewater system operational needs:

- **Develop practical strategies to enable water and wastewater systems to meet community needs.** Practical guidance is needed so that water and wastewater utilities can begin to develop resilient networks, for example, in a manner that allows for distinguishing between critical and non-critical facilities within the network. At present, all facilities located within a pressure zone are typically restored at a relatively equal pace, with no ability to fast track service to critical customers (e.g., hospitals) within the zone.
- **Develop consistent terminology and system characterization for use in creating a common set of performance goals.** Some terminology is often used interchangeably, even though there are specific differences in the technical definitions of the terms. Such terminology includes "performance objectives" versus "performance metrics" and "performance targets" versus "performance goals." Also, more consistency is needed in the use of terminology to characterize infrastructure systems. For example, this chapter defines water system components as "raw water supply," "treatment," "transmission," and "distribution" systems, and wastewater system components as "collection," "conveyance," "treatment," and "discharge/disposal" systems. By contrast, ASCE (1999) generalizes system characteristics as "source," "transmission," and "terminal" and identifies typical water system components as "transmission" and "distribution" systems. ALA (2005b) characterizes water systems in terms of

"transmission," "distribution," "facilities," and "key components" and ALA (2004b) characterizes wastewater systems in terms of wastewater "sources," "collection systems," and "treatment plants," and describes components within each category and how they relate to each other. There are many other system characterization schemes in the references cited in this report. Greater consistency and precision in the terminology will help in planning, modeling, design, and community resilience communication.

- **Foster a common understanding and use of the terms "dependency" and "interdependency."** Interdependency is often used imprecisely in reference to one-way lifeline dependencies. This use can overstate the interactions between some lifeline systems and detract from the recognition, modeling, and resilience of lifeline systems with more complex interdependent relationships.

### *7.7.6 Future Considerations and Trends*

Understanding the role provided by water, wastewater, and storm water management in supporting flood protection represents an opportunity for broader, more integrative planning to secure critical infrastructure. Further exploration of the dependencies among storm drainage, wastewater management, and flood control systems will help in planning for community resilience.

# Chapter 8
# Interdependent Infrastructure Systems

Infrastructure systems such as electric power, gas and liquid fuel, telecommunication, transportation, and water and wastewater systems are essential for the safety, economic vitality, and well-being of communities. These systems continue to grow in response to demands, as well as to adapt to technological advances, resulting in increased operational dependencies of one system on another or vice versa. These interdependent systems not only share resources, but may also share rights of way, and influence each other's management practices. They are influenced mutually by shared responsibilities, expectations of performance, and lifeline restoration times in the aftermath of a hazard event. Interdependencies generally increase reliability and efficiency during normal operation, but their effects in response to hazards are not fully understood.

Research on interdependent lifeline systems has started to influence emergency response and regional planning activities, including the use of emergency response coordination rooms, improved collection of data, and use of computational models. These efforts help infrastructure owners, government agencies, and communities understand interdependencies so they can be managed to support restoration efforts and fulfill community service expectations. However, societal expectations of performance and utility owner estimates of restoration are highly variable and context-dependent. To link community resilience with these expectations requires additional empirical evidence as well as new interdisciplinary models and analytical methods.

This chapter and Appendix E cover interdependent infrastructure systems, expectations of performance and restoration, emerging modeling approaches, and practical computational tools. It identifies gaps in research and implementation. It also assesses promising areas for future research, including interdependency management and emerging smart technologies to improve resilience.

## 8.1 Introduction to Interdependent Infrastructure Systems

The concept of interdependent infrastructure has changed over time. In the 1980s, concerns about aging public works led the National Council on Public Works Improvement (1988) to focus on public sector infrastructure, such as highways, roads, bridges, airports, public transit, water supply facilities, wastewater treatment facilities, and solid-waste and hazardous-waste services. In the 1990s, as a result of increased international terrorism, infrastructure was redefined in terms of national security. The President's Commission on Critical Infrastructure Protection, created in the summer of 1996, issued a report that emphasized critical infrastructure protection in the United States (Clinton, 1998; Marsh, 1997). After 9/11, the number of "critical" infrastructure sectors and key assets listed in the National Infrastructure Protection Plan (NIPP) was expanded to 17. In 2013 the number of critical infrastructure sectors in the NIPP was changed to 16 (DHS, 2013), including chemical; commercial facilities; communications; critical manufacturing; dams; defense industry base; emergency services; energy; financial services; food and agriculture; government facilities; healthcare and public health information technology; nuclear reactors, materials, and waste; transportation systems; and water and wastewater systems. Each of these sectors is linked with a governmental agency. NIPP 2013 places great emphasis on interdependencies across critical infrastructure, particularly reliance on information and communications technologies. The effects of extreme weather are identified as a significant threat to critical infrastructure, including rising sea levels, more severe storms, drought, and severe flooding. For a brief history on critical infrastructure protection in the United States, Brown (2006) is an excellent source.

As O'Rourke (2007) points out, the identification of numerous categories of critical interdependent infrastructure has provided for flexibility and adaptability, but has also led to ambiguities about which assets are critical and which criteria should be used to define them. To develop basic principles that govern performance and to clarify and understand interactions, it is helpful to consolidate thinking by focusing on a smaller number of sectors based on common traits. The lifeline systems covered in this report represent a subset of 16 NIPP critical infrastructure sectors and focus on the investigation of system interdependencies and associated societal expectations and considerations for their performance and restoration.

The designers of electrical networks and telecommunication systems, as key infrastructure sectors, are cooperating to improve intersystem operability. An annual report published by the ABB Group (2014) indicates that power networks can improve the system average interruption duration index (SAIDI), a measure of network reliability at the customer level during normal operations, by installing modern telecommunication systems in a handful of strategic substations. These efficiency-boosting connections result in more interdependent networks. In general, most couplings produce positive effects (Nan and Sansavini, 2015; Ouyang et al., 2015), mainly by allowing interdependent infrastructure systems to operate closer to their capacities, reduce contingency response times, increase situational awareness and control, reduce material and crew usage, and optimize task scheduling.

When hazards occur, interdependencies can become a liability if not properly managed (Ouyang and Dueñas-Osorio, 2011; Poljanšek et al., 2012). For example, during the 2003 Northeast blackout (Andersson et al., 2005), software and alarm systems failed, limiting awareness of system states, at a time when scenario-based and real-time contingency analyses were not routinely used after local failures (i.e., to assess system state and other contingencies). Multiple failures were triggered, which spread disproportionally from local events to system-wide loss of function. Operators could not contain these cascading failures, and the 2003 blackout spread throughout parts of the northeastern and midwestern United States and Ontario, Canada—ultimately affecting other infrastructure systems and many different communities (U.S.-Canada Power System Outage Task Force, 2004). Another example of unexpected interdependency effects came after Hurricane Sandy in 2012, which caused damage to petroleum supply infrastructure and electrical systems, thus triggering widespread power outages at retail fueling stations and associated gasoline shortages (DOE, 2013).

To account better for interdependency or coupling effects across systems, there is a need for design and operational standards as well as common performance goals that include reasonable restoration times. The development of standards is affected by the lack of data on performance and hazard event management across lifeline systems, as well as the absence of practical modeling and simulation methods for the study of interdependent infrastructure systems.

Only recently has the development of methodologies for the analysis and design of interdependent infrastructure systems become an active area of research. For instance, Figure 8-1 shows the number of published contributions and total citations

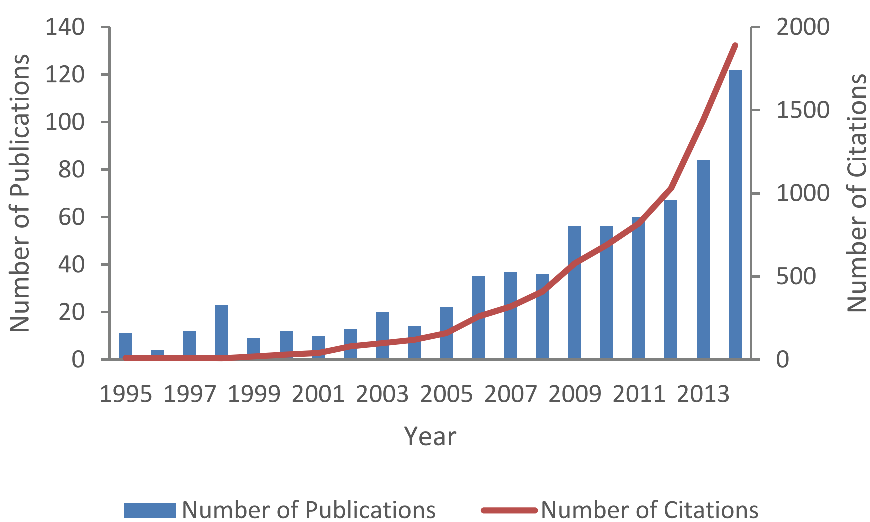



Figure 8-1 Number of papers and citations per year on "interconnected critical infrastructure" (compiled from data obtained from Thomson Reuter's Web of Science, https://webofknowledge.com/).

per year in this field of study. The steady rise in the number of contributions, particularly over the past 10 years, shows the increasing interest in this field.

The available literature suggests that the modeling and analysis of interdependent infrastructure systems is a rapidly growing subfield with both theoretical advances and practical applications. Given the interdisciplinary nature of interdependent infrastructure, joint contributions are needed from engineers, physicists, mathematicians, and applied social scientists. Such collaboration should advance the study of socio-technical systems (i.e., systems in which physical networks explicitly depend on actions from users and institutions that depend on services from infrastructure systems), their recovery processes, and their role in community resilience.

Some of the promising topics being explored on the socio-technical aspects of infrastructure focus on understanding and managing interdependencies to ensure service continuity after disruptive events (Wallace et al., 2003). However, the scarcity of data inhibits these types of analyses, which require significant empirical evidence and calibration to guide recovery and mitigation plans (Dueñas-Osorio and Kwasinski, 2012).

### *8.1.1 Classifying the Mechanisms of Interdependencies Among Infrastructure*

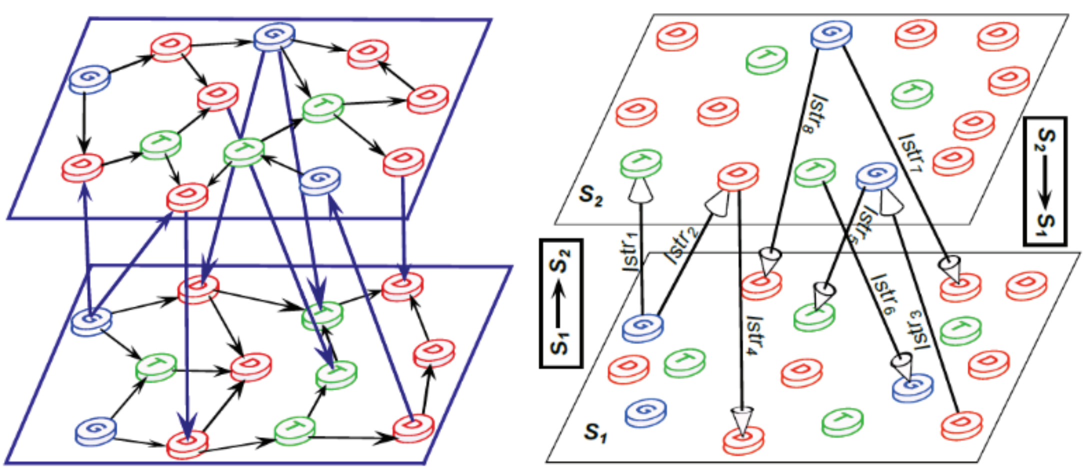
Recent literature on characterizing interdependencies (Dudenhoeffer et al., 2007; Johnson, 2014; Lee II et al., 2007; Ulieru, 2007), aligns most closely with the classification proposed by Rinaldi et al. (2001), which presents a general description of interdependencies than can be adapted to a broad range of technical and social considerations. The interdependency mechanisms are physical, geographic, cyber, and logical, all of which are interrelated.

Physical interdependence refers to the case when the performance of a given network depends on the outputs of other networks, such as power and telecommunication networks in which a power outage may impair some data centers and routers in the latter, in turn limiting power system state estimation. Geographic interdependence emerges when a local event influences the state of other networks through damage/interruption of components located nearby or along shared rights of way. For example, fixing an underground water pipeline can affect local transportation, slowing traffic and interfering with local businesses. Cyber interdependence occurs when the interdependence between two networks is based on shared information. The Smart Grid (Farhangi, 2010) is an example, wherein the telecommunication networks manage situational awareness information to maintain or restore electric power. Finally, there is logical interdependence when systems are interconnected through channels different from the previous ones. In particular, logical interdependence is observed when human decisions affect the state of the networks, for instance when decision makers prioritize the recovery of a particular network over others.

### *8.1.2 Methods for Modeling Interdependencies Among Infrastructure*

There are a number of model types used to simulate infrastructure interdependence. From a general perspective, such models can be grouped according to their goals in the following overlapping classes: performance evaluation, design, mitigation, and recovery models.

Performance evaluation models focus on numerical or analytical tools to understand the behavior of a given system and how interdependencies affect performance and resilience. These models tend to rely on mean field theories, Monte-Carlo simulation, network and reliability theory, and economic input-output principles among others (Barker and Haimes, 2009; Brummitt, Souza, and Leicht, 2012; Johansson and Hassel, 2010; Kim, Kang, and Song, 2012; Zhang, Peeta, and Friesz, 2005). Detailed reviews of existing and promising modeling techniques for interdependent infrastructure systems are available elsewhere (Ouyang, 2014; Pederson et al., 2006; Satumtira and Dueñas-Osorio, 2010). Note that in this type of performance modeling, one-way dependencies are a special case of interdependencies (i.e., two-way dependencies) for which there is no coupling from one system to another (see Figure 8-2). The figure shows fundamental features that contribute to interdependence, including types of interacting facilities (e.g., utility generation, transmission and distribution elements), geographical location of interactions, and intensity with which systems interact (e.g., via commodity flows), as captured in a normalized fashion




(a) (b)

Figure 8-2 Schematic of interdependent lifeline systems: (a) typical coupling across systems composed of generation (G), transmission (T), and distribution (D) elements along with their coupling locations, density of interconnections, and direction of commodity flow; and (b) specific coupling parameters across systems $S_1$ and $S_2$, including the intensity with which systems depend on one another (i.e., interdependent strength, *Istr*).

with a parameter called interdependence strength, *Istr*. This parameter is particularly useful in computational modeling, as it captures one-way dependencies when *Istr* = 0 in a specific direction, or full interdependencies when it is non-zero in both directions. Also, interdependence strength can vary with time, so *Istr*(*t*) would be able to reflect the evolution of interdependencies before, during and after contingencies occur.

To account for the effects of interdependence analytically, some studies explored coupled networks and their vulnerability to collapse and catastrophic cascading failures (Buldyrev et al., 2010; Huang et al., 2013; Cellai et al., 2013). Alternatively, other studies used numerical methods to show the importance of including interdependence *evolution,* or time-dependence, when assessing multi-system response to hazards (Hernandez-Fajardo and Dueñas-Osario, 2011; Zhang et al., 2016). Complex connections between different networks can lead to varying responses, including cascading failures. For instance, when hazard levels are low or routine, then disruptive effects are absorbed locally and interdependencies do not tend to amplify failures. When hazard levels are high or extreme, substantial system damage can occur, which predominates over adverse effects from interdependencies.

To acknowledge the dynamics of interdependent systems, Ulieru (2007) presented a methodological approach based on self-aware networks able to identify vulnerabilities and reconfigure themselves. More specific to urban infrastructure networks, Ouyang and Dueñas-Osorio (2011) presented an approach to design interface topologies across interdependent networks, focusing on minimizing cascading failures. Amin (2002) described the complexity of realistic interdependent networks (such as transportation, power, telecommunications, and financial, among others) and highlighted strategies to improve their security. Yagan et al. (2012) presented an approach for optimal allocation of interconnecting links between two cyber-physical networks to enhance their ability to withstand random attacks.

Research has recently concentrated on the dynamics of network interdependency during recovery. Lee II et al. (2007) presented a general network flow model for infrastructure restoration from the field of operations research by using mixed integer linear programming. Such a model determines which components should be reconstructed to recover a damaged system, but does not include costs related to the reconstruction process or provide guidance on scheduling the reconstruction work. Cavdaroglu et al. (2013) used mixed integer linear programming models to jointly study network restoration and scheduling for interdependent infrastructure systems, in which an explicit time index is used to assign reconstruction periods.

Although most restoration models are broad and consider functional interdependencies, they do not include colocation, limited availability of resources, or multiple recovery times. Recovery goals change from short-term to intermediate- to long-term, and this evolution requires models whose mathematical structures remain simple enough for general applications, yet suitable for addressing the hierarchical structures needed to support decision-making.

The modeling and design of interdependent networks should account for socio-technical constraints, evolving performance over time, and preparation for future hazards. The Interdependent Network Design Problem and its related models allow for such an initial approach (González et al., 2015).

## 8.2 Trends Across Interdependent Infrastructure Systems

There is growing interest from government and industry in enabling resilient interdependent infrastructure. The NIST *Guide* (NIST, 2015), for example, addresses interdependencies and cascading effects, as well as linkages between system performance goals and the built environment. Presidential declarations have designated September and November as the month for national preparedness (Obama, 2014b) and critical infrastructure security and resilience (Obama, 2014a), respectively. And national laboratories continue to invest resources on monitoring and modeling complex socio-technical systems (as detailed in the next subsection). Also, countries such as Australia, Canada, New Zealand, the United States, and the United Kingdom have already adopted critical infrastructure and emergency management plans (Her Majesty's Treasury, 2014; Ministry of Civil Defence and Emergency Management, 2015; Public Safety Canada, 2014; DHS, 2013). Yusta et al. (2011) provide additional perspectives on national-level initiatives towards interdependent critical infrastructure protection.

Despite the growing interest in infrastructure protection and interdependencies, there are no unified performance and restoration goals, and no methodology to account for interdependencies within the appropriate social, physical and economic contexts. Lifeline systems are the backbone for smart cities where cyber-physical couplings support community well-being and resilience (Genge et al., 2015; Kelic et al., 2008). Smart city initiatives in progress include those for Chicago and Glasgow, where sensing systems are being installed to monitor and learn about the built environment (Mone, 2015).

The great majority of studies to date about interdependent infrastructure have focused on the technical aspects of infrastructure and the impacts of hazards. The studies typically examine how long and what kind of resources are required for a given system to restore service, system-level risks posed by a critical component, or the expected monetary loss from a given hazard event. A literature survey of 140 documents, with close to 75% of them published since 2010 in the general field of interdependent infrastructure systems (see Appendix E, Sections E.1 and E.4), shows that risk assessment and management are the dominant themes of the studies, followed by interdependency effects, and cascading failures.

Figure 8-3 presents a bar chart constructed after analyzing the surveyed papers, where the relative change in publication output between 2010 and 2015 is contrasted with the output between 2005 and 2010 in terms of the types of infrastructure systems studied. Recent work in the technical literature typically involves various combinations of power, water, transportation, and telecommunication systems. Also, studies involving natural gas systems and supervisory control and data acquisition (SCADA) technologies are becoming more prominent, whereas studies involving economics, social systems, and public health have decreased in the last five years, after a rapid increase in publications after Hurricanes Katrina and Rita in 2005, and other contemporary disasters worldwide. Details regarding frequencies of infrastructure systems mentioning other systems, preferred mathematical and computational methods, hazard events, and the association of systems and methods of analysis are available in Appendix E, Section E.1.

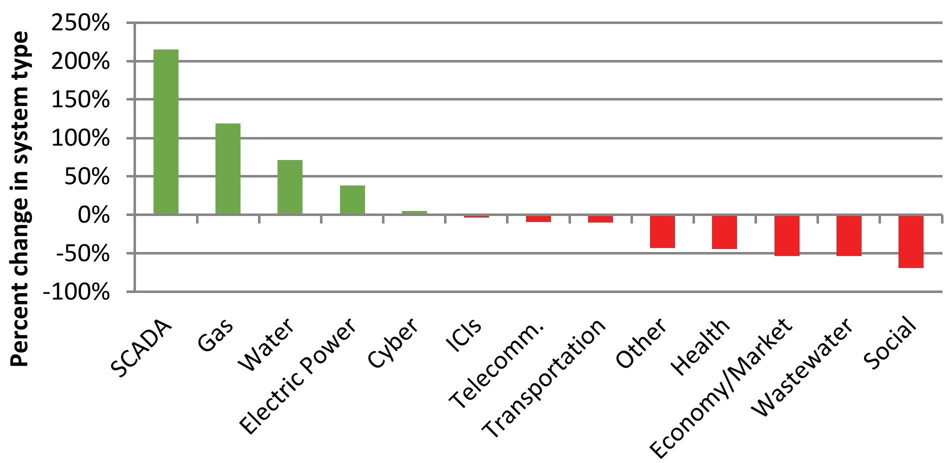



Figure 8-3 Percent change in the types of infrastructure systems analyzed between documents published in 2010-2015 relative to 2005-2010. ICIs: interdependent critical infrastructure systems.

Table 8-1 summarizes frequencies of surveyed documents in which the infrastructure system publications (left column) also mention other infrastructure systems (listed in top row). From this summary, important pairings and their frequencies can be highlighted: electric power-water, where 54% of the documents focusing on electric power networks are also paired with water networks; wastewater-water-electric power, where the wastewater studies of the sample always include water and electric power networks; SCADA-electric power, where the SCADA sample literature always involves electric power networks; telecommunications-electric power, where telecommunications are almost always paired with electric power networks (92% of the time in this study's sample); gas-electric power, where almost all gas papers involve electric power networks (93% of the time); and socio-economic, when

**Table 8-1 Frequency of Infrastructure System Publications Mentioning Infrastructure Systems**

| | Power | SCADA | Water | Wastewater | Telecomm. | Gas | Transport | Health | Cyber | Other | Economy | Social |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power | 100% | 11% | 54% | 7% | 35% | 29% | 32% | 11% | 3% | 23% | 15% | 11% |
| SCADA | 100% | 100% | 30% | 0% | 40% | 20% | 30% | 30% | 30% | 20% | 10% | 20% |
| Water | 96% | 6% | 100% | 13% | 38% | 34% | 38% | 13% | 4% | 25% | 13% | 11% |
| Wastewater | 100% | 0% | 100% | 100% | 71% | 43% | 71% | 43% | 0% | 43% | 29% | 29% |
| Telecomm. | 92% | 11% | 56% | 14% | 100% | 25% | 44% | 17% | 3% | 36% | 14% | 11% |
| Gas | 93% | 7% | 62% | 10% | 31% | 100% | 31% | 14% | 3% | 17% | 28% | 14% |
| Transport | 70% | 7% | 47% | 12% | 37% | 21% | 100% | 21% | 5% | 51% | 26% | 16% |
| Health | 77% | 23% | 54% | 23% | 46% | 31% | 69% | 100% | 8% | 62% | 31% | 31% |
| Cyber | 60% | 60% | 40% | 0% | 20% | 20% | 40% | 20% | 100% | 20% | 20% | 20% |
| Other | 59% | 5% | 35% | 8% | 35% | 14% | 59% | 22% | 3% | 100% | 16% | 27% |
| Economy | 67% | 5% | 33% | 10% | 24% | 38% | 52% | 19% | 5% | 29% | 100% | 43% |
| Social | 59% | 12% | 35% | 12% | 24% | 24% | 41% | 24% | 6% | 59% | 53% | 100% |

Note: Governing system publications are shown in the left column; infrastructure systems are listed in the top row; green shading denotes highest mention frequency and red shading denotes lowest frequency. For example, in the reviewed studies, SCADA (supervisory control and data acquisition) system documents always mention power systems, but never wastewater systems.

sampled social systems are paired 53% of the time with economic networks. In general, all network categories share a strong relationship with electric power networks.

There is a lack of research on cyber networks (and network security in general), when accounting for their interactions with other infrastructure systems. Specifically, the impact of cyber networks has not been widely evaluated for telecommunication, gas, wastewater, health, economic, and social networks. These connections require research. The Institute of Electrical and Electronics Engineers (IEEE) and the Centre for Energy Advancement through Technological Innovation (CEATI) are creating guidelines for telecommunications-electric power networks because these connections must be secured against cyber-attacks and network failures given their increasing interdependence.

Papers studying health networks frequently make connections not only to lifeline systems, but also to commercial, residential and governmental buildings and services. This dependence suggests a need for research into health networks, their supply chains, and building portfolios. Additionally, transportation network studies are weakly linked to many other networks, despite how crucial transportation is for resilience, suggesting that transportation dependencies and their multiple modes require further investigation.

In the future, other network pairings will become important. Telecommunications clearly depend on the electric power network. As technology advances, power systems will become more dependent on telecommunication technology. Although telecommunications promote a more reliable power network under normal operating conditions, their benefits in disaster scenarios are still uncertain.

The body of knowledge is still scarce regarding the socio-technical aspects of interdependent infrastructure, in which humans manage physical infrastructure systems and consume their commodities. Both communities and governments are unsure about optimal preparations for and response to hazards. Recent findings suggest that residents may be more sensitive to the seriousness of the risks as opposed to the types of risks (Morrow et al., 2015; Stein et al., 2013; Whitehead et al., 2000). Such studies suggest a useful approach that focuses first on overall expectations of performance at the community level, as opposed to expectations of technical performance for each lifeline system.

Some general trends exist, which provide initial proxies for performance and restoration goals. These proxies include: (1) recommendations from local emergency management offices, (2) volunteered data from utility operators (restoration times based on past experience), (3) post-processed data from increasingly used outage trackers to determine spatial location of outages and their duration, and (4) restoration times from analyses of post-disaster functionality curves for different utilities. Other sources of information, which are less readily available, include various types of funded capital investment projects, upgrades to design guidelines and standards, and table top exercises.

Appendix E, Section E.2 provides source data from utilities and municipalities that can serve as "proxies" for societal expectations of infrastructure performance and restoration times. Table E-2 lists publicly disclosed recovery expectations from utility companies, and Table E-3 lists publicly disclosed recovery expectations from public entities.

## 8.3 Practical Tools and Case Studies for Interdependent Infrastructure Management

A number of software packages and models have been produced to inform utility owners about the response of infrastructure systems to various hazards. Using a survey of modeling and simulation tools by Adam et al. (2011) and Haimes et al. (2005), in combination with the survey conducted for this report, several trends with respect to modeling capabilities and deficiencies have been identified.

First, the vast majority of modeling tools available to researchers, governmental agencies, and communities can handle multiple systems. Almost all these models provide risk and damage assessments for hazards. The models, however, provide limited guidance on how to reduce risk and do not provide guidance on how to restore systems and communities after a disaster. In general, these tools do not account for the socio-technical aspects of infrastructure, especially the decision-making process by operators and users that influence infrastructure systems.

Second, the vast majority of the models are calibrated and validated, to the extent possible, using case studies after disasters. Most of the case studies are from U.S. post-disaster experiences. Other popular test bed locations are New Zealand and the European Union. Additionally, many models use artificial case studies that are representative of actual infrastructure systems.

Third, there is a wide variety of risk assessment tools available; many are privately developed and some are for public use (e.g., HAZUS or ResilUS), and can include resilience considerations (FEMA, 2012; Miles and Chang, 2007). However, it is not clear what tools a particular community should use. Efforts are needed to aggregate these tools, improve their input and output capabilities, expand scales of use, and create a user-friendly interface so that communities can actually use them in a consistent and effective way. Efforts are also needed to include social systems in these models so that they can be adapted to community characteristics and expectations, and be used to support decisions about real world processes.

In addition, it is becoming clear that agent-based, system dynamics, and game theoretic modeling coupled with infrastructure system simulations provide a promising approach for merging social and technical systems. National laboratories are well equipped to handle the computational demands of these models. Work on interdependent infrastructure systems at six laboratories is reported below, including the Los Alamos National Laboratory, Sandia National Laboratories, Idaho National Engineering and Environmental Laboratory, Argonne National Laboratory, Pacific Northwest National Laboratory, and the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA).

- **Los Alamos National Laboratory.** Work at Los Alamos has concentrated on optimization-based restoration that casts the problem of interdependent system reconstruction into a mixed integer programming framework typically studying regional and city-level systems (Coffrin et al., 2012). As for integrative infrastructure modeling efforts, actor-based infrastructure tools as well as multi-scale approaches have been pursued to cover operational coupling across energy infrastructure as well as malicious disruptions and multi-system responses (Quirk and Fernandez, 2005; Visarraga et al., 2005). McPherson and Burian (2005) focused on the simulation of potable water distribution systems, sewage collection and storm water infrastructure in collaboration with the National Infrastructure Simulation and Analysis Center (NISAC). Recent work explores decision support tools for critical infrastructure protection, with applications to pandemics and in collaboration with the Sandia National Laboratories for the Department of Homeland Security (Fair et al., 2007). There are also ongoing efforts studying the effects of large-scale global warming on infrastructure systems and the benefits of small scale microgrids for community resilience.

- **Sandia National Laboratories.** These laboratories developed functional modeling and simulation methods for infrastructure and attendant interdependencies through various computational strategies. For example, the use of system dynamics, nonlinear optimization, and reliability and risk analyses has been pursued in collaboration with NISAC for multiple infrastructure systems (Conrad et al., 2006; Min et al., 2007; Rinaldi, 2004). Agent-based macroeconomic models have been used to represent interactions between physical and institutional systems, such as electric power and its open market environment (Ehlen and Scholand, 2005). Other related simulation frameworks, such as complex adaptive systems, have been applied for capturing the multiple scales of infrastructure systems, ranging from individual users to an entire nation (Brown et al., 2004). Work in collaboration with NISAC and DHS includes the study of supply chains, particularly those disrupted when conveying chemicals, such as ethylene or chlorinated hydrocarbons, which are critical for a wide range of manufacturing (Pepple et al., 2011; Welk et al., 2010). This laboratory is also currently working on strategies to defend infrastructure systems against cyber attacks, as well as techniques to model complex systems with limited information.
- **Idaho National Engineering and Environmental Laboratory.** This laboratory provided some of the initial modeling for the simulation of interdependent infrastructure systems at the local level (Pederson et al., 2006). Also, this laboratory produced heuristic approaches for modeling infrastructure systems, together with the incorporation of uncertainty and decision support in integrated systems (Dudenhoeffer and Manic, 2008; Dudenhoeffer et al., 2007; Permann, 2007). More recently, efforts have focused on the behavior of coupled infrastructure networks and industrial processes, their cyber support systems, and the challenges of distributed control (Rieger et al., 2012; Walsh et al., 2009). This laboratory also has access to the Critical Infrastructure Test Range—a physical electrical network the size of a small city—which allows performance testing on real-world infrastructure systems.
- **Argonne National Laboratory.** This laboratory was among the first to engage in regional infrastructure modeling via computational approaches, including the markets and economic sectors that are supported by infrastructure (DeMarco et al., 2001; North, 2001; Peerenboom and Fisher, 2007). Agent-based and complex adaptive system modeling tools were used to analyze cross-sector national interdependencies. More recently, this laboratory has focused on the risk assessment of interdependent waterway facilities and systems, including disruptions and cascading failure effects (Folga et al., 2009, 2010).

- **Pacific Northwest National Laboratory.** This laboratory has focused mainly on the modeling and simulation of electric power systems at various scales. A modular simulation environment is currently being pursued to include generation, transmission, sub-transmission, and distribution systems (Chassin et al., 2008). Topological analyses of these electricity systems have also been conducted (Chassin and Posse, 2005). This laboratory has recently emphasized real time system analysis and control for smart grid applications.
- **Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA).** This institution has an active research program on multi-scale infrastructure interdependencies, which ranges from measuring the intensity of interdependence across regional systems, to the assessment of multi-system, multi-scale, and multi-domain simulation platforms (Bologna et al., 2003; Casalicchio et al., 2010; Ruzzante et al., 2010). Studies with practical risk analysis applications include electric power systems combined with telecommunications via SCADA (Bobbio et al., 2009). Also, ENEA has addressed the problem of incomplete data for modeling complex interdependent systems via heuristic optimization tools (Fioriti et al., 2009).

In summary, modeling activities at national laboratories, universities, and affiliated institutions have focused on coupled infrastructure, quantification of coupling strength or intensity, distributed control of interdependent systems, supply chain disruptions, and the effects of uncertainty on data-intensive system problems. These complex problems are routinely addressed by computational simulation for decision support tools. Agent-based modeling, complex adaptive systems, and multi-domain simulation platforms are the preferred approaches for capturing the behavior of complex physical-institutional-user systems, mainly at regional and city-level scales. In terms of hazards of interest, the national laboratories focus on cyber and physical attacks, hazards with long-term effects such as global warming, and intermittency issues related to renewable energy. In comparison, the academic communities mainly study random failures and natural hazards, particularly earthquake events.

The most commonly studied lifelines in computational simulation include electric power and telecommunication systems, water and wastewater networks, and waterway systems. Restoration and recovery processes are in the initial phases of development.

Emerging needs of national importance include predicting the impacts of smart grid and microgrid technology, and determining the resilience of interdependent networks, especially when coupled with telecommunication and cyber technology. Natural gas networks are also particularly important, mainly due to their current role in the U.S. energy portfolio.

## 8.4 Challenges and Opportunities in Interdependent Infrastructure Systems for Community Resilience

To assess community resilience, it is necessary to understand recovery *processes* and the use of modern post-disaster data. These databases in turn support first-generation computational models and enable meaningful scenario-based socio-technical simulations. The empirical approach calibrates the decision making process over time with respect to observed performance, while the computational approach reveals the mechanisms that lead to particular restoration patterns. These two complementary approaches are influenced by human dynamics and their effects on infrastructure system operations and decision making (Gómez et al., 2014a; Zhang et al., 2005).

Practical modeling of interdependent infrastructure should include the failure process and the recovery process. Physical, geographical, cyber and logical couplings (Rinaldi et al., 2001) all affect performance and restoration times.

An example of interdependent lifeline modeling involves the work of Paredes-Toro et al. (2014) in which spatial and temporal changes in interdependence between electric power and water networks were approximated by local correlations between the cities of Concepción and Talcahuano in the aftermath of the 2010 Chilean earthquake. The linear correlations for restoration times at various locations in the cities of Concepción and Talcahuano after the 2010 Chile earthquake were mostly positive, indicating that electric power and water networks were both recovering similarly as a function of time. Further research is needed with respect to the spatial and temporal evolution of lifeline services to provide more robust and comprehensive models for the restoration of interdependent infrastructure systems.

Current models of interdependent infrastructure restoration often assume that recovery strategies can be developed and implemented through a unified and coordinated process. However, in practice there are significant institutional and operational differences across lifeline systems, with each infrastructure system being handled largely independently in highly decentralized decision making processes. Thus, it is imperative to optimize recovery processes with models that can simulate decentralized dynamics and socio-technical decision making during restoration (Gómez et al., 2014b; Rudnick et al., 2011; Shi et al., 2015).

There are interdependencies among different utilities and the many community-level organizations that use them. Thus, it is desirable to assess how loss of function in utilities affects community services. To organize these relationships, an array may be helpful, as hypothetically shown in Figure 8-4 for possible utility and service pairs. Each pair of utilities and services describes a dependence strength (one-way dependence of a service on a utility system), and restoration time expectations from the view point of service requiring utility commodities (for other dimensions at the base of array, see Appendix E, Section E.3).

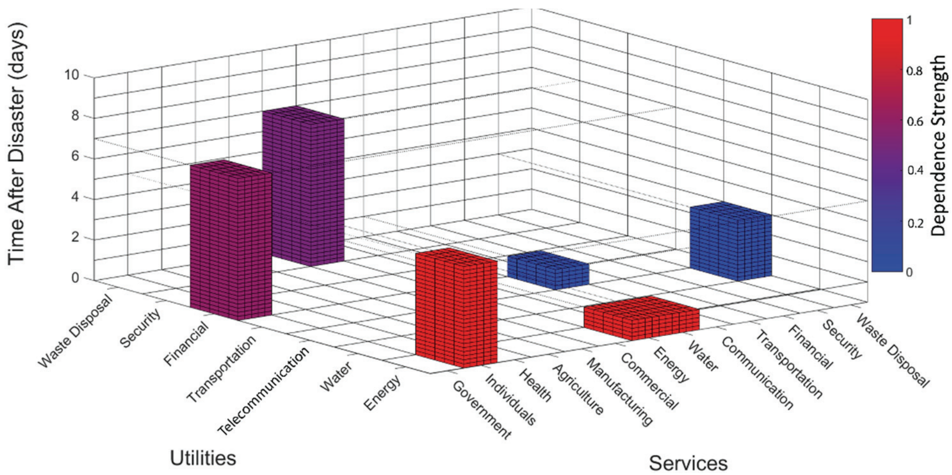



Figure 8-4 Hypothetical multi-dimensional array illustrating the dependency of various community and institutional needs on the provision of utility, lifeline and other services, expressed in terms of the time required (in days) to restore services after a disaster has occurred. Variation in colors depicts strength of dependency.

The idea behind the array is to capture the relationships between infrastructure systems and societal and institutional needs to help inform prioritization of resources. In the array shown in Figure 8-4, water and energy services show a high dependence on energy utilities (red color) and a day restoration time expectation. Financial systems are shown to affect government services (purple color), with governments expecting 7 days before financial systems recover functionality.

Such an array could guide modeling efforts for interdependent infrastructure research and implementation (DHS, 2014; Lee, 2014). It could also be used to synthesize what is known and what is missing in terms of societal and institutional expectations of performance, interdependencies, and restoration times to support community resilience.

## 8.5 Conclusions and Recommendations

Interdependent infrastructure systems are integral to modern societies. These systems are typically influenced by physical infrastructure such as energy, telecommunication, and transportation networks, as well as financial, social, and information networks. Technology, with the promise of greater efficiency and safety, is expanding and linking these systems. Technology introduces benefits as well as unique and largely unknown behaviors (and possibly liabilities). Variations of interdependence in space and time, and the role of decision makers and users, all affect the performance of interdependent infrastructure systems, particularly in response to hazards. Thus, knowing the societal expectations of service restoration will contribute to community resilience planning.

Key recommendations to improve the understanding of interdependent infrastructure systems are presented below. Recommendations pertain to design, operations and research and are based on the discussions in this chapter and material in Appendix E.

- **Develop practical tools for the modeling, analysis, visualization, and design of interdependent infrastructure systems at multiple scales**. Researchers have been developing multi-scale models of infrastructure systems that address interdependencies from local to national scales. Recent programs and resources from government agencies clearly indicate the need for such tools to become practical for widespread use. Initial efforts have focused mainly on the integration of generation, transmission and distribution across electric power systems (including decision-making from the executive to service area manager level). Improvements in modeling and visualization for cyber, telecommunication, economic, and social systems are needed, all of which are essential for community resilience assessment and emerging smart cities.
- **Develop a unified model for interdependent infrastructure systems.** There are favored modeling approaches for each system. For instance, network and reliability theory are preferred for electric power systems, and input-output models are favored for regional economic interactions. There is a need for a unified model that addresses the interdependencies of systems in modern communities. Such a model may involve consideration of real-time data, including societal and institutional behavioral data, to make informed decisions about community interactions and restoration priorities. Socio-technical processes unfold at multiple spatial and temporal scales, which require novel methods to capture evolving interactions and nested hierarchies.
- **Focus on understanding restoration processes across interdependent infrastructure systems.** To support decision making and resource prioritization, there has been significant work quantifying and modeling the risks faced by communities subjected to hazard events. However, there is a distinct lack of integrated system modeling that includes interdependencies of community recovery processes.
- **Develop tools to identify interdependent infrastructure systems and services along with their restoration criteria.** Tools should be developed to help synthesize field data, societal expectations and considerations, expert opinion, best practices, and interdependent system models relative to community resilience restoration goals. For instance, a tool, such as the array presented in this chapter, can include desired and expected restoration times that are relevant to emergency management, utility operator information, outage trackers, and restoration curves. Such arrays could help organize the current body of knowledge, identify investment priorities, enable study of dependency strengths,

restoration times, and other pertinent information, and provide insight on interdependencies between infrastructure systems and services.

- **Develop guidelines to inform the design, interoperability, and improvement of interdependent infrastructure systems.** Guidelines are needed for interdependent infrastructure operation, protection, restoration, and interface design across systems. Some guidance for interdependent designs exists for electric power and telecommunication systems. For example, the International Electromechanical Commission (IEC, 2003) has developed standards for the design of automated electrical substations with telecommunication protocols for timely control and secure interoperability. Best practices and computational models that address interdependencies and restoration of services provide opportunities to advance the understanding of socio-technical systems and their role in community resilience. What-if scenarios can be used in models to inform decision processes and generate new data for further calibration, measurement and validation.

Infrastructure systems are interdependent with each other and the communities they serve. Any changes to the systems, whether intentionally through upgrades or unintentionally after hazard events, will affect dependent systems and societal processes. Proper management of interdependencies will strengthen community resilience, particularly as smart technologies are integrated with infrastructure. Neglect of these issues can lead to cyber attacks, cascading failures and difficult restoration processes. Interdependent infrastructure systems provide many opportunities for research and implementation to improve decision-making at the community level.

# Chapter 9
# Findings and Recommendations

This chapter synthesizes the results of the assessments of lifeline system performance and the societal needs related to lifeline systems in hazard response and recovery. Specifically, Section 9.1 summarizes key findings related to the current state of lifeline codes, standards, guidelines, and performance requirements for different hazards and disruptions; the current state of knowledge about societal considerations and expectations for lifeline performance and recovery timeframes; critical interdependencies, both among different lifeline systems and the societal-serving functions that they enable; major disaster-related insights about lifeline performance and societal expectations; the key gaps and deficits between the current state of lifeline systems performance and recovery timeframes and our best understanding of societal expectations; and future considerations and trends that are beyond the scope of this study but merit further attention over time. Section 9.2 contains a series of recommendations organized to identify the needs associated with: lifeline standards, research, modeling, and lifeline system operations.

## 9.1 Findings

### *9.1.1 Lifeline Codes, Standards, Guidelines, and Performance Requirements*

The NIST *Guide* (NIST, 2015) provides a comprehensive review and discussion of codes, standards, guidelines and manuals for all the systems specifically reviewed in this study. The information provided in the NIST *Guide* has been referenced and augmented in some cases.

Overall, the study surveyed many of the codes, standards, guidelines and manuals that govern the design, construction and performance of key lifeline systems and system components. They are developed in a variety of ways to achieve functionality and safety, and to address system performance and reliability. They vary considerably from system to system and they represent various levels of consensus—most typically among operators, regulators, and engineering experts. Codes for interdependent systems are also starting to emerge, particularly in the interoperability of automated electrical substations and telecommunication systems.

Some commonalities and trends have emerged from this survey, which are relevant for improvements in community-scale resilience. In particular, there are gaps in codes and standards for the infrastructure systems reviewed. Codes, standards, guidelines and manuals tend to emphasize component-level rather than system-wide performance. They tend to cover minimum levels of safety or performance (e.g., for extreme loading conditions) of components as opposed to system response and levels of service. Most address day-to-day operations and do not cover the range of hazard types considered in this study, particularly the extreme, low-probability, high-consequence events.

The processes by which lifeline codes, standards, and guidelines are developed tend to be reactive and based upon past information. This may result in significant time lags before the latest information on hazards is incorporated into updates. Furthermore, some standards and guidelines have not necessarily been developed following rigorous and systematic processes.

The performance requirements within lifelines codes, standards, and guidelines tend to mainly address engineering for system design and construction and operational concerns, taking into account different, but a generally more limited set of societal considerations. Life safety, public health, public safety, emergency response, personnel safety, critical service provision, property and monetary loss prevention, and environmental protection are some of the most prevalent societal considerations identified in the performance requirements established by standards and codes for lifeline systems. In particular, failures in some lifeline systems (e.g., natural gas, liquid fuel, and transportation) and some lifeline service outages (e.g., power, telecommunication (911), natural gas, water, and wastewater) that can contribute to mortality and morbidity are given the greatest emphasis in codes and standards.

For electric power, gas and liquid fuel systems, certain measures of system performance are routinely assessed and even required to be reported to regulators. These measures generally address outages during normal operations and operations and often exclude disruption caused by hazard events, which can distort the true costs and impacts of system disruption and restoration. For example, electric power providers routinely report System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI)—which generally exclude data during disruptions due to hazard events.

With possibly a few exceptions, most system performance measures are not directly informed by or linked to societal expectations, nor do they differentiate between customers or consider differential hardships imposed on society from varying durations of outage. The direct and indirect costs to customers will likely vary with the duration of system disruptions (i.e., mere inconvenience in the first few hours to severe hardship after weeks of lost service). One notable exception is the service level agreement (SLA) for telecommunication systems. SLAs establish thresholds for customer service and outages that trigger contractual penalties to the system providers. However, at present, disruptions caused by hazards such as earthquakes, hurricanes, and man-made threats are generally excluded from such agreements.

The lifeline assessments also identify a number of examples of system restoration guidelines that are generally informed by an array of societal expectations that include: public safety, mobility, business continuity, and environmental protection. System restoration times and guidelines tend to be governed by scenarios often derived from recent disaster experience or the largest disruption in the region. They may not take a robust view of the range of potential hazard types or levels of hazard severity that could affect the system.

The degree to which lifeline system codes, standards and guidelines address the provision of substitutions, temporary solutions and accessibility services (e.g., bottled water and portable toilets) for lost services also varies considerably by system. Such substitutions and temporary solutions (both within and between systems as well as those undertaken by society) can significantly affect performance outcomes and societal expectations, impacts and recovery following disruption.

It is also important to recognize that codes and standards are not the only influence on lifeline system design; factors such as voluntary measures to exceed standards, injunctions of regulatory authorities to improve performance in hazard events, and other risk management practices also influence the resilience of lifeline systems. Also noteworthy is the considerable variability in lifeline system regulation and enforcement by system, hazard, and geography (i.e., national vs. state, state-to-state, and locally). Natural gas, liquid fuel, and electric power all have regulatory data requirements focused on safety and reliability. In particular, for gas and liquid fuel pipelines, there is a nationally-consistent regulatory framework defined by federal legislation. Federal regulations also guide telecommunication systems, whereas, few states now regulate Internet-based telecommunications. However, while most US jurisdictions adopt the latest codes and standards and some even add more stringent requirements to them, other jurisdictions may not adopt them in their entirety or may reduce some requirements. Even if codes and standards are adopted, their effectiveness may be jeopardized by poor enforcement during planning, design and construction of infrastructure components. This disparity in code adoption and enforcement can have significant consequences for community resilience.

### *9.1.2 Key Societal Considerations and Expectations of Lifeline System Performance*

This study has been challenging in part because of the almost total lack of empirical data on what members of the general public regard as acceptable lifeline performance following disruptions. Without such data, the study team has had to make inferences about those expectations. Gauging societal expectations is also challenging because

U.S. society is highly diverse. Expectations can vary across individuals, households, and businesses as a function of a number of factors, including: vulnerability and resilience characteristics; geographic location; hazard (including event severity, probability and duration); lifeline type; available information on the impacts of disruption; prior experience and knowledge about service disruptions; levels of resulting losses; public perceptions of the trustworthiness and competence of service providers; and the availability of substitutes and contingencies that can compensate for lifeline outages.

It is also important to understand that public expectations and tolerances for lifeline service disruptions are dynamic and likely to be shaped by both risk perception and risk communication. Factors affecting risk perception include prior experience with hazards and lifeline outages, substitutability and dependency on lost services, and available information on the impacts of disruption. Other things being equal, disruptions may be tolerated for longer periods in severe and catastrophic events than in less serious ones, because the public will be more willing to accept that extreme hazard events are more difficult for service providers to anticipate and mitigate. Public confidence and the past performance of lifeline service providers (both during routine operations and prior hazard events) can also influence expectations and tolerances.

Public perceptions and expectations are also shaped by communications regarding the risks associated with past disasters and lifeline outages. Lifeline service providers should work with emergency management, public safety, and other governmental agencies to ensure that risk communication messages reach and are understood by the affected public. Additionally, there is evidence to suggest that societal expectations and tolerances may be changing, as social and economic activity becomes more dependent upon highly reliable service provision, particularly with regard to electric power and telecommunication systems.

Using terminology from vulnerability science and resilience research, various segments of the population and sectors of the economy are differentially exposed, differentially sensitive, and differentially adaptable to lifeline service disruptions. Because vulnerability and resilience vary as a function of exposure, sensitivity and adaptive capacity, risks associated with lifeline service disruptions are not borne equally by all members of society but are imposed disproportionately on already vulnerable social and economic groups.

One approach to assessing likely societal expectations is to take a closer look at how lifeline performance and disruption can have deleterious effects on things that society members value most. This approach is consistent with the NIST *Guide* (NIST, 2015) which uses Maslow's "hierarchy of needs" framework to prioritize different building and infrastructure systems in communities. For this reason, human health and safety, the functionality of health-care systems and economic well-being are priority issues that this study has focused on in exploring societal considerations regarding performance.

The NIST *Guide* also distinguishes among short-term (days), intermediate-term (weeks to months) and long-term (months to years) response and recovery needs that planning activities must take into account. While recognizing that all three time periods are important, this study has emphasized societal considerations for the short-term period and immediate impacts, disruption, and responses, again with respect to human health and the economy.

The rationale for this more limiting discussion is that: (1) life safety and health are overriding values for communities, with economic activity following as a community priority since it provides the means through which a wide range of other institutions and community needs are satisfied; (2) although the consequences of lifeline disruption can cascade over time, impacts such as deaths, injuries, and business interruption losses are generally most acute during the immediate post-impact period; and (3) practically speaking, more research exists on shorter-term than on longer-term disruptions.

### *9.1.3 Critical Interdependencies*

This study also looked critically at the interactions among different lifeline systems during normal operations as well as restoration after hazard-related events. Dependent and interdependent relationships among lifeline systems have evolved over time with various systems and technology advances expanding and linking systems together. Although they provide efficiencies and other benefits during normal operation, they also introduce unique and largely unknown behaviors in hazard-related events and system disruptions.

Because of interdependencies, some system failures can also trigger significant cascading failures and performance impacts on multiple lifeline systems, causing a number of additional direct and indirect societal impacts. The physical proximity and colocation of lifelines can provide for enhanced efficiencies but also increase societal risks for cascading failures, complex interactions in restoration, as well as risks posed by multi-hazard effects. Collocated lifelines may also require a cross-system, cross-organizational and integrated approach to planning that is difficult to implement. Within systems there can also be choke points that amplify interdependencies. Interdependencies also exist between lifeline systems and community-level processes.

Rinaldi et al. (2001) offer a general classification of interdependency mechanisms as physical, geographic, cyber, and logical, emphasizing that they are not necessarily mutually exclusive. Physical interdependence exists when the performance of a given network depends on the outputs of other networks. Geographic interdependence emerges from the colocation and close proximity of systems. Cyber interdependence occurs when the interdependence between two networks is based on shared information (e.g., the "smart grid" which relies on telemetry and situational awareness data). Finally, there is logical interdependence when systems are interconnected through channels different from those previously discussed, including human decisions related to restoration prioritization among systems.

The body of research literature on interdependent critical infrastructure has grown over the past 20 years with risk assessment and system management dominating the themes of studies, followed by interdependency effects and cascading failures. Resilience-related studies of interdependent critical infrastructure are increasing but the volume of literature is still limited by comparison.

The literature emphasizes studies of electric power, water, transportation, and telecommunication systems in varying combinations. Studies involving natural gas systems and supervisory control and data acquisition (SCADA) technologies are becoming more prominent; while studies involving economic and social considerations, such as public health, have decreased in recent years. There is a distinct lack of research on cyber networks, network security and cyber interactions with other lifelines.

There is also a growing body of system modeling for interdependent critical infrastructure systems that can be leveraged to improve resilience across lifeline systems. These models can be generally grouped according to their modeling goals of performance evaluation, design, mitigation and recovery. Performance evaluation models emphasize numerical or analytical tools to understand the behavior of a given system or how interdependencies impact system performance and resilience. Design models are used to help conceptualize and build lifeline systems and can be used to consider how to minimize the risk of cascading failures across interdependent systems. Mitigation models emphasize preparing systems to handle future hazards, reducing associated risks and enhancing system resilience. Recovery models tend to focus on restoring systems with failed components to a functional state and minimizing recovery timeframes and associated costs.

The vast majority of interdependent infrastructure modeling tools that are currently available can handle multiple systems and different hazard inputs, but their outputs tend to emphasize risk and damage assessment of coupled infrastructures, quantification of coupling strength across systems, distributed control of such systems, supply chain disruptions, and the consideration of uncertainty effects; few look at risk reduction, system restoration, and societal impacts or considerations. Most are also calibrated and validated with U.S. post-disaster experiences or artificial case studies. While the recovery models are broad and consider functional interdependencies, they tend to exclude colocation, limitations in resource availability, and multiple and extended time horizons. Despite the noted research trends and modeling advances, there is also a lack of unified performance and restoration goals across multiple and interdependent systems. While a number of "proxies" for restoration times do exist for individual systems, only in a few cases have service providers linked up to develop unified goals.

Rigorous and readily implementable theories and methods for the study of lifeline system interdependencies are similarly lacking. The vast majority of interdependent critical infrastructure studies and tools tend to focus on the technical aspects of systems and the impacts of hazards on them. There is less emphasis on societal expectations of the performance and recovery of interdependent systems, such as restoration times expected by the public versus restoration times estimated by utilities and actions taken by individuals and institutions to prepare for or cope with the hazard-related effects of interdependency. Agent-based modeling, complex adaptive systems, and multi-domain simulation platforms are the preferred approaches for capturing the emergent behavior of complex physical-institutional-user interdependent critical infrastructure systems. Some national laboratories are leading the development of these computationally intensive and multi-scale simulation approaches. There remains, however, a substantial need for fundamental data collection across multiple systems for the same locations at community and temporal scales to help develop better theories and methods.

The lifeline-specific reviews reveal a number of critical system dependencies and interdependencies. Virtually every lifeline system depends on electric power and telecommunications for system control and monitoring. All lifeline systems also depend on fuel and transportation, particularly for post-disaster service restoration and system repairs. Fuel is also a critical contingency for power when outages occur. Water is critical for cooling in the generation processes for electric power. Water also helps with pollution control, and supports other infrastructure, such as natural gas and liquid fuel systems.

Some lifeline systems are also inherently intra-dependent and interdependent, which can provide efficiency and other benefits during normal operations, but which can also mean that failures in one component of a system can result in loss of function to otherwise undamaged components in other systems. Such is the case with transportation systems. For example, ports and airports have limited functionality if connecting roads and rail lines are closed. In major metropolitan areas, multimodal transportation network planning and design are commonplace and the ability of the network to function effectively after a hazard event will depend upon the level of redundancy in the network.

There are also some important multiple system interactions that are critical in the post-disaster performance of lifeline systems. One is between electric power, gas and liquid fuel, and water supply. The interaction between leaking gas and electric power to ignite fires also requires the availability of water supply for fire suppression, and strict clearances from electricity providers. Similarly, wastewater systems generally depend upon water and electric power to operate.

The colocation of multiple systems also creates physical interdependencies that increase the likelihood that failure in one system can damage and interrupt others. Some prime examples exist with electric power and telecommunication infrastructure, and transportation elements that also serve as corridors for buried infrastructure (e.g., pipes and conduits for water, wastewater, telecommunications, power and natural gas). However, because lifeline service providers often do not share system information, many areas of physical colocation are unknown.

Some interdependencies are also increasing with time, such as the expanding role that telecommunications and electric power have in monitoring and remote control of lifeline systems, as well as household management, personal choices for renewable power, and community planning for decentralized energy.

### 9.1.4 Disaster Lessons

In general, there is a substantial body of literature on the social and economic impacts of lifeline service disruptions, spanning studies on actual events—both hazard- and non-hazard-related—and scenario-based and probabilistic loss projections. Each of this study's lifeline-specific reviews looked at system performance in hazard events and across the three phases of disaster recovery—defined as short-term (days), intermediate-term (weeks to months) and long-term (months to years)—in the NIST *Guide* (NIST, 2015) and the *National Disaster Recovery Framework: Strengthening Disaster Recovery for the Nation* (FEMA, 2011).

This study found great variability in both the quantity and quality of data available for the various lifeline systems, among hazard types and severity, and across the phases of disaster-related response and recovery. In general, there is more information and a more complete understanding of the societal impacts and restoration patterns of short-term rather than long-term disruptions. Also, most studies of disaster related impacts on lifeline systems are event-specific; systematic, multi-event studies are generally rare. It is noted that there appear to be few, if any, systematic studies of sustained telecommunications outages. There also do not seem to be any longitudinal (long-term) studies of lifeline system restoration and its support of long-term community recovery following extreme events.

For electric power, most major and widespread outages have been caused by storms or other weather events. There is also more data on weather-related events than other hazards and more data on electric power outages in major hazard-related events, particularly with regard to technical aspects of component and system failure and restoration. Common information for electric power performance in hazard events includes: standard industry measures, peak number of customers without service, and time to restore service to all (or nearly all) customers.

Gas and liquid fuel production, transmission and distribution systems are susceptible to damage due to all forms of hazard events. Loss of power to oil refineries and pipeline pump stations during high wind and coastal inundation events will result in loss of production and transmission, causing a lack of fuel supply for businesses and consumers. The high concentration of fuel refineries and major transmission lines along the central Gulf Coast and Eastern seaboard results in increased exposure to hurricanes. Ground faulting and liquefaction caused by earthquakes can lead to rupture of gas and fuel pipelines, though appropriate design measures can mitigate these effects as demonstrated by the good performance of the Trans-Alaska Pipeline System during the design level 2002 Denali Fault earthquake.

Transportation systems are susceptible to damage or disruption during earthquakes, tsunamis and other forms of coastal inundation or riverine flooding. Common earthquake damage includes bridge failures and landslides that can hamper emergency response, particularly to remote communities. Scour induced by coastal inundation and riverine flooding can also result in bridge, rail and roadway failures. Weather events, involving wind, snow and ice, can cause disruptions but physical damage tends to be more limited. Consequently, data on transportation performance in earthquakes, tsunamis, coastal inundation and riverine flooding are more readily available.

Water and wastewater systems are also more susceptible to damage or disruptions during earthquakes, tsunamis and other forms of inundation. Disruptions to water supplies can have serious impacts on fire-fighting capacity and sanitation that can result in serious public health, safety and economic consequences. Damage to wastewater treatment systems can lead to discharge of untreated sewage into waterways and the ocean, resulting in major environmental and public health concerns. The provision of accessibility services for these two systems is also essential for community-level resilience post-disaster.

In terms of recovery timeframes, disaster experiences show that most lifeline system outages generally last from hours to weeks (short- to intermediate-term recovery). In the most severe cases, outages can last for months and longer. The longer-term outages are associated with the most destructive events when critical components of lifeline systems, such as buildings, bridges, piping, and essential equipment, must be reconstructed or replaced to restore system operability.

### 9.1.5 *Gaps and Deficits: Codes, Standards, Performance Requirements and Societal Considerations*

Overall, this assessment found uneven study and treatment of societal considerations in the codes and standards governing lifeline systems performance for different hazards. For example, water systems have different demands for water quantity and quality associated with various societal serving functions, such as potable water consumption, firefighting, cooling, industrial processing, recreation, and irrigation, but some of them are not addressed in current guidance. Similarly, telecommunication systems serve critical public safety and emergency response functions that are reflected in current guidance; however, guidance for the critical societal-serving functions of safety monitoring for other lifeline systems, commerce and banking, and business and employment is generally non-existent.

As previously noted, lifeline codes, standards, guidelines and manuals are largely associated with the performance and safe operation of components rather than system response and levels of service. In a few instances, system owners or operators have established system-level performance objectives or targets for a limited number of hazards. Most guidance does not address the range of hazard types considered in this study, particularly the extreme, low-probability, high-consequence events. In general, more is known about the lifeline impacts and performance objectives for earthquakes and wind-related hazard than for other hazards. The characterization of earthquake hazards has benefitted from the National Earthquake Hazards Reduction Act, and the research funded as part of the National Earthquake Hazards Reduction Program (NEHRP).

Also, as previously noted, there is very little information on societal expectations of system performance during routine, design, and extreme hazard events for most lifeline systems. Potential "proxies" and informants for societal expectations of lifeline performance and recovery timeframes identified in the study include: outage reporting thresholds and criteria (for electric power and telecommunications); post-disaster reviews of utility performance; policies, legislation and regulations, particularly regulatory changes made following hazard-related disruptions; societal and economic losses; and state and local energy assurance plans (for electric power, gas and liquid fuel systems). Societal expectations may also be indirectly reflected in industry practices for service restoration following outages.

While only a qualitative review, this study shows there is a substantial gap between the anticipated performance of different lifeline systems and societal expectations of lifeline performance. Currently, there is no systematic research or methods for quantifying or even bounding this gap. Examples of the potential differences between anticipated and expected system performance are offered in the lifeline assessments of transportation, water, and wastewater systems. These are mostly derived from the opinions of experts in lifeline engineering and recovery planning and are based upon post-disaster observation and engineering judgment. Systematic research and surveys are not available.

This study also identifies some important examples for how the gap between prescriptive performance and societal expectations can be filled. For gas and liquid fuel systems, some of this gap has been filled by standards requiring community planning programs and stakeholder engagement in risk reduction planning and practices. These practices provide a framework that deserves attention when developing programs for community resilience as applied to other lifelines and their interdependent behavior. The gaps can also be closed by high quality system design, detailed risk assessments coupled with appropriate emergency planning, system monitoring, well-communicated emergency response procedures, and robust contingency planning and design, such as ensuring hazard-safe locations for contingency-related equipment (e.g., generators) and supplies (e.g., fuel).

Strategies to enhance resilience will invariably require difficult investment decisions in the face of limited resources. To make rational decisions, lifeline owners and operators need to consider the tradeoff between risk reduction and financial investment. Quantitative uncertainty and risk analysis therefore need to be an integral part of performance requirements and criteria. In addition, risk communication needs to be an essential part of the overall dialogue, including public messaging.

### 9.1.6 Future Considerations and Trends

This study identified a number of considerations outside its scope as well as important trends that are likely to shape future lifeline system design and performance as well as societal expectations. As has been noted previously, societal expectations for lifeline system performance are changing, with decreasing societal tolerance for outages in general, lower thresholds for acceptable outages, and greater disruptions from outages when they occur. Future work both in research and applications related to community resilience needs to consider the following issues:

- Social vulnerabilities are increasing due to the country's aging population, urbanization, and policy changes that are increasingly enabling disabled persons to remain in their homes where they are especially vulnerable to the loss of lifeline services.
- Economic vulnerabilities are changing with the ongoing shift from a manufacturing to an information economy; the growth of "cloud" based information technology and data storage; the growth of e-commerce and the expansion of the financial service sector; increases in telecommuting; and cost-cutting and efficiency measures in business and inventory management.

- The continued rise of globalization, supply chains, and the interdependencies inherent in modern manufacturing and finance also mean that community resilience can be significantly impacted by hazard-related lifeline disruptions occurring in distant places and outside the control of local resilience policy and investments.
- The interdependencies between electric power and telecommunications and other lifeline systems are likely to continue to increase as systems become "smarter" with technology-based operational controls.
- Aging infrastructure will increase the risk of system damage and disruption in future hazard-related events and also increase the vulnerability of all lifeline systems (regardless of their current resiliency) to the cascading effects of lifeline service performance and disruptions.
- For electric power, the increasing availability of renewable resources, distributed energy resources, decentralized power management, energy storage, and grid modernization may be enhancing resilience for service providers and individual users to operate independent of the grid after a hazard event. In some case, however, they may also be stressing physical infrastructure beyond its original design, which can affect future system design and performance as well. The traditional industry structure is also changing as a result of these trends. Transmission upgrading projects are also being undertaken—many involving telecommunications and new technologies—to increase the resilience of the U.S. electrical grid.
- The effects of climate change will add to existing social vulnerabilities and lifeline service performance and disruptions. Energy and water use are projected to increase, particularly in summer. Infrastructure located in low-lying and coastal areas and those systems that are water-dependent will also face new and added risks.
- Issues of theft, cyber-attacks, and other security threats may increase with time.

Finally, the study cautions that unanticipated societal impacts will likely present themselves in future natural hazard events due to lifeline system vulnerabilities that remain poorly understood, the absence of guidance on hazard resilient construction and installation practices, unknown and unfavorable states of repair, issues with system functional capacity, and ongoing changes in technology.

## 9.2 Recommendations

Recommendations resulting from this critical assessment of lifeline system performance and the societal needs of lifeline systems in disaster recovery are discussed in the following sections. They are consistent with the NIST Community Disaster Resilience Program and its various components, including the NIST *Guide*, the Community Resilience Panel, and research efforts. They also target lifeline operators, practitioners, regulators and researchers concerned about societal considerations in hazard-related system performance and potentially involved in lifelines standards and code development related activities.

The following set of overarching recommendations was derived from the individual assessments of the study team. They were then discussed and prioritized with the review panel. All recommendations shown below were deemed high priority. Readers are reminded to review the full suite of recommendations that are provided in each of the chapters.

### *9.2.1 Lifeline Codes, Standards, and Guidelines*

As noted in Section 9.1.5, this study reveals critical gaps in the many codes, standards, guidelines and manuals that govern the design, construction, and performance of different lifeline systems and system components. The following ten recommendations are offered to address lifeline-standards-related needs emerging from the study. The priority rankings reflect organizational and framework needs, available information, new knowledge needs, guidelines and standards development needs, and scoping breadth, with recommendations that pertain to broad issues and improving community resilience considered higher priorities than recommendations for specific lifelines.

**A1. Identify or establish an organization and process for advocating, harmonizing and unifying the consensus procedures for lifeline guidelines and standards development.** For nearly a decade, the U.S. lifelines community has lacked an oversight organization for lifelines guidelines and standards development and to lead the national process necessary to develop consensus among a wide range of users. More rigorous and systematic approaches to lifeline standards development, such as those defined by the American National Standards Institute (ANSI), are also needed. Such a process would include an organized investigation of the existing standards, guidelines and best practices from across the United States and internationally, the identification of gaps and deficiencies, the prioritization of needs, the development of pre-standards, and the designation of organizations to complete the development process. Innovations in the standards development processes that other countries, such as Great Britain, are employing also need to be evaluated.

**A2. Develop more consistent terminology for lifeline standards.** More consistent terminology is needed so that it is possible to more easily compare standards and set future directions for the standards development of different lifeline systems. Example terminology that merits clarification include: performance targets, goals, and objectives; system characterization terms such as transmission, distribution, and facilities; characterization of uncertainty; and system interdependencies versus dependencies.

**A3. Develop an up-to-date and complete suite of codes, standards, and guidelines for all lifeline systems to reflect the current state of practice, knowledge, and performance requirements.** This study has identified a number of critical systems and system components that lack codes, standards and performance requirements for important hazard events and hazard levels considered. Also, in some cases, current codes, standards, and guidelines were developed years ago and need to be updated to reflect current standards of practice, new knowledge, and treatment of uncertainty. For example, engineering design in the electric power sector is governed by codes and standards at the individual asset or component level, primarily for extreme wind and snow/ice loads. For, water and wastewater systems there is no established set of performance requirements for any hazards and, as a result, only a few system owners and operators have established performance objectives or targets for a limited number of hazards (mostly earthquake, but some related to climate change).

**A4. Develop a methodology to combine component-based design criteria into system level performance targets.** The design of system components based on codes and standards has no direct correlation to intended systemic performance targets. For example, designing pipelines and pumping stations to a 2% chance of exceedance in 50 years does not mean the system will meet the performance objectives set for an extreme hazard, nor does it indicate the actual design margin.

**A5. Develop lifeline system performance requirements that relate to community resilience and better reflect societal considerations.** Currently, there are no consistent resilience-based performance requirements for lifeline systems. In addition, consideration needs to be given as to how performance requirements can better account for the effects on the restoration of core community services that each lifeline system provides. Viewed from the perspective of societal expectations and considerations, at a minimum, lifeline systems should perform in ways that do not lead to additional deaths, injuries, and disabilities and minimize lifeline-related economic losses to the greatest extent feasible. Several important aspects of societal considerations are: outage characteristics that are important in causing societal impacts; "downstream" effects on other critical infrastructure; vulnerable populations; adaptability and capacity of people, businesses, and other organizations to cope with disruptions; integration of contingencies, substitutions, and accessibility services during system outages; and value of improved information both prior to and during outage, including communications regarding risk and uncertainty.

**A6. Develop consensus-based guidelines and standards for the design of new lifelines and the retrofit of existing lifelines that reflect community resilience performance requirements and societal considerations.** The progression of technology development in the lifelines community is well served with the initial development of guidelines, which are typically based on currently available research and best practices, followed by the conversion into standards that reflect the input of the broader stakeholder community. Current guidelines and standards for lifeline systems mainly take into account life safety, environment protection, and emergency response requirements. In addition, most are intended for the design of new lifelines, as opposed to the retrofit of existing systems. Future guidelines and standards need to address both the design of new lifelines and the retrofit of existing lifelines as well as a broad range of societal considerations that address the requirements of social groups, economic sectors, and key service-providing institutions. Future guidelines and standards also need to consider a broader range of societal considerations than are currently considered by most standards: lifeline system dependencies and interdependencies; the potential for cascading impacts; and potential "choke points" that can amplify dependencies and interdependencies.

**A7. Develop guidelines to inform the design, interoperability, and upkeep of lifeline system dependencies.** Guidelines are needed for dependent and interdependent lifeline system operation, protection, restoration, and interface design across systems, including data collection protocols that exploit modern technologies. An example standard dealing with power and telecommunication system interdependencies comes from the International Electromechanical Commission for the design of automated electrical substations and requires consistent telecommunication protocols for timely control and secure interoperability.

**A8. Reduce inconsistencies in the compendium of codes and standards that guide design, construction and resilience of the built environment, such as fire codes, building codes, and lifelines codes, standards, and guidelines.** There are gaps and conflicts among the different codes and standards that need to be addressed for community resilience. As an example, fire codes often require diesel generators and/or local fuel tanks to be located in basements that may be vulnerable to flooding.

**A9. Develop consistent policy and standards on accessing information and databases about critical infrastructure systems that is coordinated with Department of Homeland Security critical infrastructure activities.** There is currently a gap between the need to identify locations and functions of critical infrastructure to support safety and resilience planning and the actual access to information about these factors from lifeline system operators. The Pipeline Information Management Mapping Application developed by the Pipeline Hazardous Materials Safety Administration (PHMSA) may provide a framework for sharing information about potentially sensitive system components and facilities, including information about combined systems and collocated facilities.

A10. **Provide updated guidance for evaluating gas and liquid fuel pipeline and facility response to seismic hazards, floods, coastal storms, and tsunami-related inundation.** Such guidance would help fill existing gaps between codes and standards and the design and operation of gas and liquid fuel systems for natural hazards.

### *9.2.2 Research*

The study has identified a number of gaps in data and knowledge necessary to improve the fundamental understanding of acceptable lifeline performance. Fifteen recommendations pertaining to systematic study and research needs are offered. All are considered high priority, with those encompassing all lifelines and broader topics listed before those related to only one lifeline.

B1. **Gather information on and systematically study the relationships between service disruptions, and societal impacts and expectations to better understand lifeline system performance.** This study identifies some key information gaps about the fundamental research on system operations that would be useful to the standards development recommendations identified in Section 9.2.1. They include: data on spatial patterns of power outage (especially in relation to societally important aspects, such as service to critical facilities and vulnerable populations); information on societal impacts and responses to hazard events; and sufficient data on service outages in hazard types. Data should be gathered systematically, using consistent measures so as to enable comparisons across events, utility companies, states, and other factors. While data from actual disasters provide the most direct evidence on performance, other sources such as disaster preparation exercises should also be tapped, as they can also provide valuable information on, for example, potential power outages in areas that have not experienced recent disasters. Study needs include understanding how impacts scale up in outages and the thresholds for deterioration in functionality, impacts, losses and tolerances, and the role of contingencies and accessibility services (within and between lifeline systems and across society). Such data will be important for understanding current system vulnerabilities, making the case for reducing them, and developing systems-based lifeline standards. The resulting insights may also encourage the development of duration-related standards that reflect societal impacts and expectations.

**B2. Develop and conduct a targeted research program to assess societal expectations associated with lifeline system performance.** This social science-driven research is necessary to help close the gap between what is considered as acceptable design levels (including what is defined as extreme events) and what communities find to be acceptable performance. The research should be lifeline-specific and hazard-specific in order to understand whether societal expectations vary as a function of those differences. It should involve studies that employ randomly selected representative samples of units of analysis that are of interest, such as households and businesses. Since resilience building is a long-term process of investment, research to assess and enhance community resilience also must account for trends and future considerations related to both the physical vulnerabilities of infrastructure systems and changing social vulnerabilities.

**B3. Systematically study and compare the array of design approaches and methods for addressing societally-based performance requirements within current codes, standards and guidelines for lifeline systems.** For example, gas transmission pipeline design factors must consider urban development and population density, and integrity management programs are required by codes for gas transmission pipelines in high consequence areas. High consequence areas include navigable waterways, highly populated areas, and unusually sensitive areas (involving drinking water and ecological resources). Also, gas and liquid fuel pipeline standards require operators to develop, manage and periodically evaluate public awareness programs to promote safety and raise awareness with stakeholders near pipelines. These programs must: define objectives, explain the concept of tradeoff between risk reduction and financial investment, obtain management commitment, establish program administration, identify pipeline assets, and identify stakeholder audiences. Communications systems have multiple layers of functionality with a range of societal-serving applications. Consideration should also be given to the performance-based design method in the ALA *Seismic Guidelines for Water Pipelines*, which present varying design requirements for different types of pipelines, depending on their overall importance to network performance.

**B4. Investigate the differential vulnerability among social groups to lifeline system outages.** As earlier discussions have shown, some groups within the U.S. population are more vulnerable to outages than others. In the case of electric power outages, for example, of special concern are those who lack access to alternative energy sources such as generators; disabled persons and those suffering from chronic illnesses; and community residents who are dependent on electrical power for assistive devices and refrigeration. Generally speaking, electric power service outages can be expected to have a greater negative impact on the health and economic well-being of low-income community residents, hourly workers who may lose income as a result of power outages, and others whose livelihoods depend on uninterrupted lifeline services. Small businesses may be especially vulnerable to service disruptions, while larger businesses are more likely to have business continuity plans and access to backup services. Some types of businesses are more dependent on electrical power and telecommunications than others and thus may suffer larger proportional losses when these system outages occur. More research is needed to better understand these and other vulnerabilities, to determine how vulnerabilities are changing as a consequence of social, economic, and climate trends, and to make future projections.

**B5. Systematically collect and review various "proxies" and secondary evidence for societal expectations of lifeline performance and restoration timeframes.** Candidate proxies include electric power outage reporting thresholds and criteria, post-disaster utility performance reviews, policies and regulatory changes made following disaster-related disruptions, societal and economic losses from hazard events, and state and local energy assurance plans. Lifeline service providers, emergency management agencies, and other organizations collect and use this information to improve restoration processes for future disasters. In some cases, utility service providers have outage and restoration models, as well as restoration policies and procedures for some systems and some hazards that also may be useful in assessing and establishing societally-based performance requirements. It is important to keep in mind that societal expectations are likely to change and that tolerances for disruptions may be decreasing.

**B6. Assess the various lifeline performance programs and practices for public safety and develop guidance on their application to other critical lifelines, including multiple, interdependent systems and collocated facilities.** Some lifeline code requirements and standards involve programs and practices for public safety that can be adapted more broadly for hazard-related community resilience programs. For pipelines, they include the identification of high-consequence areas, pipeline integrity management and public awareness programs, and emergency response plans. For telecommunications, service level agreements are a market/penalty-based approach. For water and wastewater, the American Water Works Association (AWWA) risk and resilience assessment and management guidance offers a standardized process for reducing risk and increasing resilience to multiple hazards. Research and development of best practices and advanced methods could be advantageous for other lifeline systems.

**B7. Conduct research on needed service restoration times, including how system operability as a performance metric supports community resilience.** System operability is defined as the cumulative time needed to restore the range of community services provided by a particular system, beyond its basic functionality. For example, water system domestic operability is fully achieved when water quality and quantity are restored throughout the system, not just water delivery. This is needed in relation to other lifelines and overall societal expectations, with due consideration of accessibility services.

**B8. Study lifeline system operator organizational issues and how they affect community-scale lifeline performance and resilience planning.** In any given community, some systems may have a single operator (e.g., commonly this is the case for water and wastewater), while other systems have multiple operators (e.g., notably telecommunications and power). Also, some systems are typically publicly-owned (e.g., water and wastewater), while others operate in a highly competitive, private market place (e.g., liquid fuel and telecommunications in limited circumstances). There are also differences in the extent to which members of the public can exercise choice by opting out of particular services; for example, most households have limited choice in their selection of landline broadband providers. Ongoing changes in the regulatory environment and industry structures for different lifeline systems may also be affecting "whole system" performance and resilience efforts in new and different ways.

**B9. Enhance the understanding of infrastructure-related failures and cascading effects resulting from low-probability/high-consequence events.** While it may not be economically feasible to mitigate against low probability but high consequence events, it is still reasonable to direct some attention to the societal implications of rare but catastrophic disasters. By their very nature, such events can result in large-scale mortality, morbidity, damage, loss, community disruption, population displacement, and permanent demographic shifts. They can also result in public loss of trust and confidence in government and other societal institutions as well as major shifts in public opinion that can, in turn, stimulate significant legal, policy, and other forms of social change. It is also noteworthy that system disruptions, especially in major or extreme hazard events, can go well beyond the location of the physical disruption, making it a multi-jurisdictional problem in which societal expectations and performance objectives can vary greatly.

**B10. Develop post-disaster data collection protocols to assess lifeline system recovery and restoration timeframes and improve the understanding of**

**restoration processes across individual and interdependent lifeline systems.** Realistic field conditions and observations are needed of the decision making processes and other societal and technical mechanisms that lead to particular restoration patterns following lifeline system disruptions and failures. While larger service providers may have models to simulate system performance under different hazard conditions, many smaller providers do not have such capabilities. The industry as a whole would benefit from data on actual performance.

**B11. Develop tools to identify interdependent infrastructure systems and services along with their restoration criteria.** A repository is needed to synthesize what is known from field data, expert opinion, best practices, and technical modeling regarding community resilience expectations and community behavior. A multi-dimensional representation (as shown in Figure 8-4) could help organize the current body of knowledge and can be constructed with the aid of first generation computational models along with promising proxies for societal expectations, which include emergency management preparedness recommendations, utility operator information, outage trackers, and restoration curves. Such representations could capture dependency strengths, restoration time gaps, and other pertinent information as a function of time and space as governed by physical systems and societal processes. They ultimately could help identify resilience investment priorities.

**B12. Establish procedures to quantify hazards for spatially distributed systems.** This is Priority Topic 3 in the NIST *Earthquake-Resilient Lifelines: NEHRP Research, Development, and Implementation Roadmap* (NIST, 2014) report. Procedures from such a developmental effort should address the hazard quantification for multiple hazard types and hazard levels across large geographically distributed and interconnected lifeline networks. It also should define procedures to assess differential risks posed to system components and overall system performance by different hazards and hazard related effects, such as, in the case of earthquakes, liquefaction, fault movements, landslides and other forms of ground failure.

**B13. Enhance the understanding of lifeline system supply sources and end-point facilities and their role in system performance, restoration, and community and regional recovery with the goal of improving databases and modeling of such sources and facilities.** Dams and large reservoirs for water supply, power plants for electric power systems, and refineries and processing plants for gas and liquid fuel are all sufficiently complex and self-contained components that they have been regarded for practical purposes as separate systems. Nonetheless each is an important part of the lifeline supply chains and their disruption can have a major impact on overall system performance and restoration, as well as intermediate and long term phases of both community and regional recovery.

**B14. Perform studies on changes in water demand considering an array of hazards as well as seasonal and longer-term climate variability, like drought.** Loss of water due to hazard-related damage is essentially an imposed drought. Current events (e.g., the current California drought) and changing behavior can be assessed to determine what is possible and the extent to which communities can adapt before having damaging impacts. Studies should include behavior change of institutions and individuals.

**B15. Improve knowledge, databases and modeling for the impact of widespread flooding and storm damage on regional fuel supplies.** Fuel supplies involve multi-modal transportation involving pipelines, shipping, port facilities, and truck transport on the upstream side and gasoline stations, jet fuel delivery, airport operation, train service, and automobile usage on the downstream side. Research is needed to understand these complex transportation interactions and to account better for the restoration of crucial services that depend on fuel as well as on regional economic recovery. Analytical models that simulate these systems would provide the means for reliability-based analyses of the most effective protective measures and operational improvements.

### *9.2.3 Modeling*

There is a growing body of system modeling for critical infrastructure and infrastructure interdependencies that can be leveraged to improve resilience across lifeline systems, but there are also notable limitations in focus, outputs, integration, and validation that need to be addressed. Three modeling related recommendations are offered. All are considered high priority, with those encompassing all lifelines and broader topics listed before those related to only one lifeline.

**C1. Aggregate the existing suite of infrastructure modeling tools and create a user-friendly interface so communities can properly assess their lifeline-related system performance and restoration risks, including uncertainty.** Currently, there are favored model types for different lifeline systems (e.g., electric power systems use network and reliability theory; economic networks favor input-output models) even though most models, in principle, can admit any system. There are also a number of tools available to researchers and governments to model multiple infrastructure systems. An aggregated suite of models is needed to capture lifeline interdependencies and their multiple processes at multiple spatial and temporal scales at once. Such models will be able to start supporting community resilience analyses, and identify ways to improve system performance and restoration times.

C2. **Develop first-generation models and practical tools to analyze community resilience that account for lifeline system dependencies and interdependencies.** Integrated modeling of hazard-related, population-related, building, environmental, and interdependent lifeline system vulnerabilities could lead to a better understanding of where severe problems with service delivery and severe societal consequences are most likely. This kind of modeling is already being done in a basic way for some lifelines and some hazards—for example, through the FEMA-developed HAZUS MH multi-hazard damage and loss estimation software, although it excludes restoration processes and their socio-technical nature. The academic community has led the development of interdependent lifeline systems modeling tools, but such tools have yet to become practical and offer quality visualizations for widespread use by communities.

A "next generation" approach to modeling needs to account for vulnerabilities related to lifeline dependency relationships, vulnerabilities associated with structural and environmental factors, and the characteristics of exposed populations (e.g., race, class and poverty, gender, age, and social capital). Such modeling efforts will require intensive engagement of multi- and interdisciplinary teams. Models also need to be practical and flexible to allow exploration of resilience-enhancing operations and cost-effective strategies for reducing vulnerabilities by both lifeline service providers and communities. They also need to consider the different response and restoration strategies that can be taken and their effects on resilience, and sufficiently differentiate the pre-disaster measures and investments that can be taken to enhance lifeline system performance in hazard events.

The evolving modeling processes should eventually be able to include human-driven restoration decisions as disasters and system disruptions unfold, feed the decisions back into the model, and further improve system recovery and restoration processes. These processes could also inform planning for system upgrades, expansions, and targeted decommissioning via what-if scenarios.

C3. **Improve numerical modeling of water and wastewater systems, with emphasis on validation of models, developing the most effective simulation procedures, and applications in real systems.** The complex performance of water and wastewater systems in response to hazards, including in particular severe earthquakes and floods, requires complex network modeling to capture the effects that pipeline leaks and breaks, as well as the structural damage to treatment, storage, and control facilities, have on network behavior. Improvements would be beneficial in existing modeling techniques, including algorithms for quantifying flow and pressure in heavily damaged hydraulic networks, and hydraulic network analytical methods that have the potential for providing a more refined assessment of post-hazard water available for firefighting in smaller pipeline networks.

### *9.2.4 Lifeline System Operations*

The study also identifies a number of needs related to lifeline system operations and operational design. These too must be addressed in order to improve community resilience and bridge the gap between the disaster capabilities of different lifeline systems and the societal expectations of their performance. Five recommendations are offered. All are considered high priority.

**D1. Develop a process for major utilities to conduct self-assessments of their preparedness for various natural hazard events, as a basis for prioritizing improvement to system robustness and post-event response.** Guidance should be provided with support from federal, state, and local government for these assessments to provide some consistency of approach among lifelines. Each utility should have reasonable knowledge of their customer base and relative importance and priority for continuity of service. The self-assessments should be mandatory first for utilities that have a relatively large customer base. As experience is gained with the process and lessons learned, self-assessments could be extended to smaller utilities and smaller localities. The results of self-assessments could then be used to prioritize improvements to system robustness and post-event response. Improvements to community resilience can be best accomplished by taking immediate steps to get the utilities to develop an understanding of the problem, assess vulnerability of their systems, and undertake an action plan. It is essential for appropriate organizations (e.g., NIST) to guide the process, and provide technical resources to assist and incentives to participate.

**D2. Develop guidance for lifeline service providers on how to engage and collaborate with communities, including emergency management agencies and other key community institutions, in developing resilience strategies and preparing system restoration and contingency plans.** Practical guidance is needed to help service providers interact with communities to identify system performance expectations and work to address the gap between anticipated and expected performance in disasters. Communications regarding hazard related risks should take place throughout the hazard cycle: under normal conditions, in the period preceding disaster impact, during and immediately after impact, and during restoration and recovery. Providers also need guidance on how to work with communities to fund resilience efforts over reasonable timeframes; many providers already face significant financial pressures just to maintain existing systems. Providers also need guidance on how to better distinguish between critical and non-critical facilities and develop plans that restore system operability according to community priorities and needs, and also minimize threats to life and health that hazard-related lifeline failures may cause. For example, post-earthquake power restoration can be coordinated with natural gas system repairs to avoid fire ignitions. The development of restoration and contingency plans (including the provision of accessibility services) also needs to take community vulnerabilities into account (to the extent possible).

**D3. Develop guidance for local planning (e.g., for fuel delivery to emergency responders and critical infrastructure).** As recent major hurricanes demonstrate, there is a serious gap between expectations for the availability of fuel and the threat to fuel supplies from hurricanes, floods, and earthquakes. Guidance for local planning to close these gaps is needed, with emphasis on securing fuel for emergency responders and critical infrastructure, such as telecommunication hubs, compressor stations, and pump stations for liquid fuel and water supplies.

**D4. Develop guidance for lifeline service providers to evaluate the effects of system component failures, both in isolation and in combination, and considering upstream and downstream dependencies.** For example, the assessment of disaster-related lessons for telecommunications systems found that backup plans did not work as anticipated or that presumed system redundancy either did not exist or had disappeared due to engineering changes, leading to a false sense of resiliency. The "chaos monkey" approach pioneered by Netflix runs on a configurable schedule and tests the resilience and recoverability of their cloud computing services to ensure that applications continue working under a variety of failures and disruptions. A similar approach could be used for testing lifeline system resilience.

**D5. Design protocols for lifeline service providers, working with emergency management and other community institutions, to communicate to the public the likely impacts of different hazard events on service provision and disruption.** Such communication guidance should be specific with regard to potential outage times for hazard-related disasters of different types and levels of severity, potential consequences and cascading effects of outages, associated uncertainties, and what members of the public can do to reduce their risks and cope with such hazard-related outages across all phases of the hazards cycle—during normal times, during impact, and during the restoration and recovery period. This communication should be made available in multiple formats and in the languages spoken by community residents. Barriers to the disclosure of such information should be addressed.

# Appendix A

# Supplement to Electric Power Analysis

The following sections supplement the material presented in Chapter 3—Electric Power—in the main body of the report.

## A.1 Designing for Hazard Loads

For transmission system assets, which are mostly designed and constructed by investor-owned utilities, the sections of the National Electric Safety Code (NESC) (IEEE, 2012) most relevant to hazards pertain to grades of construction, loading requirements, and strength requirements (sections 24-26), as well as vegetation management. While NESC is intended as a safety code, in practice, it serves as an engineering design code (NIST, 2015). Individual utilities have developed standards for their own systems that meet or exceed the NESC baseline standards. As noted in NIST (2015, p. 143), however, "[T]he question... is whether the baseline set forth in the NESC addresses the performance desired for resiliency when considering all hazards (flood, wind, seismic, ice, and other natural hazards and man-made threats)."

The NESC considers ice and wind hazards in their loading criteria. Basic loading pertains to combined ice and wind loads. Criteria for extreme wind loads, which typically occur along coastlines and during extreme events such as hurricanes, have been included since 1977 and apply to structures over 60 feet above the ground. Thus, transmission lines are generally designed for extreme winds, but most distribution system assets are not—"something that may need to be reconsidered depending upon performance of these systems during hurricanes and tornadoes over the past 2 decades" (NIST 2015, p. 144). For extreme ice events, most utilities have their own loading criteria; in addition, the 2007 NESC introduced a combined ice and wind criterion that accounts for extreme ice events. Thus, most transmission system assets will be designed for extreme ice but most distribution system assets will not.

In the NESC, applicable extreme wind loads for structures over 60 feet are defined according to geographic location, and some utilities implement standards that exceed the NESC. For example, on the Gulf Coast, NESC wind loads near the coast are 150 miles per hour (mph) and decrease to 120 mph further inland. At Entergy Louisiana, new transmission lines are designed for 150 mph on the coastal tip and 140 mph inland (DOE, 2010).

Seismic design is addressed separately. ASCE 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010), exempts electrical lines from seismic design. Generally, wind governs the design of transmission lines, though failures due to soil/foundation issues continue to occur. ASCE 113, *Substation Structure Design Guide* (ASCE, 2008), addresses seismic design criteria for electrical substations. IEEE 693, *Recommended Practice for Seismic Design of Substations* (IEEE, 2005), provides suggested loading and qualification measures that should be taken while evaluating or specifying transmission substation components. Utilities will often write their own design criteria that emphases their high risk hazards; these criteria often exceed national standard requirements or just enumerate/blend and follow more advanced existing standards.

Distribution system assets are designed according to different design criteria than transmission assets. More effort goes into the seismic design of high voltage (transmission) equipment than in lower voltage (distribution) equipment. However, the loading environment that lower voltage equipment must withstand in its life includes loading that is much greater than seismic loading (e.g., loading from transport and handling of components); therefore, lower voltage equipment generally performs better than higher voltage equipment in earthquakes. The vulnerability of distribution system assets often lies in the way they are installed and/or anchored, vulnerabilities of non-utility entities they are near, or lack of deterioration mitigation. The cooperatives and municipalities that manage electric power distribution systems use design manuals and standards produced by the Rural Utilities Service (RUS), including RUS bulletins 1724-150 (USDA, 2014) through 1724-154 (USDA, 2003), to which more stringent wind and ice loads are applied (NIST, 2015).

Other aspects besides design of assets for wind and ice loads also affect potential system failures in hazard events (NIST, 2015). Tree fall or debris is a major source of outages; tree-trimming and vegetation management is an area where codes, standards, and “industry-accepted best management practices” are needed (NIST, 2015, p. 144). Independent of industry codes and standards, floodplain management practices and requirements have begun to also influence utility construction practices on the East Coast since Hurricane Sandy; for example, by encouraging elevating of structures at existing stations or relocating stations outside flood zones.

Current codes and standards also do not apply to older electric power assets, which are more vulnerable to failure in hazard events (NIST, 2015). In many cases, they pre-date modern codes and were not specifically designed for hazard loads.[29] Some hazard resistance may have been incorporated through practices such as siting based

[29] Some 70% of the U.S. electric power transmission lines and transformers are over 25 years old (Campbell, 2012, cited in Executive Office of the President, 2013a).

on historical storm experience, conservative design, or use of hazard-resistant materials.

The NIST *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (NIST, 2015) identifies some common ways in which older power assets are vulnerable in hazard events. For example, transformers may be clustered in underground vaults and below-grade substation yards that are vulnerable to flooding, not only in flood disasters but also in other events such as mudslides and earthquakes. Single poles may have been used at substations to carry both incoming and outgoing lines, creating a potential single point of failure. The cost-saving practice of using fuses rather than breakers and reclosers in many locations also reduces resiliency. Lack of automation hinders power restoration using alternate configurations, because switching would need to be done manually.

On the other hand, newer infrastructure assets are highly dependent on the reliable operations of communications and control networks during hazards events (NIST, 2015). These networks are themselves vulnerable in many ways. Newer systems may be especially vulnerable to communication systems failures if they rely on them for automated or remotely controlled outage-response tasks such as circuit switching, sectionalizing, and reconfiguration. Impaired communications in a hazard event can also reduce operators' situational awareness about the damage and service status of infrastructure assets. As capacity demands increase and lead us into uncharted technical areas, new failure modes will most likely emerge.

## A.2 Current Measures of System Performance

### *A.2.1 Electric Power Sector*

As noted in Chapter 3, the most commonly used measures of system performance by the electric power industry are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI). Many utilities regularly report their performance according to these reliability measures; however, extraordinary events such as storms and other natural disasters are often excluded. Moreover, they are not directly informed by or linked to societal expectations of electric power performance.

Keogh and Cody (2013) provide an insightful critique of these measures from the perspective of resilience. They argue that measures such as SAIDI and SAIFI suffer from several key shortcomings. First, they focus on normal operating conditions; roughly half of utilities that report SAIDI and SAIFI omit major events, however defined, from these measures because they distort restoration cost calculations. Second, utilities using such measures do not consider the differential hardships imposed on society from different durations of outage. That is, "the duration formulas—SAIDI and CAIDI—value each lost kilowatt hour (kWh) equally across time. But customers value costs differently in the first few hours of an outage, when it's merely inconvenient, than they do after weeks of lost service, when modern life becomes simply impossible" (Keogh and Cody, 2013, p. 8). Relatedly, these measures do not differentiate between customer classes (e.g., residential, industrial, and commercial), even though the cost of disruption may differ between these groups. Furthermore, the measures do not consider the cause of outages.

Keogh and Cody (2013) argue that new or modified measures are needed to address disaster resilience. While frequency-based measures such as SAIFI may be appropriate for normal conditions, duration-based measures such as SAIDI and CAIDI (including major events) are more suitable following disasters in the recovery period. New measures are needed, however, to meaningfully capture performance during an event (i.e., for the response period), reflecting such issues as differential cost or value across time and customer classes. A useful measure for major events would need to account for duration, scale (number of customers affected), and value of lost load to different groups of customers.

Little research exists on the latter topic, and more is needed to better understand differences between utilities' costs of outages and the value of those outages to customers.

### *A.2.2 State and Local Governments: Utility Regulation, Energy Security*

States regulate many of the activities of electric power utilities including, to varying degrees, performance in natural hazard events. The Edison Electric Institute (EEI, 2014a), an association of all U.S. investor-owned electric utilities, provides a detailed compendium and review of state policies and regulations related to electric utilities' storm hardening and resiliency.

As major storms have become more frequent and disruptive in recent years, state regulatory activity has increased. In the last decade, several state utility commissions have issued rules and regulations—often following post-disaster reviews of utilities' performance—that have led to actions by utilities to increase their systems' hardening and resilience (see: DOE, 2010; EEI, 2014a). In some cases, "utilities must meet higher standards for performance that are aligned with higher customer expectations of reliability..." (EEI, 2014a, p. 27). Examples of regulatory changes include (EEI, 2014a):

- A Connecticut law requiring state regulators to review a utility's performance in responding to storms, set new performance standards, and identify the most cost-effective levels of tree trimming and system hardening needed to achieve maximum system reliability and minimize outages. Financial penalties may be imposed for non-compliance with the performance standards.

- A Massachusetts law that expands the authority of the Department of Public Utilities to oversee utility storm restoration and set performance standards for emergency preparation and restoration of utility service. Financial penalties may be imposed for non-compliance with the performance standards.
- Development by New York regulators of a process to change the regulatory model for achieving policy objectives that include assurance of system reliability and resiliency. The regulatory model will include performance and outcome-based incentives.
- In the wake of Hurricane Sandy, the [New Jersey] legislature has introduced numerous bills... calling for the New Jersey Board of Public Utilities to establish performance standards in emergency situations...

While it unclear whether societal expectations were rigorously assessed in support of such changes, policy and regulatory decisions do provide a potentially valuable—if indirect—indication of societal expectations. For example, in California, widespread power outages in a December 2011 windstorm led to a new law (AB 1650) that requires the California Public Utilities Commission to establish standards for emergency preparedness plans (EEI, 2014a), indicating that such outages (or at least the associated emergency planning and coordination) were not societally acceptable. In Connecticut, following Tropical Storm Irene and a snowstorm in 2011 that caused widespread power outages, the State enacted a law (SB 23) requiring the Public Utilities Regulatory Authority to review a utility's performance when over 10% of its customers experience outage for over 48 consecutive hours (EEI, 2014a). This indicates a threshold that could perhaps be interpreted as societally unacceptable from the perspective of policy-makers. In Maryland, the Public Service Commission investigated a derecho storm in 2012 that caused widespread outages; it found a "disconnect" between the public's expectations for distribution system reliability and the ability of the system to meet those expectations (EEI, 2014a).

The New York Public Service Commission adopted a "scorecard" in 2013 to provide guidance to utilities regarding the Commission's expectations and for assessing their performance in major storms (EEI, 2014a). The scorecard (New York PSC, 2013) assesses preparation, operational response, and communications. Specific guidance provides some indication of societal expectations, at least from the perspective of regulators and policy-makers. For example, specific communications guidelines are provided for outages of different expected durations: less than 48 hours, over 48 hours (but five days or less), and over five days. Among many performance measures is one on "time it takes utility to restore power to 90% of customers affected," however, no specific measurement criterion is specified for this.

One of the most specific public policy statements regarding acceptable performance can be found in the Maryland Public Service Commission's Rule-Making 43 (effective May 2012). The regulations "require at least 92% of sustained outages during normal events be restored w/in 8 hrs." and "require at least 95% of sustained outages during "Major Events" of <400,000 or 40% of customers be restored w/in 50 hrs." (EEI, 2014a, p. 41 and p. 82). Such specificity is very rare, however, and may even be unique at the present time. It is unclear what penalties utilities would face if they do not meet these requirements.

There is indirect or anecdotal evidence that societal expectations with regard to acceptable performance may be changing. For example, in association with summer storms in 2011, the Illinois Commerce Commission ruled that a utility could be liable for economic losses (e.g., food spoilage) resulting from power outages; although the legal statute had existed for 15 years, utility liability had previously been waived consistently "typically on the basis of findings that damage was unpreventable due to severity of weather" (EEI, 2014a, p. 38). The Centre for Resilience of Critical Infrastructure at the University of Toronto has found that "market tolerance for energy service interruptions has decreased significantly, from weeks in 2001 to hours in 2015" (personal communications with A. Hay, cited in Quest, 2015, p. 6).

In addition to documented policies and legislation, another potential source of evidence on societal expectations regarding electric power performance is after-action reports, investigations, and testimony following major power outage events. For example, the Emergency Preparedness Partnerships (EPP, 2012) gathered information from six public hearings, 110 interviews, and nearly 800 responses to data requests to assess the effectiveness of electric distribution companies following Tropical Storm Irene in 2011. Many of the criticisms of the utilities focused not on the actual restoration times, but on poor communication to the public and elected officials regarding estimated restoration times. Among other findings, the report recommended that "a common set of metrics must be established for the EDCs (electric distribution companies) to communicate the magnitude of outages and restoration efforts to the BPU (board of public utilities). When comparing the severity of an event, it is important to look at the percentage of customers out of service, as well as the peak number of customers impacted" (EPP, 2012, p. 14)[30].

In addition to state public utility commissions, another potential source of information on societal expectations consists of state and local efforts in planning for energy emergencies. Energy assurance planning has evolved since the oil crises of the 1970s, and has been given impetus by energy shortages in disasters such as the September 11, 2001 terrorist attacks, the 2003 Northeast Blackout, and numerous recent hurricanes including Katrina, Rita, Gustav, and Ike (NASEO, 2009). In recent years, the number of state and local governments with response and recovery plans

[30] It may be useful to conduct a research project that extracts and synthesizes evidence on societal expectations from similar post-disaster testimony across many events.

for energy emergencies has grown. The American Recovery and Reinvestment Act of 2009 awarded over $8 million to 43 cities across the nation to engage in energy assurance planning (PTI, 2011). In some cases, energy assurance plans such as the California Energy Assurance Planning program have established performance goals for energy systems following a disaster (NIST, 2015).

While a systematic collection and review of state and local Energy Assurance Plans is beyond the scope of the current report, examples and guideline documents for developing such plans suggest the kinds of insights on societal expectations that might be gained from such a study. For example, in a guideline document for states, the National Association of State Energy Officials (NASEO) defines four levels of energy emergencies (NASEO, 2009).[31] The definition of these levels relates to petroleum, natural gas, and/or electric power supply, and the power-related criteria are shown in Table A-1, with the implication that states should plan for different types of responses according to different levels of shortages.

**Table A-1 Levels of Energy Shortages (after NASEO, 2009)**

| Level | Criteria |
|---|---|
| Normal Conditions, Level 1 | No discernable shortage. |
| Shortage Level 2, *Mild Shortage* | Localized storm damage causing short-term electric transmission/distribution loss. |
| Shortage Level 3, *Moderate Shortage* | Severe storm damage to electric transmission/distribution infrastructure. |
| Shortage Level 4, *Severe Shortage* | Electricity outages extend for several weeks. |

The state of Virginia's Energy Assurance Plan (Commonwealth of Virginia, 2012) notes that "Shortage Level 3 - Moderate Shortage" may apply when "[there is] storm damage to electric transmission/distribution infrastructure or a loss of electric power that will affect a large number of customers for at least 72 hours" (Commonwealth of Virginia, 2012, p. 2-11). In such a situation, media and public reaction may include: "Public begins losing patience with mild inconvenience. Some reports of economic impact published, mainly regarding retail commerce" (Commonwealth of Virginia, 2012, p. 2-12). Appropriate responses may include instituting mutual aid agreements and encouraging reduction in electricity demand.

The situation is considered a "Shortage Level 4 - Severe Shortage" if there are "widespread electricity outages extending for several weeks" (Commonwealth of Virginia, 2012, p. 2-14). Power outages may lead to failures in energy pipelines, water and wastewater infrastructure, and loss of pump capability at gas stations. If occurring in winter, "governments may need to open heated shelters and take other

[31] PTI (2011) provides guidelines for local-level energy assurance planning.

measures to protect public health, welfare, and safety" and "media will follow events and critical editorials and op-ed columns can be expected" (Commonwealth of Virginia, 2012, p. 2-14). With long-term power disruptions, the expectation is that "Media attention is constant. Economic impact is widespread" (Commonwealth of Virginia, 2012, p. 2-16). Responses may include calls for voluntary and/or mandatory energy conservation. Impacts include: "Individuals using electric powered home medical devices may be affected" so health and social services offices "should be prepared to receive and process multiple requests for assistance" (Commonwealth of Virginia, 2012, p. 2-17).

Insights into societal impacts and expectations can also be gleaned from local energy assurance plans. For example, the Portland (Oregon) Local Energy Assurance Plan notes that "Most hospitals are prepared for approximately three to seven days, depending on the energy disruption. ...Clinics have more limited resources; not all of them have back-up generators" (City of Portland, 2012, p. 39).

## A.3 Power Outages: Multi-Event Trends and Models

Several studies have analyzed and developed models using outage and restoration data from many events. For the most part, these focus on storm-related outages since storms are the most common source of sustained electric power outages in the United States. Broadly speaking, some models and data sources focus on SAIDI and related industry performance measures while others consider performance in terms of customers without service and time to restoration. These two types are summarized in turn below.

Several analyses have examined data on SAIDI and SAIFI.[32] Eto et al. (2012) analyzed 10 years' worth of these data (2000-2009) for 155 U.S. electric utilities, both including and excluding "major events." They found that reported reliability has been declining modestly (at about 2% per year); however, the reasons for this are unclear. NERC data (cited in Castillo, 2014) show that number of weather-related power outages in the United States has increased from a range of 5 to 20 in the 1990s to 50 to 100 in the latter 2000s, due to greater storm durations and intensities (Castillo, 2014).

Data on large outages are routinely reported and are useful for assessing trends and patterns. The U.S. Department of Energy (DOE) and the North American Electric Reliability Council (NERC) both require utilities to submit reports for disturbances exceeding specified thresholds, and the data demonstrate substantial agreement for blackouts greater than 300 megawatts (Hines et al., 2009). Analyzing trends over time, Hines et al. (2009) find statistical evidence to reject the hypothesis that blackout

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[32] A few other models have analyzed trends and factors for SAIDI and SAIFI but omitting major event days. Factors include undergrounding of power lines, and size of utility, level of vegetation. See Fenrick and Getachew (2012).

frequency is decreasing over time, although insufficient evidence to demonstrate an increasing trend. They also found that blackouts are more frequent in summer and winter, as well as during mid-afternoon hours, and that the relationship between blackout size and frequency appears to follow a power-law statistical relationship.

There is enough experience data to allow guidelines and models to be developed regarding power outages in hurricanes. The National Hurricane Center has developed a public information sheet[33] (National Weather Service, 2015) that relates hurricane force to power outage severity, as shown in Table A-2.

**Table A-2 Saffir-Simpson Hurricane Winds and Selected Impacts (Source: after National Weather Service, 2015)**

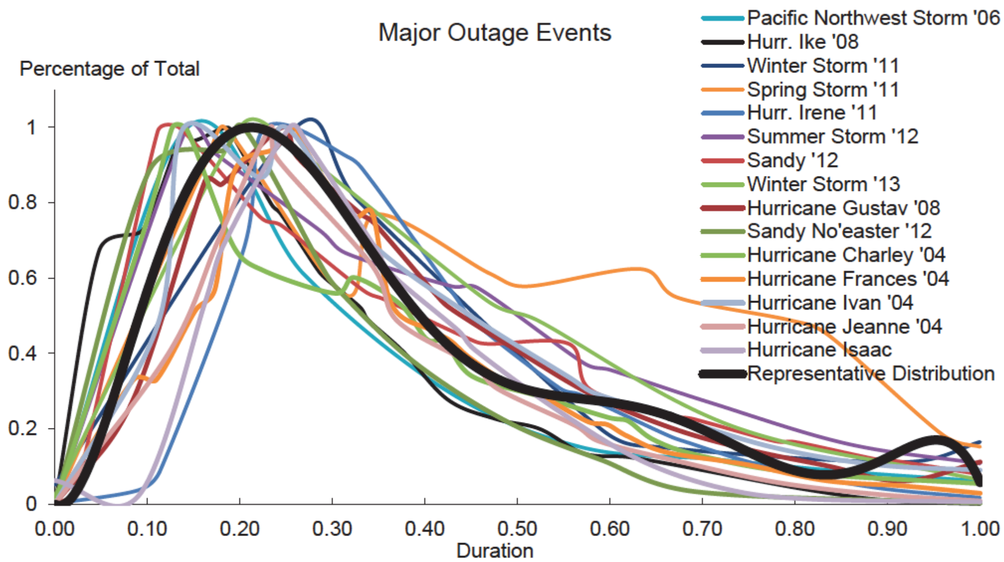
| Category | Winds | Impact to Electric Power Systems |
|---|---|---|
| 1 | 74-95 mph | Extensive damage to power lines and poles will likely result in power outages that could last a few to several days. |
| 2 | 96-110 mph | Near-total power loss is expected with outages that could last from several days to weeks. |
| 3 | 111-130 mph | Electricity will be unavailable for several days to a few weeks after the storm passes. |
| 4 | 131-155 mph | Power outages will last for weeks to possibly months. |
| 5 | >155 mph | Power outages will last for weeks to possibly months. |

Liu et al. (2008) and Han et al. (2009) developed models to predict the occurrence of power outages based on hurricane and electric power system characteristics, as well as (in the case of Liu et al., 2008) a similar model for ice storms. A model by Winkler et al. (2010) is distinctive in explicitly addressing how network topology affects power system performance in storms.

Models have also been developed to estimate restoration. Nateghi et al. (2014) develop a model of power outage duration and calibrate it on data from three Gulf Coast hurricanes; key predictive variables pertain to wind attributes of the storm and climate and geography of the service area. In one recent study, Zorn and Shamseldin (2015) gather data from 63 disasters worldwide on restoration of electric power, water, gas, and telecommunications infrastructures. They use these data to statistically develop restoration curves based on initial outages or earthquake shaking intensity to estimate time to restore 90% operability. Liu et al. (2007) developed models to predict power restoration times in hurricanes and ice storms, based on data from 14 U.S. East Coast events. Hines et al. (2009) found that, surprisingly, there is no evident correlation between blackout size and duration; however, they note that this result may derive in part to the insufficiency of reported data on outage duration. In Executive Office of the President (2013a), analysts were able to construct generic,

[33] Impacts to buildings and water systems are also described.

scaled restoration curves for storms based on restoration data for 15 major U.S. events in the last decade. As shown in Figure A-1 below, while the storm durations ranged from three to 20 days, when normalized to peak customers without service, the profiles were similar. Reed et al. (2010b) also developed and compared restoration curves based on empirical data for various storms and other disasters using a different functional form.




Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Figure A-1 Electric power restoration curves (Executive Office of the President, 2013a, p. 21).

While these data sources and models provide valuable, relatively complete data on outages, they are limited in the degree to which to provide information relative to societal expectations. For example, for major power outages, the DOE data include information such as cause, physical characteristics of event, number of customers without power at peak outage, and time to restore full service (or sometimes, customers without power at a specific timeframe such as two days after the event) (DOE, 2015). For major outages, DOE also prepares Emergency Situation Reports (see http://www.oe.netl.doe.gov/emergency_sit_rpt.aspx) that are publicly available and include details such as number of customers in different states that are without power at different points in time. However, they do not appear to include information such as impacts of outages to critical facilities, number of associated deaths, and estimated economic impact.

In this sense, a model by Ouyang and Dueñas-Osorio (2014) is especially interesting, in that it adopts a resilience perspective. The model is composed of sub-models pertaining to the hurricane hazard, the damageability of system elements (component fragility), outage (power system response), and restoration. Notably, the restoration sub-model differs from many in the literature in that it is not statistically based; rather, it assumes a generic restoration process that considers different restoration strategies, in terms of resource mobilization and restoration sequence. This is important in that it allows utility planning for restoration strategies to meet performance goals. Furthermore, different metrics of system performance are modeled: besides damage, outage (e.g., customers with power), and restoration times, the model considers the percent of critical facilities that have electric power (see Figure A-2). Economic loss in terms of repair costs and customer power interruption costs are also estimated.

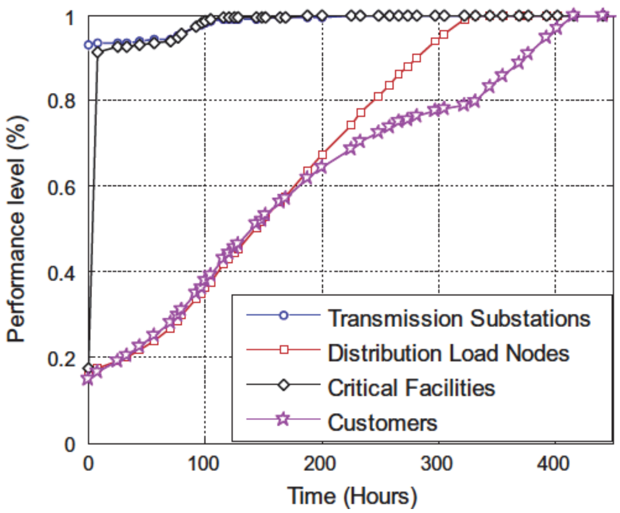



Figure A-2 Modeled restoration curves when the performance levels are measured by different metrics. Points at a specific time in the figure represent the percentage of non-damaged and repaired transmission substations, the percentage of non-damaged and repaired distribution nodes, the percentage of critical facilities with power restored or without power outage, and the percentage of customers with power restored or without power outage (Ouyang and Dueñas-Osorio, 2014).

The conditionality of restoration curves and timeframes on restoration processes is especially important to consider since there is anecdotal evidence (besides logical expectation) that utilities and other organizations learn from past outage experiences and improve restoration processes for future disasters. For example, DOE (2009) notes that electric power recovery in the major hurricanes of 2008 (Hurricanes Ike and Gustav) was "hastened by the actions of the energy industry and Federal, State, and local government agencies, which were better prepared to mount extensive restoration efforts after the experience gained from 2005" (DOE, 2009, p. 2).

A similar argument can be made for utility mitigation actions that are spurred by damage and outages in disaster events. Disasters often instigate improvements in power systems, whether in terms of strengthening infrastructure or better emergency response and restoration plans.

Aside from storms, several models of power outages have been developed for the earthquake hazard. These tend to be very system-specific rather than statistical, e.g., developed to simulate performance of a particular utility's system, and in a few cases model not only damage and outage but also societal consequences such as economic disruption loss to businesses, population displacement, and impact on healthcare facilities (e.g., Shinozuka et al., 2007, Chang et al., 2009b, Yavari et al., 2010).

## A.4 Industry Practices Regarding Restoration of Service

Societal expectations may, however, be indirectly reflected in industry practices regarding restoration of service following outages. The NIST *Guide* (NIST, 2015) recommends that restoration be prioritized to customers according to a three-tiered response scheme: the focus should firstly be on restoring services to critical and essential facilities, secondly on restoring critical public works and access for infrastructure repair crews, and thirdly on general system restoration for the community at large. This prioritization is similar to the typical restoration process in a utility's storm restoration plan, as described by EEI:

> "...a utility will first assess affected power plants, transmission lines, and substations to determine the extent of any damage. Power is then restored to critical facilities, such as hospitals, police and fire stations, water and water-treatment facilities, and nursing homes; main thoroughfares that host supermarkets, gas stations, and other essential community services; and, finally, individual neighborhoods." (EEI, 2014b, p. 2)

Florida Power and Light maintains the following restoration order (PTI, 2011):

- hospitals;
- public service entities including emergency operations centers, critical government facilities, and Red Cross facilities;
- communications infrastructure serving emergency responders, including police and fire and others such as telecommunications and the media;
- water and sewage facilities;
- transportation infrastructure;
- gas supply utilities;
- electric company facilities;
- schools, nursing homes, and critical care facilities; and
- others as designated in coordination with government and the emergency operations centers.

The extent to which the electric power sector adheres to such practices in all hazard events is unclear.

## Appendix B

# Supplement to Gas and Liquid Fuel Analysis

This appendix supplements the material presented in Chapter 4—Gas and Liquid Fuel—in the main body of the report.

### B.1 Regulatory Framework

Congress passed the Natural Gas Pipeline Act of 1968 (USA Public Law 90-481, 1968), which created the Office of Pipeline Safety within the U.S. Department of Transportation (DOT) to implement safety regulations for gas and liquid fuel pipelines. Subsequent legislation pertaining to gas and liquid fuel pipeline systems include the Hazardous Liquid Pipeline Safety Act of 1979 (USA Public Law 96-129, 1979), Pipeline Safety Improvement Act of 2002 (USA Public Law 107-355, 2002), and the Pipeline Inspection, Protection, Safety and Enforcement Act of 2006 (USA Public Law 109-468, 2006). The Pipeline and Hazardous Materials Safety Administration (PHMSA) was created in 2004 and is composed of the Office of Pipeline Safety and Office of Hazardous Materials Safety. Through the Office of Pipeline Safety, PHMSA administers the DOT national regulatory program for the transportation of natural gas, petroleum, and other hazardous fluids by pipeline, including regulations pertaining to the safety of pipelines and associated facilities. In addition to administration of the regulatory program, PHMSA oversees the implementation of risk management and risk based programs by pipeline operators and provides technical and resource assistance for state pipeline safety programs.

Gas and liquid fuel pipeline system operators are also overseen by state regulatory agencies. For example, California operators are regulated by the California Public Utilities Commission (CPUC) whose rules affecting pipeline systems are codified under *State of California Rules Governing Design, Construction, Testing, Operation, and Maintenance of Gas Gathering, Transmission, and Distribution Piping Systems* as part of General Order 112E (NTSB, 2011). PHMSA certifies state regulatory agencies like CPUC annually and provides federal funds to improve performance and pipeline safety. As much as 80% of state pipeline safety programs are supported by PHMSA, including the cost of personnel and equipment. In 2009-2010, the CPUC received 64% of its annual funding from PHMSA (NTSB, 2011). Since 1986, the pipeline safety program at PHSMA has been funded by a user fee assessed on a per mile basis on each operator that is regulated.

## B.2 Key Codes, Standards, and Guidelines

Detailed descriptions of the codes, standards, and guidelines summarized in Table 4-1 in Chapter 4 are provided under the headings that follow.

### *B.2.1 Code of Federal Regulations*

#### B.2.1.1 49 CFR Part 192 Transportation of Natural and Other Gas by Pipeline

49 CFR Part 192 (Office of the Federal Register, 2013a) is the federal regulation that prescribes minimum safety standards for pipeline facilities for the transportation of natural gas. The regulations are detailed and extensive, and encompass over 110 double-column pages in the October 2013 edition. The code addresses pipe materials; pipe and component design; welding in steel pipelines and joining of other types of pipe; general construction requirements; customer meters and services; corrosion control; test requirements; uprating pipelines to a higher internal pressure; operations; maintenance; personnel qualification; and gas transmission and distribution integrity management.

The design pressure for steel pipe, or maximum allowable operating pressure (MAOP), is established on the basis of hoop stress, which is the stress in the circumferential direction of the pipe. 49 CFR Part 192 prescribes methods for determining the tensile strength of the pipe steel as well as a design factor, longitudinal joint factor, and temperature derating factor. The design factor is a reduction in the pipe pressure to lower the risk of excessive hoop stress according to class locations that are based on the density of dwellings and the presence of places where people assemble, such as playgrounds and recreational areas. Class locations are defined as onshore areas that extend 220 yards (yds) either side of a continuous 1-mile (mi)-long section of pipeline.

The four class locations defined in 49 CFR Part 192 are summarized with respect to design factors in Table 4-2 in Chapter 4. Each design factor represents the percentage of the steel yield strength that can be allowed for each class location. For example, design factors of 0.72 and 0.40 apply for pipe in Class 1 and 4 locations, respectively, and indicate that the pipe must be designed with sufficient wall thickness to limit hoop stress to 72% and 40% of yield strength in Class 1 and 4 locations, respectively, before other reductions are applied depending on the presence and type of longitudinal welds and operating temperature. From the table, it can be seen that the class representing the greatest population density (Class 4) results in a reduction in allowable stress to nearly one-half that permitted for the lowest population density (Class 1).

Requirements for welding steel pipelines and joining plastic pipelines are specified. Nondestructive testing is required for at least 10%, 15%, and 90% (100% if practical) of steel welds, respectively, at Class 1, Class 2, and both Class 3 and 4 locations. Nondestructive testing targets of 100% of all welds also apply at major crossings of rivers, railroad and highway rights-of-way, tie-ins to other pipelines, and replacement sections.

The code includes protection from hazards, by requiring the operator to take all practical steps to protect each transmission pipeline from washouts, floods, unstable soil, landslides, or hazards that may cause the pipeline to move or to sustain abnormal loads. Offshore pipelines must be protected from damage by mudslides, water currents, hurricanes, ship anchors, and fishing operations.

The code contains requirements for corrosion control, including external protective coating, and cathodic protection. Compliance criteria for cathodic protection are listed. Methods for corrosion monitoring are specified.

Methods for assessing the strength of steel pipelines by hydrostatic tests are provided. Test requirements for pipelines operated at various internal pressures and levels of steel yield stress in the circumferential direction are given.

Operational requirements covered by the code include surveillance and damage prevention programs, emergency plans, and public awareness programs that comply with API Recommended Practice 1162 (API, 2010), which is described below. In addition, the code prescribes minimum requirements for an integrity management program for a gas transmission pipeline, as well as the integrity management of gas distribution lines.

The integrity management program for a gas transmission pipeline is centered on the identification of high consequence areas (HCAs) where the pipeline is located near dwellings, buildings, and places at which people congregate. Methods for identifying these areas are specified. Implementation standards are incorporated by reference to the relevant sections of ASME B31.8 (ASME, 2014). In the integrity management program the operator is required to identify threats in HCAs such as corrosion, fabrication and construction defects, third-party and outside damage, and human error. The operator must conduct a risk assessment that follows the recommended practices in ASME B31.8 and uses the risk assessment to prioritize pipeline segments for baseline and continual assessments as well as preventative and mitigation measures. Corrective measures to address integrity issues are also provided. The operator must include in its integrity management program methods to measure whether the program is effective in evaluating various pipeline segments. Moreover, the operator must maintain, for the useful life of the pipeline, compliance with the integrity management program. Documentation required to support these activities is specified.

#### B.2.1.2 49 CFR Part 195 Transportation of Hazardous Liquids by Pipeline

49 CFR Part 195 (Office of the Federal Register, 2013b) is the federal regulation that prescribes minimum safety standards and reporting requirements for pipeline facilities used for the transportation of liquid fuels, including $CO_2$. The regulations are detailed and extensive, and encompass over 68 double-column pages in the October, 2013 edition. The code includes by reference 40 standards developed by the American Society of Mechanical Engineers (ASME), American Petroleum Institute (API), American Society for Testing and Materials (ASTM), Pipeline Research Council International (PRCI), Manufacturers Standardization Society for Valve and Fitting Industry (MSS), National Fire Protection Association (NFPA), Plastics Pipe Institute (PPI), and National Association of Corrosion Engineers International (NACE). The code addresses annual accident and safety-related condition reporting, design requirements, construction, pressure testing, operation and maintenance, qualification of pipeline personnel, and corrosion control.

The code prescribes requirements for periodic reporting and for reporting accidents and safety-related conditions. Each operator must annually complete and file a report with PHMSA for each type of liquid fuels facility in operation, including separate reports for crude oil, highly volatile liquids, refined products, and $CO_2$ pipelines. An accident report is required for each failure in a pipeline which involves a release of contents that results in unintentional fire or exceeds 5 gallons. Each operator must also report safety-related conditions, including corrosion, material defects, malfunctions or operating errors, emergency leaks, and safety-related conditions that result in significant pressure reduction. Such reports also cover unintended movement or abnormal loading of a pipeline by environmental causes, such as an earthquake, landslide, or flood that impairs serviceability.

Similar to 49 CFR Part 192, the code for gas liquid fuel pipelines establishes the design pressure for steel pipe, or maximum allowable operating pressure (MAOP), on the basis of hoop stress, and prescribes methods for determining the tensile strength of the pipe steel as well as a design factor and longitudinal joint factor. The design factor is 0.72 except that a design factor of 0.60 is used in offshore and inland waterway locations. A design factor of 0.56 is specified for certain fabrication and heating conditions. The regulations require that pipeline design account for external loads, such those related to earthquakes, vibration, and thermal expansion/contraction.

Minimum requirements are prescribed for constructing new pipeline systems with steel pipe, and for relocating, replacing, and changing pipeline systems with steel pipe. Requirements for welding steel pipelines are specified. Nondestructive testing is required for at least 10% of the girth welds (circumferential welds connecting adjacent sections of the pipeline) made each day by each welder. All girth welds must be tested by nondestructive means at locations of water bodies, state government subdivisions, railroad and highway rights-of-way, tie-ins to other pipelines, and populated areas such as residential subdivisions, schools, and shopping centers.

Methods for assessing the strength of steel pipelines by hydrostatic tests are provided. Test requirements for pipelines operated at various internal pressures and levels of steel yield stress in the circumferential direction are given.

The regulations require each operator to prepare and follow, for each pipeline system, a manual of written procedures for conducting normal operations and maintenance activities as well as handling abnormal operations and emergencies. Procedures that must be followed during an emergency are specified, such as notices to appropriate fire, police, and other public officials; response to notices; and emergency shutdown and pressure reduction.

Public awareness programs that comply with API Recommended Practice 1162 (described below) are required. The program must include provisions to educate the public, appropriate government organizations, and persons engaged in excavation activities. In addition, each operator must carry out a written program to prevent damage from excavation activities and adjacent construction disturbance.

The code requires operators to develop a written integrity management program that addresses the risks affecting pipelines in high consequence areas. High consequence areas include navigable waterways, highly populated areas (as defined in the regulations), and unusually sensitive areas, which involve drinking water and ecological resources that are unusually sensitive to damage from a liquid fuel pipeline release. A risk analysis must be undertaken of pipeline segments in HCAs that identify additional actions to enhance public safety and environmental protection, such as damage prevention best practices, improved monitoring of corrosion control, shorter inspection intervals, remote control valves, and additional personnel training and emergency response drills. The operator must assess the integrity of each pipeline segment in an HCA every five years.

The code contains requirements for corrosion control, including external protective coating, and cathodic protection. Compliance criteria for cathodic protection are listed. Methods for corrosion monitoring are specified.

### *B.2.2 ASME Standards*

#### B.2.2.1 ASME B31.8 Gas Transmission and Distribution Piping Systems

ASME B31.8 (ASME, 2014) covers the design, fabrication, installation, inspection, and testing of pipeline facilities for the transportation of natural gas. It also covers safety aspects of the operation and maintenance of gas pipeline facilities. It is referred to extensively in 49 CFR Part 192 (Office of the Federal Register, 2013a) and is one of the backbone standards that supports the federal code with respect to natural gas pipeline safety. The standard covers materials and equipment; welding, piping system components and fabrication details; design, installation, and testing; operating and maintenance procedures; corrosion control; offshore gas transmission; and sour gas (gas containing significant amounts of hydrogen sulfide) service. It applies predominantly to gas transmission and distribution systems, service lines, and some gathering lines.

The design pressure equation is identical to that in 49 CFR Part 192, which is derived from the ASME code. ASME B31.8 provides methods for determining the tensile strength of the pipe steel as well as a design factor, longitudinal joint factor, and temperature derating factor.

The design factor varies in accordance with four class locations, which are the same as defined in 49 CFR Part 192 (see Table 4-2) except that Class 1 locations are further distinguished as Division 1 and 2, where design factors as high as 0.80 can used for Division 1 and the design factor for Division 2 is identical to 0.72 as specified in 49 CFR Part 192.

In addition to design based on allowable hoop stress, ASME B31.8 also provides design procedures for fracture control as well as equations for longitudinal stress design. The standard indicates that conditions causing additional stress in any part of the line or its appurtenances shall be provided for, including long self-supported spans, unstable ground, mechanical or sonic vibration, weight of attachments, earthquake-induced stresses, stresses caused by temperature differences, and Arctic conditions. The standard also calls for protection of pipelines and mains from natural hazards, such as washouts, floods, unstable soil, landslides, earthquake-related effects, or other conditions that may cause serious movement of, or abnormal loads on, the pipeline. The standard identifies protective measures for natural hazards as increased wall thickness, construction of revetments, erosion control, and anchors. Little additional guidance is given for how to deal with natural hazard conditions.

When pipelines are subject to ground displacement, the longitudinal and combined stress limits may be replaced by an allowable strain limit provided due consideration is given to the ductility and strain capacity of seam weld, girth weld, and pipe body materials, and to the avoidance of buckling, swelling, or coating damage. Maximum strain for continued serviceability (i.e., without interruption) is typically limited to 2%; however, higher strain limits are often specified for extreme ground displacements such as fault surface rupture, for which the objective is to maintain pressure integrity but with recognition that the resulting deformation condition may require repair.

The actual strain limit for strain-based design is established via qualification per testing, fracture mechanics, or other means. Limits of 2% or less are typical for pipelines that must remain serviceable. For extreme conditions (e.g., fault rupture), higher limits are sometimes used (e.g., 3.5% to 4.0%), but such limits come with the recognition that maintaining pressure integrity is the objective and that post-event repair likely will be required.

ASME B31.8 covers operating and maintenance procedures for gas transmission and distribution systems, including written plans for operation and maintenance as well as emergency procedures. It calls for training programs for operator personnel, liaison with emergency responders and entities in or near pipeline rights-of-way, and educational programs for customers and the general public to recognize a gas emergency and report it to the appropriate officials.

The standard provides minimum requirements and procedures for corrosion control of exposed, buried, and submerged metallic piping and components. Provisions for corrosion control are described for buried and submerged installations, above-ground piping exposed to the atmosphere, and internal pipe surfaces.

#### B.2.2.2 ASME 31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids

The ASME B31.4 standard (ASME, 2010) covers the design, materials, construction, assembly, inspection, and testing of pipelines transporting liquids between production facilities, tank farms, natural gas processing plants, refineries, pump stations, ammonia plants, terminals, and other delivery and receiving points. It is referred to extensively in 49 CFR Part 195 (Office of the Federal Register, 2013b). The standard covers design; materials; dimensional requirements; construction, welding, and assembly; inspection and testing; operation and maintenance procedures; corrosion control; and offshore liquid pipeline systems.

The standard classifies loads as sustained, occasional, construction-related, and transient. Sustained loads include internal pressure, external hydrostatic pressure, self-weight, residual loads, and those resulting from subsidence. Occasional loads include earthquake effects related to ground vibrations, soil liquefaction, landslides, and active faulting. Equations are given for calculating hoop stress from internal pressure, stress intensification factors, thermal expansion stress, and longitudinal stress in restrained and unrestrained pipe. Allowable wall thickness is determined from equations linked to hoop stress under internal pressure and various yield strengths, diameters, and weld joint factors. The design factor is defined similarly to that in ASME B31.8, and should not exceed 0.72.

When pipelines are subject to ground displacement, the longitudinal and combined stress limits may be replaced by an allowable strain limit provided due consideration is given to the ductility and strain capacity of seam weld, girth weld, and pipe body materials, and to the avoidance of buckling, swelling, or coating damage. Maximum strain for continued serviceability (i.e., without interruption) is typically limited to 2%; however, higher strain limits are often specified as described previously with respect to ASME B31.8 *Gas Transmission and Distribution Piping Systems*.

The standard calls for consideration of slope failure at locations of potential mudslides, steep slopes, and areas of seismic slumping. Also, design for soil liquefaction is required for areas of known or expected occurrence. If it is not practical to design the pipeline system to survive slope failure, the pipeline shall be designed for controlled breakaway with provisions to minimize the loss of pipeline contents. In earthquake prone areas, including active fault crossings, consideration shall be given to flexibility by means of breakaway couplings, slack loops, flexible pipe sections, or other configurations. Little additional guidance is given for how to deal with these natural hazard conditions.

Specifications are provided for pipeline materials by reference to appropriate ASTM standards, and dimensional requirements are referenced to appropriate ASME and MSS standards. Detailed construction, welding, inspection, and testing specifications are provided.

The standard calls for written plans and training programs for employees that cover operating and maintenance procedures. Pipeline integrity assessments and repairs are specified utilizing hydrostatic tests and in-line inspection devices, followed by remediation of anomalies judged to be unfavorable for safety.

A written emergency plan shall be established in the event of system failures, accidents, or other emergencies. The plan shall provide for training emergency personnel and for liaison with state and local agencies, such as fire and police departments, and entities in or near the pipeline right-of-way, such as utilities, highway authorities, and railroads. The standard calls for communications with residents along the piping system to recognize and report an emergency to the appropriate operating personnel.

The standard contains minimum procedures for controlling external and internal corrosion of exposed, buried, or submerged metallic pipelines and components. The standard is applicable to new pipelines and associated pipeline systems as well as the operation and maintenance of existing pipelines and associated piping systems.

### B.2.3 API Recommended Practice 1162: Public Awareness Programs for Pipeline Operators

API Recommended Practice 1162 (API, 2010) provides guidance for pipeline operators to develop and manage public awareness programs to promote safety for communities near gas and liquid fuel pipelines. It is contained in 49 CFR Parts 192 and 195 by reference in Sections 192.616 and 195.440, respectively. The principal objectives of the standard are to provide a framework for pipeline operators to establish and manage a public awareness program, as well as a process for periodic program evaluation. API Recommended Practice 1162 was first issued in 2003, and a Second Edition was issued in 2010. The Second Edition contains updated guidance for aligning baseline messages (those operators must communicate) with core safety messages. The guidance is focused on promoting safety with regard to third-party damage in a pipeline right-of-way, including excavation disturbance and impact. It does not include communication during emergencies nor include reference to natural hazards. Nevertheless, the framework of the standard could be used as a basis for public risk communication and awareness programs related to community resilience.

API Recommended Practice 1162 is intended to help pipeline operators comply with 49 CFR Parts 192 and 195 through public education, emergency responder liaison activities, and damage prevention. As described in the standard, a public awareness program consists of five activities: (1) define objectives, (2) obtain management commitment, (3) establish program administration, (4) identify pipeline assets, and (5) identify stakeholder audiences. Public awareness programs should raise stakeholder awareness of pipelines in their communities as well as the role stakeholders can play in helping prevent pipeline emergencies and releases of gas or liquid fuel, including third-party damage. They should help stakeholders understand how to prevent and respond to a pipeline emergency.

API Recommended Practice 1162 identifies the stakeholder community as people who live and work adjacent to a natural gas or liquid fuel transmission pipeline right-of-way, gas distribution pipelines, gathering lines, and major facilities, such as a tank farm, storage field, or pump/compressor station. It also identifies places where people assemble or work on a regular basis, such as schools, businesses, churches, hospitals and medical facilities, and parks/recreational facilities, including playgrounds. Emergency response stakeholders include fire departments, police, county and state emergency management agencies, and emergency dispatch and 911 centers. Public officials are part of the stakeholder community, and include planning and zoning boards, licensing and permitting departments, building code enforcement departments, city and county managers, public utility boards, and local governing councils. As mentioned above, the standard is focused on excavation disturbance and impact, and excavators are identified as part of the stakeholder community, including construction companies, excavation equipment rental companies, highway departments, landscapers, well drillers, utilities, land developers, and home builders.

Two categories of messages are identified, involving baseline and enhanced messages. Baseline messages are core safety messages, which should be delivered to each stakeholder community. They involve messages about damage prevention, emergency preparedness, leak/damage recognition and response, pipeline location, potential hazards, and right-of-way encroachment. Enhanced messages go beyond core safety, and may involve messages about areas of high consequence, population density, land development, environmental considerations, and other issues.

The standard addresses the frequency and methods of message delivery. Delivery methods include operator web sites, media news coverage, community and neighborhood newsletters, drills and exercises, open houses, community events, operator employee participation, and pipeline markers.

The standard covers program implementation, which involves the actions of a pipeline operator to plan, conduct, review, evaluate, document, and improve public awareness programs. Program evaluation includes pre-test effectiveness of public awareness materials, including focus groups with in-house and/or external participants. Program evaluation includes formal annual assessment of the program, using internal self-assessment, third-party assessment, or regulatory inspection. It also includes measures of program effectiveness, such as surveys that are operator-designed and conducted, surveys pre-designed by a third party or industrial association, and trade association conducted surveys. The standard contains example forms for annual, internal self-assessment and additional information on conducting surveys.

### B.2.4 Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines

*Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (PRCI, 2004) provide recommended procedures and methods for the assessment of new and existing natural gas and liquid hydrocarbon pipelines subject to seismic-related loading conditions. They provide guidance for determining pipeline response to specific seismic hazards. They are intended to be an update of the *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984; see Section B.2.5) to account for improvements in knowledge and more recent research findings.

The guidelines are provided in two parts: Part I *Guidelines and Recommended Procedures* and Part II *Commentary*. Part I uses a format in which a concise set of general procedures is presented. Background information and references and more detailed discussion of the concise general procedures are presented in the *Commentary*.

The guidelines address general provisions, quantification of seismic hazards, pipeline performance criteria, pipeline analysis procedures, and mitigation options. Seismic hazards include surface faulting, liquefaction, landslides, seismic wave propagation, and transient ground movements related to narrow valleys with weak soils and sites that undergo liquefaction in soil confined by non-liquefiable material.

The guidelines provide methods for quantifying permanent ground movement effects associated with surface faulting, liquefaction-induced lateral spreading, and landslides, as well as seismic wave propagation effects. Analytical procedures for evaluating soil-pipeline interaction are provided, using the quantified ground movements in conjunction with two dimensional finite element analysis in which the soil reactions are modeled in the lateral, vertical, and longitudinal directions relative to the pipeline. Strain based criteria are used to evaluate pipeline performance.

### *B.2.5 Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*

*Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984) were issued as a collaborative effort among pipeline system operators, consultants, and academic researchers, and were accepted as a de facto standard for seismic design within the gas and oil industry for over 20 years. The guidelines address seismic hazards; quantification of seismic hazards; design criteria for pipeline systems; differential ground movement effects on buried pipelines; wave propagation effects on buried pipelines; seismic response and design of liquid fuel tanks; seismic response analysis of structures, equipment, and aboveground pipelines; and operations and maintenance. Although they are a valuable supplement to the *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (PRCI, 2004), access to these guidelines is limited since they no longer are available in published form through ASCE.

## Appendix C

# Supplement to Transportation Analysis

The following sections supplement the material presented in Chapter 6—Transportation—in the main body of the report.

## C.1 Key Codes, Standards, and Guidelines

Table 6-2 in Chapter 6 summarizes the design codes, structural standards and guidelines governing transportation systems in the United States. The following sections provide greater detail on the approaches to designing for various hazards contained in some of the more important of these documents.

### *C.1.1 AASHTO Bridge Design Specifications*

The American Association of State Highway and Transportation Officials (AASHTO) administers the primary codes for use in design of highways, bridges, tunnels and other structures associated with highway transportation.

#### C.1.1.1 AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications

The AASHTO *LRFD Bridge Design Specifications* (AASHTO, 2014) are intended for use in the design, evaluation, and rehabilitation of highway bridges. These specifications employ the load and resistance factor design (LRFD) methodology using factors developed from current statistical knowledge of loads and structural performance. Since 2007, the Federal Highway Administration (FHWA) and all U.S. states mandate that this LRFD standard be used to design all new and total replacement highway bridges. A new edition of these specifications is published every two years, with interim editions in the year after its release.

AASHTO members are the 50 state highway or transportation departments, the District of Columbia, and Puerto Rico. Each member has one vote. The U.S. Department of Transportation (DOT) is a nonvoting member. Revisions are voted on by the AASHTO member departments prior to the publication of each new edition of the specifications and, if approved by at least two-thirds of the members, they are included in the next new edition as standards of the Association. They are then implemented by every state highway or transportation department for all future bridge design, evaluation and rehabilitation.

#### C.1.1.2 AASHTO Guide Specifications for LRFD Seismic Bridge Design

This *AASHTO Guide Specifications for LRFD Seismic Bridge Design* covers seismic design for typical bridge types and applies to non-critical and non-essential bridges (AASHTO, 2011). It is an approved alternate to the seismic provisions in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2014). It differs from the current procedures in the *LRFD Specifications* in its use of displacement-based design procedures, instead of the traditional force-based, R-Factor method. It includes detailed guidance and commentary on earthquake-resisting elements and systems, global design strategies, demand modeling, capacity calculation, and liquefaction effects. Capacity design procedures underpin the *Guide Specifications*' methodology; and include prescriptive detailing for plastic hinging regions and design requirements for capacity protection of those elements that should not sustain damage (AASHTO, 2011).

### *C.1.2 American Railway Engineering and Maintenance-of-Way Association (AREMA) Manuals*

Formed in 1997, AREMA was the result of a merger of four separate associations, namely the American Railway Bridge and Building Association, the American Railway Engineering Association, the Roadmasters and Maintenance of Way Association, and the Communications and Signals Division of the Association of American Railroads. AREMA publishes recommended practices for the design, construction and maintenance of railway infrastructure, which are requirements in the United States.

#### C.1.2.1 AREMA Manual for Railway Engineering

The *Manual for Railway Engineering* (AREMA, 2015a) is an annual publication released every April. The *Manual* consists of more than 5,000 pages of railway engineering reference material—the recommended practices for the industry. It contains principles, data, specifications, plans and economic information pertaining to the engineering, design and construction of the fixed plant of railways (except signals and communications), and allied services and facilities. The material is developed by AREMA technical committees and is published as a guide to railways to use in establishing their individual policies and practices relative to the subjects, activities and facilities covered in the *Manual*. Its main aim is to assist railways in engineering and constructing a railway plant that has inherent qualities of safe and economical operation as well as low maintenance cost. The *Manual* consists of four volumes covering track design and construction, bridge and other railway structure design, infrastructure and passenger facilities, and systems management. The volume on bridge structure design includes a chapter on "Seismic Design for Railway Structures."

#### C.1.2.2 AREMA Railway Communications and Signals Manual

The *Communications and Signals Manual* (AREMA, 2015b) is a manual of recommended practice written by AREMA technical committees in the interest of establishing uniformity, and promoting safety, efficiency and economy. No special attention is paid to the performance of communication and signal systems during wind or seismic hazards.

### C.1.3 Airport Design

The Federal Aviation Administration (FAA) develops engineering, design, and construction standards for civil airports, heliports, and seaplane bases. They include standards for airfield pavement; airport lighting, marking, signs, and other visual aids; safety during construction; surveying and GIS data; deicing, aircraft rescue and fire-fighting, and other facilities; bird radar and foreign object detection systems; and more (FAA, 2009, 2012 and 2014).

### C.1.4 Port Design

#### C.1.4.1 Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS)

California oil terminals are currently designed and maintained to the latest standards provided in the *Marine Oil Terminal Engineering and Maintenance Standards* (MOTEMS) (CSLC, 2010) incorporated into the *California Building Code* (CBSC, 2013). The MOTEMS requirements include mechanisms for rapidly shutting down oil pipelines to minimize the risk of an oil spill during a seismic event. A similar approach would be used during a tsunami event.

The purpose of this code is to establish minimum engineering, inspection and maintenance criteria for marine oil terminals in order to prevent oil spills and to protect public health safety and the environment. This code does not, in general, address operational requirements. Relevant provisions from existing codes, industry standards, recommended practices, regulations and guidelines have been incorporated directly or through reference, as part of this code.

It is current practice within most ports in the United States to construct a containment dike or wall around tank farms and pipelines. These containment dikes are designed to retain any leakage within the designated area, but could also be designed to be of sufficient height to reduce or eliminate tsunami overtopping.

#### C.1.4.2 World Association for Waterborne Transport Infrastructure (PIANC)

The performance-based *Seismic Design Guidelines for Port Structures* (PIANC, 2001) are intended to address the limitations present in conventional design, and establish the framework for a new design approach. They are recommended for use in conjunction with the legally adopted seismic design provisions in port jurisdictions.

### C.1.5 American Society of Civil Engineers (ASCE) 7-10, Minimum Design Loads for Buildings and Other Structures

ASCE 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010) provides loading and design provisions for design of buildings and other structures. It includes loads due to live, dead, wind, seismic, riverine and coastal flooding, ice and snow. The 2016 edition of ASCE 7 will for the first time also include a chapter on Tsunami Loads and Effects. ASCE 7 is incorporated by reference into the *International Building Code* (IBC), which has been adopted (in one version or another) by virtually all jurisdictions in the United States. Although local jurisdictions are permitted to modify, delete or add provisions to the IBC when adopting it as the local code, these amendments seldom impact the wind and seismic design provisions.

### C.1.6 American Concrete Institute (ACI) 318, Building Code Requirements for Structural Concrete, and Commentary

*ACI 318-11 Building Code Requirements for Structural Concrete, and Commentary* (ACI, 2011) is referenced in the *International Building Code* (ICC, 2015) for use in the design of new concrete structures. It contains extensive design requirements for all loading conditions on reinforced concrete structural elements and systems, with comprehensive seismic design provisions. It is used by all U.S. jurisdictions through their adoption of the IBC.

### C.1.7 American Institute of Steel Construction (AISC) Manuals

#### C.1.7.1 AISC Steel Construction Manual

This consensus standard is produced by the AISC for use in the design of new steel structures. It is used by all jurisdictions in the United States through their adoption of the IBC.

#### C.1.7.2 AISC Seismic Design Manual

The AISC *Seismic Design Manual*, companion manual to the AISC *Steel Construction Manual*, specifically deals with design and detailing issues relating to the seismic design of steel structures.

## C.2 Estimating Recovery Time

Table C-1 provides an example of expert opinion about the differences in the public's perception of anticipated performance of primary transportation infrastructure components, compared with the anticipated engineering performance of these

**Table C-1 Expert Opinion on Expectations of Transportation System Damage and Recovery Times**

| Transportation System | Component | Hazard | Anticipated Damage State: *Public Perception* | Anticipated Damage State: *Engineering Anticipation* | Recovery Time: *Public Perception* | Recovery Time: *Engineering Anticipation* |
|---|---|---|---|---|---|---|
| Highway Transportation | Roadways | Earthquake | Pavement cracking but passable | Localized pavement cracking | 1 week | 3-7 days |
| | | Tsunami | Pavement washed away | Debris on roadway and some washout | 1 month | 1-2 weeks |
| | Highway Bridges | High Wind | None | Debris on roadway | 1 day | 1-3 days |
| | | Earthquake | Occasional collapse | 5-10% with major damage or collapse | 1 month | 1-3 months |
| | | Tsunami | All bridges washed away | 10-20% with major damage or collapse | 6-12 months | 1-6 months |
| | Highway Tunnels | Earthquake | None | Potential landslides at tunnel entrance | None | 1-5 days |
| | | Tsunami | None | Debris in tunnel | None | 1-3 days |
| Railway Transportation | Roadbeds and Tracks | Earthquake | Some misalignment | Horizontal and vertical misalignment | 1 week | 1-3 weeks |
| | | Tsunami | Debris on tracks | Tracks washed away | 1 week | 3-6 weeks |
| | Railway Bridges | Earthquake | Occasional collapse | 5-10% with major damage or collapse | 1-3 months | 6-24 months |
| | | Tsunami | All bridges washed away | 10-20% with major damage or collapse | 6-12 months | 6-24 months |
| | Railway Tunnels | Earthquake | None | Potential landslides at tunnel entrance | None | 1-5 days |
| | | Tsunami | None | Debris in tunnel | None | 1-3 days |
| | Control System and Signals | Earthquake | Power failure | Power failure | 1-3 days | 1-5 days |
| | | Tsunami | Washed away | Water damage and overhead lines damaged | 3 months | 1-3 months |

**Table C-1 Expert Opinion on Expectations of Transportation System Damage and Recovery Times (continued)**

| Transportation System | Component | Hazard | Anticipated Damage State: *Public Perception* | Anticipated Damage State: *Engineering Anticipation* | Recovery Time: *Public Perception* | Recovery Time: *Engineering Anticipation* |
|---|---|---|---|---|---|---|
| Port Transportation | Waterfront Structures (wharf, pier, seawall) | Earthquake | Limited cracking and deformation | Damage due to liquefaction and component failure | 1-4 weeks | 1-3 months |
| | | Tsunami | Extensive damage | Damage to access panels and slab-on-grade aprons | 6-12 months | 1-3 months |
| | Cranes and Cargo Handling Equipment | Earthquake | Limited damage | Jump tracks, major damage or collapse | 1-4 weeks | 1-6 months |
| | | Tsunami | All cranes washed away | Water damage to mechanical and electric components | 6-12 months | 1-8 weeks |
| | Fuel Facilities | Earthquake | Limited damage to pipes | Pipe and tank ruptures, leading to fires | 1-3 weeks | 1-3 months |
| | | Tsunami | All tanks float away | Some tanks float and/or ruptured, leading to fires | 6-12 months | 3-6 months |
| | Boats and Ships | Earthquake | None | None | None | None |
| | | Tsunami | All evacuate harbor prior to tsunami | Some remain in harbor – damaged or sunk | None | 1-3 weeks |
| | Shipping Containers | Earthquake | None | Some high stacks topple | None | 1-3 days |
| | | Tsunami | All washed away | Washed into structures and sink in harbor | 1 week | 1-3 weeks |

**Table C-1 Expert Opinion on Expectations of Transportation System Damage and Recovery Times (continued)**

| Transportation System | Component | Hazard | Anticipated Damage State: *Public Perception* | Anticipated Damage State: *Engineering Anticipation* | Recovery Time: *Public Perception* | Recovery Time: *Engineering Anticipation* |
|---|---|---|---|---|---|---|
| Airport Transportation | Runways | Earthquake | Pavement cracking but passable | Localized pavement cracking | 1 week | 3-7 days |
| | | Tsunami | Pavement washed away | Debris on runways and some washout | 1 month | 1-2 weeks |
| | Airport Buildings | Earthquake | Occasional collapse | 5-10% with major damage or collapse | 1 month | 1-3 months |
| | | Tsunami | All buildings washed away | 10-20% with major damage or collapse | 6-12 months | 1-6 months |
| | Fuel Facilities | Earthquake | None | Damage to pipes and storage tanks | None | 1-5 days |
| | | Tsunami | None | Damage to pipes and storage tanks | None | 1-3 days |

structures assuming they are designed to current code requirements. Also provided are perceptions of both public and engineering anticipations of time required to restore the damaged component to functional operation. These data are offered as a starting point in efforts to assess societal expectations of transportation system performance. The earthquake estimates are based on Jones et al. (2008), and the tsunami estimates are based on FEMA (2012). The basis for wind event estimates provided in Table 6-3 is not included in Table C-1, as those estimates reflect the opinions of the authors of this report. No surveys or systematic research data were available to inform these estimates.

# Appendix D

# Supplement to Water and Wastewater Analysis

The following sections supplement the material presented in Chapter 7—Water and Wastewater—in the main body of the report.

## D.1 Key Codes, Standards, and Guidelines

Table D-1 summarizes the codes, standards, guidelines, and manuals governing water and wastewater systems that are of highest significance for community resilience. As indicated in Table D-1, there are a wide variety of codes, standards, guidelines, and manuals provided by a number of different organizations related to different systemic aspects, specific components, preparedness, and response for hazards associated with water and wastewater systems and critical users for these services (e.g., fire departments and hospitals).

**Table D-1 Summary of Key Codes, Standards, and Guidelines for Water and Wastewater Systems**

| Category | Title | General Description/Use |
|---|---|---|
| Code | 2015 *International Building Code* or applicable jurisdictional building code (ICC, 2015) | Design of new structures (other than pipelines) including treatment plant office and laboratory buildings, pump stations, process tanks, water storage tanks and reservoirs. |
| Standard | ASCE 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010) | Minimum load requirements for the design of buildings and other structures subject to building code requirements. |
| Standard | ASCE 24, *Flood Resistant Design and Construction* (ASCE, 2014a) | Minimum requirements for design and construction of structures located in flood hazard areas and subject to building code requirements; applicable to water and wastewater system structures. |
| Standard | ASCE 41-13, *Seismic Evaluation and Rehabilitation of Existing Buildings* (ASCE, 2014b) | Deficiency-based and systematic procedures that use performance-based principles to evaluate and retrofit existing buildings to withstand the effects of earthquakes; applicable to existing water and wastewater system buildings. |
| Standard | ACI 350-06, *Code Requirements for Environmental Engineering Concrete Structures* (ACI, 2006) | Structural design, materials selection, and construction of environmental engineering concrete structures used for conveying, storing, or treating liquid or other materials, such as solid waste; includes ancillary structures for dams, spill-ways, and channels. |
| Standard | ACI 371R-08, *Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks* (ACI, 2008) | Recommendations for materials, analysis, design, and construction of concrete-pedestal elevated water storage tanks, including both the all-concrete tank and the composite tank, consisting of a steel water storage vessel supported on a cylindrical reinforced concrete pedestal. |

**Table D-1 Summary of Key Codes, Standards, and Guidelines for Water and Wastewater Systems (continued)**

| Category | Title | General Description/Use |
|---|---|---|
| Standard | ACI 372R-03, *Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures* (ACI, 2003) | Design and Construction of wrapped, circular, prestressed concrete structures (constructed of thin cylindrical shells of either concrete or shotcrete) commonly used for liquid or bulk storage |
| Standard | AWWA D100-11, *Welded Carbon Steel Tanks for Water Storage* (AWWA, 2011d) | Minimum requirements for the design, construction, inspection, and testing of new welded carbon steel tanks for the storage of water at atmospheric pressure. |
| Standard | AWWA D110-13, *Wire- and Strand-Wound, Circular, Prestressed Concrete Tanks* (AWWA, 2013) | Recommended practice for the design, construction, inspection, and maintenance of wire- and strand-wound, circular, prestressed concrete water-containing structures for four types of core walls. |
| Standard | AWWA D115-06, *Tendon-Prestressed Concrete Water Tanks* (AWWA, 2006a) | Describes current and recommended practice for the design, construction, and field observations of concrete tanks using tendons for prestressing; applies to containment structures for use with potable water, raw water, or wastewater. |
| Standard | ISO 16134, *Earthquake and Subsidence Resistant Design of Ductile Iron Pipes* (ISO, 2006) | Design of earthquake and subsidence resistant ductile iron pipes; provides means of determining and checking resistance of buried pipelines; applicable to buried ductile iron pipes and fittings with joints with expansion/contraction and deflection capabilities. |
| Standard | ASCE 15-98, *Standard Practice for Direct Design of Buried Precast Concrete Pipe using Standard Installations* (ASCE, 1998) | Direct design of buried precast concrete pipe using Standard Installations; reviews the design and construction of the soil/pipe interaction system that is used for the conveyance of sewage, industrial wastes, storm water, and drainage. |
| Standard | AWWA G100-11, *Water Treatment Plant Operation and Management* (AWWA, 2011c) | Management standard on critical requirements for the effective operation and management of drinking water treatment plants. |
| Standard | AWWA G430-14, *Security Practices for Operation and Management* (AWWA, 2014) | Management standard on critical requirements for establishing and operating a protective security program for a water, wastewater, or reuse utility. |
| Standard | AWWA G440-11, *Emergency Preparedness Practices* (AWWA, 2011b) | Management standard providing minimum requirements to establish and maintain an acceptable level of emergency preparedness based on the identified and perceived risks facing utilities in the water sector. |
| Standard | AWWA J100-10, *Risk and Resilience Management of Water and Wastewater Systems* (AWWA, 2010) | Sets the requirements for all-hazards risk and resilience analysis and management for the water sector and prescribes methods that can be used for addressing these requirements. |
| Guidelines | ALA *Guidelines for Implementing Performance Assessments of Water Systems* (ALA, 2005a) | Recommendations for evaluating and characterizing anticipated performance of water systems and for making risk management decisions for natural hazard and human threat events. |
| Guidelines | ALA *Guidelines for the Design of Buried Steel Pipe* (ALA, 2001a) | Design provisions to evaluate integrity of steel buried pipe for a range of loads. |
| Guidelines | ALA *Seismic Design and Retrofit of Piping Systems* (ALA, 2002) | Comprehensive guidance for the seismic design and retrofit of piping systems in essential facilities; describes seismic qualification of new or existing above ground piping systems. |
| Guidelines | ALA *Seismic Fragility Formulations for Water Systems* (ALA, 2001b) | Detailed procedures that can be applied to any water transmission system in order to evaluate the probability of damage from earthquake hazards to various components of the system. |

**Table D-1 Summary of Key Codes, Standards, and Guidelines for Water and Wastewater Systems (continued)**

| Category | Title | General Description/Use |
|---|---|---|
| Guidelines | ALA *Seismic Guidelines for Water Pipelines* (ALA, 2005b) | A cost effective approach to seismic design of water pipelines; three design methods are presented. |
| Guidelines | ALA *Wastewater System Performance Assessment Guideline* (ALA, 2004b) | Recommendations for evaluating and characterizing anticipated performance of wastewater systems and for making risk management decisions for natural hazard and human threat events. |
| Guidelines | ALA *Guide for Seismic Evaluation of Active Mechanical Equipment* (ALA, 2004a) | Recommendations for evaluating the seismic operability of valves, pumps, compressors, fans, air handling units, and chillers. |
| Guidelines | ATC-25-1, *A Model Methodology for Assessment of Seismic Vulnerability and Impact of Disruption of Water Supply Systems* (ATC, 1992) | A methodology for assessing water supply system earthquake vulnerability and the impact of failure and disruption. |
| Guidelines | ASCE 12-05, *Standard Guidelines for Design of Urban Surface Drainage* (ASCE, 2005b) | Design of urban subsurface drainage systems, covering topics such as site analysis, system configuration, filters and envelopes, hydraulics and hydrology, structural considerations, and materials. |
| Guidelines | ASCE 13-05, *Standard Guidelines for Installation of Urban Surface Drainage* (ASCE, 2005c) | Installation of urban subsurface drainage and discusses subjects such as site inspection, soil erosion, excavation, foundation preparation, and inspection of materials, equipment, and construction. |
| Guidelines | ASCE 14-05, *Standard Guidelines for Operation and Maintenance of Urban Surface Drainage* (ASCE, 2005d) | Operation and maintenance of urban subsurface drainage, including design criteria, maintenance procedures, safety, water quality, inspection, and rehabilitation. |
| Guidelines | ASCE TCLEE, *Guidelines for Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984) | Guidelines for the seismic design of buried oil, gas, or refined petroleum product pipelines and surface facilities, such as a pumping and compressor stations, storage tanks, and miscellaneous terminal facilities; often used for design of water system components. |
| Guidelines | ASCE TCLEE Monograph 15, *Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities* (ASCE, 1999) | Guidelines for the seismic evaluation and upgrade of water supply and transmission and wastewater conveyance and discharge facilities. |
| Guidelines | NIST GCR 97-730, *Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Following Earthquakes* (NIST, 1997) | Procedures to help quantify water system reliability using vulnerability evaluation techniques for pipelines and reservoirs, and mitigation measures for systems and components and alternatives for alternate water supplies. |
| Guidelines | *Guide Document: Earthquake Vulnerability of Water Systems* (KJC, 1993) | Guidance on assessing earthquake vulnerabilities of water systems and suggested performance objectives. |
| Guidelines | *Minimizing Earthquake Damage: A Guide for Water Utilities* (AWWA, 1994) | Information to assess the effects of earthquake hazards on water purveyors. |
| Guidelines | *Business Continuity Planning for Water Utilities: Guidance Document* (WRF, 2013) | Guidance on how to prepare a business continuity plan for water and wastewater system operators. |
| Guidelines | *Emergency Water Supply Planning Guide for Hospitals and Health Care Facilities* (CDC and AWWA, 2012). | Information for health care facilities to develop an Emergency Water Supply Plan to prepare for, respond to, and recover from a total or partial interruption of the facilities' normal water supply. |
| Guidelines | *Guide for Municipal Wet Weather Strategies* (WEF, 2013b) | Management of wet weather flows in the wastewater collection and treatment system |

**Table D-1 Summary of Key Codes, Standards, and Guidelines for Water and Wastewater Systems (continued)**

| Category | Title | General Description/Use |
|---|---|---|
| Manual | AWWA M9, *Concrete Pressure Pipe* (AWWA, 2008a) | Design, selection, specification, installation, transportation, and testing of concrete pressure pipe in water service. |
| Manual | AWWA M11, *Steel Pipe: A Guide for Design and Installation* (AWWA, 2004b) | Information for designing, installing, and maintaining steel pipe and fittings for potable water transmission and distribution. |
| Manual | AWWA M19, *Emergency Planning for Water Utilities* (AWWA, 2001) | Guidance and tools for water and wastewater managers in preparing for either natural or human-caused emergencies. |
| Manual | AWWA M23, *PVC Pipe—Design and Installation* (AWWA, 2002) | Design, installation, and maintenance of PVC pipe for drinking water systems. |
| Manual | AWWA M31, *Distribution System Requirements for Fire Protection* (AWWA, 2008b) | Designing water distribution systems to meet fire protection and suppression requirements. |
| Manual | AWWA M41, *Ductile-Iron Pipe and Fittings* (AWWA, 2009) | Specification, design, installation, and maintenance of ductile-iron pipe and fittings for potable water systems. |
| Manual | AWWA M55, *PE Pipe—Design and Installation* (AWWA, 2006b) | Design, specification, installation, and maintenance of polyethylene (PE) water pipe. |
| Manual | *Emergency Power Source Planning for Water and Wastewater* (AWWA, 2004a) | Guidance for assessing the vulnerability, condition, and reliability of primary electrical equipment; evaluating options for on-site electrical-generating equipment; assessing placement locations to facilitate integration with the existing electrical systems; determining current and historical electrical load demands and estimating future electrical demands; and determining backup-power capacity needed to meet peak demand. |
| Manual | AWWA M60, *Drought Preparedness and Response* (AWWA, 2011a) | Information to help water managers facing water shortages by illustrating how to employ tried-and-true strategies and tactics of drought mitigation, as well as new tools and methods. |
| Manual | *Planning for an Emergency Drinking Water Supply* (EPA, 2011) | Development of an emergency drinking water plan by a local water utility. |
| Manual | MCEER-08-0009, *Fragility Analysis of Water Supply Systems* (Jacobson and Grigoriu, 2008) | A procedure to assess the seismic performance of water supply systems. |
| Manual | MCEER Monograph No. 3, *Response of Buried Pipelines Subject to Earthquake Effects* (O'Rourke and Liu, 1999) | Reviews the behavior of buried pipeline components subjected to permanent ground deformation and wave propagation hazards, and existing methods to quantify pipeline response. |
| Manual | MCEER Monograph No. 4, *Seismic Design of Buried and Offshore Pipelines* (O'Rourke and Liu, 2012) | Reviews behavior of buried pipeline components subject to permanent ground deformation and wave propagation hazards, as well as existing methods to quantify the response. |
| Manual | ASCE TCLEE Monograph 22, *Seismic Screening Checklists for Water and Wastewater Facilities* (ASCE, 2002) | Checklists to screen for seismically vulnerable water and wastewater facilities; the checklists facilitate seismic vulnerability assessment for water and wastewater system components, and provide useful information for improving loss mitigation programs. |
| Manual | ASCE TCLEE Monograph No. 26, *Fire Following Earthquake* (ASCE, 2005a) | Covers the entire range of fire following earthquake issues, state-of-the-practice insight on how to address the problem, and implement mitigations. |

**Table D-1 Summary of Key Codes, Standards, and Guidelines for Water and Wastewater Systems (continued)**

| Category | Title | General Description/Use |
|---|---|---|
| Manual | *Emergency Planning, Response, and Recovery* (WEF, 2013a) | Information to help utilities develop an emergency response plan to recover from events such as infrastructure failure, small- and large-scale natural hazard events, and human-created incidents; includes case studies from around the world. |
| Manual | WEF MOP 28, *Upgrading and Retrofitting Water and Wastewater Treatment Plants* (WEF, 2005) | Covers the latest upgrading and retrofitting procedures and shows how to avoid common pitfalls, cost overruns, and permit violations. |
| Manual | WEF MOP 8, *Design of Municipal Wastewater Treatment Plants* (WEF, 2009) | Reference for contemporary plant design practices of wastewater engineering professionals, augmented by performance information from operating facilities. |
| Manual | WEF MOP FD-17, *Prevention and Control of Sewer System Overflows* (WEF, 2011) | Up-to-date information necessary to help managers and engineers understand and analyze an overflow problem, and guidance on finding the most efficient, feasible, and cost-effective strategies to reduce or eliminate such overflows. |
| Manual | WEF MOP 23, *Design of Urban Storm Water Controls* (WEF, 2012) | Consolidates technologies under a comprehensive view of storm water management in an attempt to foster a convergence between traditional storm water controls and green infrastructure. |
| Manual | *Recent Earthquakes: Implications for U.S. Water Utilities*, Web Report #4408 (WRF, 2012) | Reviews water system performances in the 2010 Maul Chile Earthquake, 2010-2011 Canterbury Earthquake Sequence, and 2011 Great East Japan Earthquake; provides recommendations for utilities and describes some utility performance goals. |
| Manual | *Domestic Water Quantity, Service Level Health* (WHO, 2003) | Requirements for water service level to promote health. |
| Manual | *Minimum Water Quantity Needed for Domestic Use in Emergencies* (WHO, 2005) | Provides water quantities to meet basic human needs and how to calculate the volumes. |
| Manual | The Sphere Handbook, *Humanitarian Charter and Minimum Standards in Humanitarian Response* (The Sphere Project, 2011) | Minimum standards for hygiene, water supply, excreta disposal, vector control, solid waste management, and drainage, as related to water and wastewater systems. |

Descriptions of the codes, standards, and guidelines summarized in Table D-1 are provided under the following subheadings:

### *D.1.1 Buildings and Other Structures*

The design of new aboveground structures (e.g., treatment plant office and laboratory buildings, pump stations, process tanks, water storage tanks and reservoirs) is typically governed by local building codes and design standards. Most states in the United States adopt the *International Building Code* (IBC) (ICC, 2015), with possible modifications. Design loads are prescribed by a consensus-based standard, *ASCE 7-10 Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010). ASCE 7 sets minimum design provisions for dead, soil, live, hydrostatic uplift, flood, wind, snow, rain, ice, and seismic loads. Tsunami loads are currently being developed. The

ASCE 7 standard uses the concept of Risk Category to increase the design force level for important structures. Typical buildings are assigned to Risk Category II. Water and wastewater treatment facilities are assigned to Risk Category III, because failure of these facilities can cause disruption to civilian life and potentially cause public health risks. Water storage facilities and pump stations required to maintain water pressure for fire suppression are assigned to the highest category, Risk Category IV. In addition, buildings and structures within the scope of the *International Building Code* proposed to be constructed in flood hazard areas must be designed in accordance with ASCE 24-14, *Flood Resistant Design and Construction* (ASCE, 2014a). Many water and wastewater facilities are located in flood hazard zones by necessity of respectively collecting or discharging the waters.

Standards dictating the design and construction of many types of tanks and reservoirs are governed by ACI 350-06, *Code Requirements for Environmental Engineering Concrete Structures* (ACI, 2006); ACI 371R-08, *Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks* (ACI, 2008); ACI 372R-03, *Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures* (ACI, 2003); American Water Works Association (AWWA) D100-11, *Welded Carbon Steel Tanks for Water Storage* (AWWA, 2011d); AWWA D110-13, *Wire- and Strand-Wound, Circular, Prestressed Concrete Tanks* (AWWA, 2013); and AWWA D115-06, *Tendon-Prestressed Concrete Water Tanks* (AWWA, 2006a). These standards generally follow the same criteria outlined in ASCE 7 (ASCE, 2010). Thus, all new structures following these codes and standards should have the same or similar performance when subjected to the hazards for which loading criteria are provided.

The *International Building Code* (ICC, 2015) intends for structures designed as Risk Category III or IV to remain operational or require only minor repairs to be put back into operation following a design level wind, seismic, or other event. By designing for this performance target for the design level event, water and wastewater systems should remain operational under a routine level event and may experience moderate to major damage during an unexpected or extreme level event. However, this understanding is based on the current knowledge level of the hazards. The design levels have been modified over the years as experience has been gained and knowledge has improved. As a result, buildings and other structures built in conformance with prior codes do not necessarily meet current code requirements. ASCE 41-13, *Seismic Evaluation and Rehabilitation of Existing Buildings* (ASCE, 2014b) establishes procedures to evaluate existing structures, identify deficiencies, and apply systematic procedures to retrofit them to withstand the effects of earthquakes. ASCE 41-13 evaluations can be undertaken to target multiple performance objectives including those meeting current code provisions or a basic performance objective reaching a level at about 75% of the current code.

### *D.1.2 Dams, Levees, and Tunnels*

Dams, levees, and tunnels generally require specialized geotechnical and structural engineering expertise and designs are modified to site-specific conditions. Historically, many levees were not engineered. State agencies generally have special requirements and jurisdictional oversight for high-risk dams. The Federal Energy Regulatory Commission (FERC) controls the design of dams associated with hydroelectric generation. The design and evaluation of dams are based on life-safety performance objectives. In many cases the safe performance of a dam can be achieved for flood and earthquake without the same level of functionality intended for critical facilities in ASCE 7. Thus, the life safety evaluation for dams and reservoirs does not imply a better performance than other structures within water or wastewater systems; to ensure common performance levels specific reviews need to be made.

Unlike dams, levees generally do not have any jurisdictional oversight and no performance objective requirements related to critical hazards, other than to meet the design flow containment (which may not be clearly defined for many levees across the country). There are guidelines and manuals to aid the proper design of levees for floods, earthquakes and other hazards that have not been reviewed as part of this project.

Tunnel construction is usually overseen by state occupational safety departments to ensure safe design and construction practices. Designs usually are based on proper state-of-the-practice engineering using experts in the field to properly incorporate hazards of concern (e.g., floods, earthquakes). Manuals and guidelines are available for water tunnels but have not been reviewed for this project.

### *D.1.3 Pipelines*

Unlike for building structures, there are no existing codes or standards in the United States for pipeline designs to address earthquake or any other extreme hazard. Typical water and wastewater pipe design, installation, operation, and maintenance in the United States utilize the following standards, guidelines, and manuals: ASCE 12-05, *Standard Guidelines for Design of Urban Surface Drainage* (ASCE, 2005b); ASCE 13-05, *Standard Guidelines for Installation of Urban Surface Drainage* (ASCE, 2005c); ASCE 14-05, *Standard Guidelines for Operation and Maintenance of Urban Surface Drainage* (ASCE, 2005d); ASCE 15, *Standard Practice for Direct Design of Buried Precast Concrete Pipe using Standard Installations* (ASCE, 1998); AWWA M9, *Concrete Pressure Pipe* (AWWA, 2008a); AWWA M11, *Steel Pipe: A Guide for Design and Installation* (AWWA, 2004b); AWWA M23, *PVC Pipe—Design and Installation* (AWWA, 2002); AWWA M41, *Ductile-Iron Pipe and Fittings* (AWWA, 2009); and AWWA M55, *PE Pipe—Design and Installation* (AWWA, 2006b).

These guidelines and manuals cover many pipe materials and joints and the following typical loads: soil; traffic (roadway and railroads); construction; thermal; thrust; dead; internal and external pressures; and water hammer and surge pressures. The design of joints and fittings consistent with the prescribed load conditions is addressed, as well as protections against corrosion. None of the standards, guidelines or manuals cover the design for extreme hazards and little attention is given to how permanent ground movements affect pipes. To the contrary, some specifically identify how useful the pipe materials are for addressing these special considerations, without providing any direction on how to design for them, even though the pipe systems have certain known vulnerabilities to the hazards requiring specialized design procedures. For example, the following quote from AWWA M41, *Ductile-Iron Pipe and Fittings* (AWWA, 2009), has existed for many decades:

> "Special use considerations should be given to such situations as expansive soils, earthquakes, and other geologically hazardous conditions. Field studies have shown that certain clay soils can exhibit high swell pressures that can cause significant beam loading on underground pipe. It has been estimated that 50,000 earthquakes occur annually throughout the world that are of sufficient magnitude to be felt or noticed without aid of instruments. Ductile-iron pipe's inherent strength and the availability of specialized joints make it an excellent choice for such applications."

In this example, it is known that ductile iron pipes can withstand a certain amount of ground movement without failure. However, experience also shows how these pipes can be seriously damaged when subjected to extreme hazards. Such statements in standards, guidelines, and manuals need to be quantified with acceptable design procedures. The review undertaken for this project identifies how the commonly used pipe design guidelines and manuals do not address performance criteria for extreme events. Some of these guidelines and manuals (e.g., AWWA, 2009) imply an inherent adequate performance to extreme conditions without need for specialized design, which is contrary to what is needed for increasing water system, wastewater system, and community resiliencies.

Some international standards do exist for the design of pipelines for extreme loads. The ISO 16134 standard, *Earthquake and Subsidence Resistant Design of Ductile Iron Pipes* (ISO, 2006), provides methodologies for designing and installing special seismic joints to accommodate ground movements through axial flexibility and joint rotation. This standard is not used in the United States for water or wastewater pipe design and the example from AWWA M41 (AWWA, 2009) given above was not intended to refer to such joint design. ISO 16134 (ISO, 2006) was developed for a special earthquake resistant ductile iron pipe (ERDIP) joint type, which until recently was only available in Japan. Features of the joint type include 1% axial extension or compression per pipe length and up to 8 degrees rotation at each joint. Earthquake resistant ductile iron pipe has the capability of improving water and wastewater system performance. It is not only helpful for resisting earthquakes, but also for many types of extreme conditions, including erosion, landslides, differential settlement, thermal strain, freezing ground, and other strain related conditions found across the country. The recent importing of earthquake-resistant ductile iron pipe by the City of Los Angeles and other cities along the West Coast has sparked interest in improving pipe performance capabilities, not only in ductile iron, but also other materials. There is a current movement by several ductile iron, PVC (polyvinyl chloride), and HDPE (high-density polyethylene) pipe manufacturers to improve product robustness for improved system resilience capabilities. This current effort will inevitably make its way into some, if not all, the above listed pipe design standards, guidelines, and manuals and influence the normal pipe design methodologies.

Several guidelines and manuals do exist in the United States to address pipe design for earthquakes and a few other hazards. These include the Americana Lifelines Alliance (ALA) *Guidelines for the Design of Buried Steel Pipe* (ALA, 2001a); ALA *Seismic Design and Retrofit of Piping Systems* (ALA, 2002); ALA *Seismic Guidelines for Water Pipelines* (ALA, 2005b); ASCE Technical Council of Lifeline Earthquake Engineering (TCLEE) *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984); MCEER Monograph No. 3, *Response of Buried Pipelines Subject to Earthquake Effects* (O'Rourke and Liu, 1999); and MCEER Monograph No. 4, *Seismic Design of Buried and Offshore Pipelines* (O'Rourke and Liu, 2012). These guidelines and manuals were issued over the past few decades by several different authors and organizations. They address seismic hazards, quantification of seismic hazards, design criteria for pipeline systems, differential ground movement effects on buried pipelines, wave propagation effects on buried pipelines, and aboveground pipelines. Some also address seismic response and design of liquid fuel tanks, seismic response analysis of structures, equipment, and operations and maintenance. All the documents provide simplified pipe analysis methods and a few present more advanced computer methods. All but the ASCE (1984) document are available online.

In addition to earthquake and other common loads addressed in previous subsections, the ALA *Guidelines for the Design of Buried Steel Pipe* (ALA, 2001a) address surface impact loads, buoyancy, thermal expansion, mine subsidence, movement at pipe bends, nearby blasting, and fluid transients. These guidelines also provide suggested acceptance criteria, but do not present any significant hazard design level criteria.

The ALA *Seismic Design and Retrofit of Piping Systems* (ALA, 2002) addresses earthquake inertial loads on piping systems in essential facilities, mostly pipes in buildings and other structures located above ground. Several load analysis methods are presented, including selecting seismic loads using the *International Building*

*Code* procedures (ICC, 2015), which then establishes piping performance criteria consistent with those required for structures meeting that code. Qualification methods are presented for piping and anchorage systems falling within allowable limits.

The ALA *Seismic Guidelines for Water Pipelines* (ALA, 2005b) provides a cost-effective approach to seismic design of water pipelines applicable throughout the United States. As a result, it presents varying design requirements for different types of pipelines, depending on their overall importance to the network performance of the water utility and the localized earthquake risks. A performance-based design method is used that considers resilience and community impacts. Performance objectives are presented in terms of target performance levels and seismic hazard levels. Pipeline functions are identified using a Pipe Function Class, which defines pipeline importance in achieving the system performance goal and its needed reliability. Using the Pipe Function Class criteria for transient and permanent ground motions, landslide movements, liquefaction and lateral spreading, and fault rupture are defined. Ground motions are selected using procedures consistent with the *International Building Code* (ICC, 2015). Ground movements are selected for other hazards in a manner providing a uniform confidence of loads not being exceeded that is consistent with the ground motions. Hazard load criteria may be modified for multiple use, continuity, supply source, branch lines and isolation, and redundancy. More detailed descriptions on the process are provided in Davis (2005) and Davis (2008).

The *ASCE TCLEE Guidelines for Seismic Design of Oil and Gas Pipeline Systems* (ASCE, 1984) document is commonly referenced for seismic design of water and wastewater pipelines. The document provides seismic design criteria for two earthquake levels—a Probable Design Earthquake having recurrence intervals of 50 to 100 years, and a Contingency Design Earthquake recurring on the order of 200 to 500 years or more. The system should remain operable during and after a Probable Design Earthquake, while the Contingency Design Earthquake may cause limited damage. This document is described in more detail in Appendix B, Section B.2.5.

MCEER Monograph No. 3, *Response of Buried Pipelines Subject to Earthquake Effects* (O'Rourke and Liu, 1999), describes how different types of piping systems behave when subjected to transient and permanent ground movements. Methods for assessing the seismic hazards are described, but no recommendations for design criteria are presented. MCEER Monograph No. 4, *Seismic Design of Buried and Offshore Pipelines* (O'Rourke and Liu, 2012), presents information in a similar manner and includes offshore pipelines.

### D.1.4 Mechanical Equipment

The ALA *Guide for Seismic Evaluation of Active Mechanical Equipment* (ALA, 2004a) document provides recommendations for evaluating the seismic operability of valves, pumps compressors, fans, air handling units, and chillers (active equipment with moving parts). The recommendations are in the form of seismic evaluation checklists, static and dynamic calculation methods and seismic testing protocols. The guide does not cover aspects related to ensuring power to the equipment. The seismic function is best specified as: (a) position retention, (b) leak tightness, or (c) operability. The seismic design of industrial equipment has generally followed the rules of the applicable building code, with the exception of equipment in nuclear facilities for which seismic design rules are specified in regulations such as the U.S. *Code of Federal Regulations* 10 CFR, Part 50. The *International Building Code* (ICC, 2015) contains explicit rules for developing seismic input for the analysis and qualification of equipment. The consequence of their failure is deemed to represent a safety hazard. Thus, current state of practice establishes life safety performance. The ALA document also lists several civil, structural, mechanical, and electrical standards that can be used to qualify components needed in water and wastewater systems.

### D.1.5 Water and Wastewater System Assessment and Performance

Several guidelines and manuals address the systemic performance of water and wastewater systems, some of which provide guidance on selecting performance criteria. These include ALA *Guidelines for Implementing Performance Assessments of Water Systems* (ALA, 2005a); ALA *Wastewater System Performance Assessment Guideline* (ALA, 2004b); ATC-25-1, *A Model Methodology for Assessment of Seismic Vulnerability and Impact of Disruption of Water Supply Systems* (ATC, 1992); *Minimizing Earthquake Damage, A Guide for Water Utilities* (AWWA, 1994); *Guide Document Earthquake Vulnerability of Water Systems* (KJC, 1993); NIST GCR 97-730, *Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Following Earthquakes* (NIST, 1997); and ASCE TCLEE Monograph 15, *Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities* (ASCE, 1999).

The ALA *Guidelines for Implementing Performance Assessments of Water Systems* (ALA, 2005a) and ALA *Wastewater System Performance Assessment Guideline* (ALA, 2004b) provide recommendations for evaluating and characterizing anticipated performance of water and wastewater systems, respectively. The documents focus on specific hazards, system vulnerabilities to different hazard levels, and potential system performance. Some guidance is given on the potential consequences of system performance. Seven hazards are included: earthquake, general ground deformation, wind, tornado, icing, flooding, and human threats. Earthquake hazards include shaking, fault rupture, liquefaction, landslide, and tsunami. General ground deformations include landslide, settlement, and frost heave. Criteria is provided for three realtive hazard levels: low, medium, and high. Recommendations are provided for three types of evaluation:

- A *Level 1* analysis is simple and can be completed rapidly (within days to weeks);
- *Level 2* is an intermediate, more quantitative analysis and can be completed within weeks to months; and
- *Level 3* is considered the most detailed and quantitative, which can be performed within the state-of-the-practice and may take months to years to complete.

Information is also included that can be used to inform or guide risk management decisions for natural hazard and human threat events (e.g., to provide water and wastewater system owners and operators with a defensible basis for risk management decisions).

The ATC-25-1 Report, *A Model Methodology for Assessment of Seismic Vulnerability and Impact of Disruption of Water Supply Systems* (ATC, 1992) provides the means to conduct a preliminary "first phase" examination of the potential impacts of earthquakes on water system functionality at the local or regional level. Application of the methodology enables the user to develop estimates of direct damage to system components and the time required to restore damaged facilities to pre-earthquake usability. Performance goals are not addressed. Instead, ATC (1992) recommends using earthquake scenarios.

The AWWA (1994), KJC (1993), NIST (1997), and ASCE (1999) documents provide information on:

- Past system and component performances,
- Geotechnical earthquake hazards,
- Performance goals,
- Risk analysis, and
- Seismic retrofitting and mitigation examples and/or alternatives.

The documents focus only on geotechnical earthquake hazards and include ground shaking, liquefaction and lateral spreading, settlement, landslide, and fault crossings. ASCE (1999) describes methods for identifying associated evaluation and design values for each geotechnical hazard. AWWA (1994), KJC (1993), and NIST (1997) include system monitoring and control issues. KJC (1993) was a predecessor document to AWWA (1994).

These four documents recommend using the same two earthquake levels, defined as:

- *Operating Basis Earthquake, Moderate Earthquake, or Probable Earthquake*. This is an earthquake likely to occur within the design lifetime of regularly constructed facilities and could be defined as a 50% chance of occurrence within a 50-year time frame, or about a 72-year recurrence interval.

- *Design Basis Earthquake, Large Earthquake, or Maximum Earthquake.* This is an earthquake that could possibly occur within the design lifetime of regularly constructed facilities and could be defined as a 10% chance of occurrence within a 50-year time frame, or about a 475-year recurrence interval.

AWWA (1994) specifies that the basis for selecting these levels was consistency with the *Uniform Building Code* (UBC) (ICBO, 1997), which was the code in effect at the time the AWWA document was developed. As described by ASCE (1999), the Operating Basis, Moderate, or Probable Earthquake is not meant to guarantee that a water system will not sustain damage or service outages when the earthquake occurs. The Design Basis, Large, or Maximum Earthquake does not necessarily represent the maximum possible level of shaking from a Maximum Credible Earthquake.

NIST (1997) focuses on issues related to water supply for firefighting. Several chapters are devoted to specific evaluation of tanks and treatment systems. Strategies for managing water between water systems and fire departments are also explored in detail.

ASCE (1999) provides guidelines for the seismic evaluation and upgrade of water supply transmission and wastewater conveyance facilities. The document mainly focuses on water supply and transmission facilities with some information on wastewater facilities. In addition to that identified above, specific risk assessments performed by water system owners and operators are described in detail, including mitigation and retrofit programs, emergency operations, cost-benefit analysis, and examples on working with the customers and stakeholders for implementing improvements.

The most important aspects of the AWWA (1994), KJC *(*1993), NIST *(*1997), and ASCE (1999) documents, as related to the purpose of this report, are the performance goals and criteria they describe; providing details on these aspects was beyond the scope of this report.

The ASCE TCLEE Monograph 22, *Seismic Screening Checklists for Water and Wastewater Facilities* (ASCE, 2002) provides checklists to provide guidance on performing site-specific reviews of water and wastewater system facilities and components in preparation for a seismic performance evaluation. The document covers most types of facilities and equipment found in water and wastewater systems. A summary of water and wastewater system vulnerability assessments is provided and is relatively consistent with those previously described for other documents. There is a difference in the recommendations on how to include earthquake levels and performance goals. ASCE (2002) recommends that three levels of earthquake be considered in vulnerability evaluations as follows:

- Lower Level Earthquake (e.g., 72-year return interval);

- Upper Level Earthquake (e.g., 475-year return interval); and
- Maximum Considered Earthquake.

Additional documents have been prepared to assist in assessing the seismic vulnerabilities of water system components using fragility functions. Two documents providing recommended seismic fragility functions are: ALA *Seismic Fragility Formulations for Water Systems* (ALA, 2001b) and MCEER-08-0009, *Fragility Analysis of Water Supply Systems* (Jacobson and Grigoriu, 2008). However, none of these documents provide any guidance or recommendations on design or performance criteria, and therefore are not reviewed in more detail in this report.

The Water Resource Foundation (WRF) document, *Recent Earthquakes: Implications for U.S. Water Utilities* Web Report #4408 (WRF, 2012), summarizes water system performances during the 2010 Maule, Chile earthquake, 2010-2011 Canterbury, New Zealand earthquake sequence, and 2011 Great East Japan earthquake. In addition, and most important to this report, WRF (2012) provides information in an appendix describing performance goals by other water agencies, specifically those in the United States. The performance goals are described in Section D.2.

### *D.1.6 Security*

AWWA has prepared a set of standards to aid in water and wastewater systems management and operations, as well as planning for and responding to emergencies related to a wide variety of hazards. These include AWWA G430-14, *Security Practices for Operation and Management* (AWWA, 2014), and AWWA J100-10*, Risk and Resilience Management of Water and Wastewater Systems* (AWWA, 2010). The AWWA (2014) standard deals with terrorist-type threats. It covers design and construction, threat level-based protocols, emergency response and recovery plans and business continuity plans, internal and external communications, partnerships, documentation, human resources, and equipment.

The AWWA (2010) standard: deals with security as well as natural hazards; sets requirements for all-hazards risk and resilience analysis and management of water and wastewater systems; and prescribes methods to address the requirements set forth. The hazards addressed include manmade hazards or accidents, hurricanes, earthquakes, tornadoes, and floods. AWWA (2010) further recommends wildfire, ice storms, extreme cold weather, avalanche, tsunami, landslide, mud slide, and other hazards be included “if the probability of occurrence and the consequences are as high or higher than the four basic natural hazards in the specific location.” The procedure attempts to establish a common base for system risk and resilience assessment using the following equations:

$$\text{Risk} = (\text{Threat Likelihood}) \times (\text{Vulnerability}) \times (\text{Consequence})$$

$$\text{Resilience} = (\text{Duration}) \times (\text{Severity of Service Loss}) \times (\text{Vulnerability}) \times (\text{Threat Likelihood})$$

There are some shortcomings to the process. The procedure assesses each asset or component individually and adds up total risk or resilience in a linear fashion, whereas water and wastewater systems usually are not linear. The document provides a separate method for reviewing system resilience in a simplified manner, which does not link back to the original standard risk and resilience analysis. The hazards are intended to cover an entire probability distribution from common to very rare with an established frequency for each event. However, the consequences and vulnerability assessments use worst reasonable case assumptions without regard to the uncertainties. As a result, the risks associated with each hazard cannot be compared on an equal basis as implied by the standard.

The natural hazards were incorporated under the belief they are consistent with the ASCE 7 and IBC methodologies. Unfortunately, AWWA (2010) describes inconsistencies with the building code by "assuming that only initiating events that exceed the design basis would cause damage," and "assume[ing] that the greater the difference between the design basis event and the actual event, the greater the expected damage." Building codes are based on life safety and structures may be significantly damaged while continuing to protect life whereas AWWA (2010) is utilizing this philosophy to assume water and wastewater facilities may remain operable without consideration of the actual code-level design. Thus, these discrepancies can easily provide misleading results.

The risk and resilience management step in the AWWA (2010) standardized process is identified as the most important to reducing risk and increasing resilience. In this step, managers are to "decide" what risk and resilience levels are acceptable for each asset-hazard pair. There is no guidance on asset or system performance levels. This, coupled with the inability to compare risks for each asset-hazard pair, can provide misleading results and a perceived high comfort level for utility owners and operators, potentially contrary to the reality of true risks that are not properly assessed. Nonetheless, this method can easily identify low-cost, easy-to-implement mitigation actions to reduce risks and improve resilience; unfortunately, these may not have a significant effect on the high-impact, low-frequency events.

### *D.1.7 Water Systems and Fire Hazards*

The AWWA M31 document, *Distribution System Requirements for Fire Protection* (AWWA, 2008b), provides information for designing water systems to be able to provide water at sufficient volume and pressure to aid in fighting fire hazards under normal operating conditions. However, the document does not provide information on how to ensure the water system will be operable following an earthquake or other hazard event that may damage the system, potentially rendering it inoperable, and at the same time, result in cascading fire hazards.

The ASCE TCLEE Monograph No. 26*, Fire Following Earthquake* (ASCE, 2005a), provides a comprehensive overview of fire following earthquake. It also describes fires occurring after other events and how fire hazards are increased when associated with wind and other hazards. The book reviews past fire following earthquake events and fires from non-earthquake events. Analysis and modeling for the fire following earthquake hazard is reviewed in detail. The impacts of fire department capabilities and water system performance are addressed. The occurrence of fires following earthquakes is capable of overwhelming fire department personnel because the number of potential ignitions, coupled with their primary role as first responders, stretches resources so thin that firefighting may not be the first priority. The role of water in firefighting is essential and loss of water system operability can greatly hinder fire suppression. The potential performance of gas, electric power, communications, and roadway systems in earthquakes is described, and the respective systemic roles in fighting fires following earthquakes are identified. Methods for mitigating fire following earthquake and retrofitting existing systems with inclusion of cost-benefit analysis are also presented. In addition, alternate water sources and auxiliary and secondary water supply systems are described, as well as approaches for dealing with specific earthquake hazards, such as fault rupture impacts on pipelines. Specific recommendations for design and performance criteria are not provided, but numerous references are given for standards, guidelines, and manuals. AWWA (1994) is referenced for water system performance standards. A primary message given throughout the monograph is how important water supply is after an earthquake to aid in fire suppression (using either the primary network or alternate sources).

There are also state health and safety codes governing fire protection, including mechanical codes, and fire codes dealing with building structures. These are not specifically addressed in this report, but in general the state codes do not address fires following hazard events, such as earthquakes.

### *D.1.8 Water and Wastewater System Plans and Preparations for Emergencies*

Several documents address water and wastewater system plans and preparations for emergencies. These include: *Business Continuity Planning for Water Utilities* (WRF, 2013); AWWA G440-11, *Emergency Preparedness Practices* (AWWA, 2011b); AWWA M19, *Emergency Planning for Water Utilities* (AWWA, 2001); AWWA M60*, Drought Preparedness and Response* (AWWA, 2011a); *Emergency Power Source Planning for Water and Wastewater* (AWWA, 2004a); *Planning for an Emergency Drinking Water Supply* (EPA, 2011); *Emergency Water Supply Planning*

*Guide for Hospitals and Health Care Facilities* (CDC and AWWA, 2012); and *Emergency Planning, Response, and Recovery* (WEF, 2013a). None of these documents directly address system performance or design aspects. The WRF (2013a) business continuity planning document targets a 30-day restoration period for business recovery activities. AWWA (2004a) applies mostly to preparing for conditions once power is lost. Similarly, AWWA (2011a) applies mostly to preparing for conditions once a drought has ensued.

EPA (2011) aids in helping water systems prepare for conditions that may result in the need for emergency drinking water. This document provides useful information on how alternate water supplies may be obtained for interim use when the system is unable to provide potable water. The information has limited use for developing performance criteria. It states its use is limited to outages on the order of 21 days, but notes the expectation of impacts from potential disasters in the United States lasting much longer than 21 days. It emphasizes the need to have a plan for emergency water that covers the gap between the existing population and the targeted level of post-event service. The document recommends planning for one gallon per day per person as a minimum based on basic survival needs, but notes there is wide range of recommendations on what is needed for basic survival; this aspect is covered in more detail in Section D.1.11 on societal performance needs.

### D.1.9 Water and Wastewater Treatment Plants

Several standards and guidelines exist for the design, retrofit, management and operation of treatment plants. These include AWWA G100-11, *Water Treatment Plant Operation and Management* (AWWA, 2011c); Water Environment Federation (WEF) MOP 28, *Upgrading and Retrofitting Water and Wastewater Treatment Plants* (WEF, 2005); and WEF MOP 8, *Design of Municipal Wastewater Treatment Plants* (WEF, 2009). These documents do not address specifics on how to design, upgrade or retrofit treatment plants for specific types of hazard events.

### D.1.10 Wastewater Management

Several standards, guidelines, and manuals exist that address storm water systems, management and controls. These include ASCE 12-05, *Standard Guidelines for Design of Urban Surface Drainage* (ASCE, 2005b); ASCE 13-05, *Standard Guidelines for Installation of Urban Surface Drainage* (ASCE, 2005c); ASCE 14-05, *Standard Guidelines for Operation and Maintenance of Urban Surface Drainage* (ASCE, 2005d); the WEF *Guide for Municipal Wet Weather Strategies* (WEF, 2013b); WEF MOP FD-17, *Prevention and Control of Sewer System Overflows* (WEF, 2011); and WEF MOP 23, *Design of Urban Storm Water Controls* (WEF, 2012). These documents do not specifically deal with hazards other than flood, as related to storm water controls (e.g., urban storm water runoff). Additionally, they do not generally deal with extreme events, but instead a standard 50- or 100-year event.

#### *D.1.11 Societal Performance Needs*

The World Health Organization (WHO) and The Sphere Project provide information for understanding the volumes of water needed by society and guidance on how to deliver in emergencies. These include the WHO *Domestic Water Quantity, Service Level Health* (WHO, 2003); WHO *Minimum Water Quantity Needed for Domestic Use in Emergencies* (WHO, 2005); and The Sphere Handbook, *Humanitarian Charter and Minimum Standards in Humanitarian Response* (The Sphere Project, 2011). The Sphere Project handbook also describes minimum humanitarian standards needed for hygiene and how to maintain basic public health and safety in areas where water and wastewater systems are nonfunctional. These documents are useful for providing guidance on minimum levels of performance that water and wastewater systems should have to meet basic human needs. Additional studies (e.g., Gleick, 1996) provide valuable information on how to develop basic level and increased performance over time. These may be coupled with the use of alternative water sources similar to that described by EPA (2011).

## D.2 Performance Requirements

Table 7-3 in Chapter 7 summarizes the performance levels for different types of facilities or subsystems based on specific documents dealing with water and wastewater system performance requirements. The regulatory framework within which systems operate help to dictate many performance requirements. NIST (2015, p. 216) provides a good summary of the regulatory framework of water and wastewater systems. This information is not repeated in this report, but is referenced to aid in understanding performance requirements.

AWWA (1994) provides a practical outline for establishing seismic performance goals that has been used as a basis for many recommendations and applications. There are no similar performance recommendations for other hazards. ASCE and ALA present several different recommendations for performance requirements based on the original AWWA (1994). One key factor for the continued use of AWWA (1994) is the practical application to water and wastewater system operations and its form, which meets what is now called performance-based design. Further, it links system performance to expected performance of other community systems and buildings, and in doing so attempts to integrate water and wastewater systems to improve community resilience. Unfortunately, the foundation from which AWWA (1994) was created (i.e., the *Uniform Building Code*) is outdated. ALA (2005b) developed a set of performance objectives related to the *International Building Code* (ICC, 2015), which in some ways provides an updated and improved version of the

AWWA (1994) performance targets, but is only intended to apply to the design of water pipelines.

Additional shortcomings of AWWA (1994) and other similar performance objectives are described by Davis (2014a) and relate mostly to the lack of linking the performance to actual water system serviceability functions. An alternate set of services defined in Tables 7-5 and 7-6 can be used to define objectives for infrastructure performance. The services defined in Tables 7-5 and 7-6 are linked directly to actual system restoration strategies and how utilities can best make use of these strategies to improve community resilience. Application of these concepts are scalable from an individual service connection (e.g., hospital) to pressure zones, to entire service areas and have been verified as applicable through studies of the 1994 water system performance in Los Angeles (Davis et al., 2012; Davis, 2014a).

Performance targets relate a level of acceptable service losses and timeframe for restoring services in relation to hazard levels. NIST (2015) provides recommendations to investigate routine, design, and extreme hazards. In general, the graded criteria for good performance specifies limited damage for routine hazards, some acceptable service losses at design hazards, and more acceptable losses and longer recovery for extreme hazards; this is reasonable and matches societal expectations as described in several places in this report.

Example performance targets implemented by several water and wastewater systems, many of which used AWWA (1994) as the basis from which to work, are provided in Section D.2.1 and D.2.2, respectively.

### *D.2.1 Performance Criteria for Water Systems*

#### D.2.1.1 East Bay Municipal Utility District Water System – General Performance Goals

Tables D-2 and D-3 provide the performance goals adopted by the East Bay Municipal Utility District (EBMUD) (WRF, 2012). The goals generally use the earthquake definition as provided by AWWA (1994) and ASCE (1999). WRF (2012) states:

> "Within EBMUD's context, a "Probable" earthquake was considered to be a Magnitude 6 earthquake on the Hayward fault occurring somewhere within the EBMUD's service area; or similar sized earthquakes on the Concord, Calaveras and other faults within the service area, or even larger magnitude earthquakes on faults located further away from the District's service area.
>
> Within EBMUD's context, a "Maximum" earthquake was considered to be a characteristic earthquake on the Hayward fault rupturing through the entire

**Table D-2 EBMUD Water System Service Goals – Probable Earthquake (WRF, 2012)**

| Service Category | | Probable Earthquake |
|---|---|---|
| General | 1 | Minimal secondary damage and risk to the public |
| | 2 | Limit extensive damage to system facilities |
| | 3 | All water introduced into the distribution system minimally disinfected |
| | 4 | All water introduced into the distribution system fully treated |
| Fire Service | 5 | Sufficient portable pumps and hose to provide limited fire service in all areas |
| | 6 | All areas have minimal fire service (one reliable pumping plant and reservoir) |
| | 7 | High risk areas have improved fire service (all facilities reliable, minimum fire reserves) |
| | 8 | Normal service to all hydrants within 20 days |
| Hospitals and Disaster Centers | 9 | Minimum service to affected area within 1 day (water available via distribution system near each facility) |
| | 10 | Impaired service to affected area within 3 days (water available via distribution system to each facility, possibly at reduced pressures) |
| Domestic Users | 11 | Potable water via distribution system or truck within 1 day |
| | 12 | Impaired service to affected area within 3 days (water available via distribution system to each domestic user, possibly at reduced pressures) |
| Commercial, Industrial and Other Users | 13 | Impaired service to affected area within 3 days (water available via distribution system to each commercial or industrial user, possibly at reduced pressures) |

**Table D-3 EBMUD Water System Service Goals – Maximum Earthquake (WRF, 2012)**

| Service Category | | Maximum Earthquake |
|---|---|---|
| General | 1 | Minimal secondary damage and risk to the public |
| | 2 | Limit extensive damage to system facilities |
| | 3 | All water introduced into the distribution system minimally disinfected |
| | 4 | All water introduced into the distribution system fully treated |
| Fire Service | 5 | Sufficient portable pumps and hose to provide limited fire service in all areas |
| | 6 | All areas have minimal fire service (one reliable pumping plant and reservoir) |
| | 7 | High risk areas have improved fire service (all facilities reliable, minimum fire reserves) |
| | 8 | Normal service to all hydrants within 100 days |
| Hospitals and Disaster Centers | 9 | Minimum service via distribution system or truck within 3 days |
| | 10 | Minimum service within 10 days (water available via distribution system near each facility) |
| | 11 | Impaired service within 30 days (water available via distribution system to each facility, possibly at reduced pressures) |
| Domestic Users | 12 | Potable water at central locations for pickup within 3 days |
| | 13 | Minimum service to 70% of customers within 10 days |
| Commercial, Industrial and Other Users | 14 | Potable water at central locations for pickup within 1 week |
| | 15 | Minimum service to 70% of customers within 10 days |
| | 16 | Impaired service to 90% of customers within 30 days (water available via distribution system to 90% of commercial or industrial users, possibly at reduced pressures) |

length of the service area, or characteristic earthquakes on the Concord or Calaveras faults, rupturing within or very near the service area."

#### D.2.1.2 Contra Costa Water District – Reliability and Seismic Criteria

Tables D-4 and D-5 provide the "reliability criteria" adopted by the Contra Costa Water District (CCWD) (WRF, 2012; ASCE, 1999). WRF (2012) states:

> "The reliability criteria set goals for the post-earthquake restoration of different types of service, as defined in Table 9-2 [reproduced here as Table D-4], beginning with emergency fire service within 2-8 hours and ending with permanent repair (as opposed to temporary fixes often used to quickly restore service) of all damaged facilities within 2 years.
>
> Seismic criteria were developed in order to set forth a consistent and prioritized set of standards for the earthquake resistant evaluation and design of CCWD facilities, such as the Contra Costa Canal, necessary to meet reliability criteria. The seismic criteria establishes a four level facility classification system (Class I to Class IV) based on the importance of the facility remaining functional to meet post-earthquake fire service demands.

**Table D-4 CCWD Reliability Criteria – Raw Water System (WRF, 2012)**

| Service Category | | Reliability Criteria - Raw Water (RW) |
|---|---|---|
| General | RW-1: | No primary damage to District facilities that endangers the general public and CCWD staff. |
| | RW-2: | No direct secondary damage to non-District facilities due to catastrophic failure of District facilities. |
| | RW-3: | Temporary repairs to achieve emergency fire service and essential service as soon as possible. |
| | RW-4: | Temporary repairs to achieve full service within 30 days. |
| | RW-5: | Permanent repairs to all raw water facilities completed within 2 years. |
| Wholesale Municipal | RW-6: | Emergency and normal fire service needs at user point of delivery within 2 days after earthquake. Customers utilizing storage or other services to fight fires in the interim. |
| | RW-7: | Partial service within 10 days at user point of delivery after earthquake with periodic 3 day interruptions for repairs. |
| | RW-8: | Full service within 30 days after earthquake. |
| Industrial Users | RW-9: | Emergency and normal fire service needs at user point of delivery within 2 days after earthquake. Standby customers utilizing storage or other services to fight fires in the interim. |
| | RW-10: | Restoration priority based on minimizing economic loss. |
| | RW-11: | Partial service within 10 days at user point of delivery after earthquake with periodic 3 day interruptions for repairs. |
| | RW-12: | Full service within 30 days after earthquake. |
| Standby Users<br>Agricultural Users<br>Landscape Users | RW-13: | Emergency and normal fire service needs at user point of delivery within 2 days after earthquake. Standby customers utilizing storage or other services to fight fires in the interim. |
| | RW-14: | Restoration priority based on minimizing economic loss. |
| | RW-15: | Partial service within 10 days at user point of delivery after earthquake with periodic 3 day interruptions for repairs. |
| | RW-16: | Full service within 30 days after earthquake. |

**Table D-5 CCWD Relationship Between Reliability and Seismic Criteria (WRF, 2012)**

| Seismic Criteria Facility Class | Class Description | Type of Service | Related Reliability Criteria (see Table D-4) | Criteria for Max. Duration of Loss | Example District Facilities | Facility Reliability | System Reliability |
|---|---|---|---|---|---|---|---|
| I | Critical | Emergency Firefighting | RW-6 | 1-2 days | Contra Costa Canal Milepost 0.0 to 26.0; Raw Water Storage Reservoirs | 99.5% | 90% |
| II | Essential | Emergency and Critical Care | RW-3, RW-6, RW-9, RW-13 | 2-5 days | Secondary Municipal and Industrial Laterals | 95.0% | 80% |
| III | Important | Partial and Sanitary | RW-4, RW-7, RW-11, RW-15 | 5-15 days | Contra Costa Canal Turnouts | 90.0% | 50% |
| IV | Standard | Full | RW-1, RW-2, RW-8, RW-12, RW-16 | 15-60 days | All Contra Costa Canal Facilities | 80.0% | 0-30% |

Table 9-4 [reproduced here as Table D-5] illustrates these classifications and their relationship to the type of service and reliability criteria."

#### D.2.1.3 Humboldt Bay Municipal Water District Service Goals

The Humboldt Bay Municipal Water District (HBMWD) is a water wholesaler serving the cities of Eureka, Arcata, McKinleyville and several other smaller communities around Humboldt Bay, California. HBMWD operates water treatment facilities and large diameter raw water and treated water pipelines. HBMWD delivers water to various retail water agencies. Tables D-6 and D-7 provide the performance goals adopted by this utility (WRF, 2012). The following describes the goals in more detail:

1. **Minimal Secondary Damage and Risk to the Public.** Damage to the infrastructure should pose minimal risk to the public. For example, chlorine releases should not occur, and occupied buildings should not collapse.
2. **Limit Extensive Damage to System Facilities.** Undue amounts of damage to HBMWD's own facilities could result in the inability for the HBMWD to respond after an earthquake. Damage to critical facilities should be avoided (such as the designated areas for emergency operations coordination). Damage posing a life-safety threat to HBMWD's own personnel should be avoided.
3. **All Water Introduced into the Potable Water Transmission System Minimally Disinfected.** All water from the HBMWD raw water source should be at least minimally disinfected prior to introduction into the treated water transmission system, immediately after the earthquake. This means that no "untreated" water should be introduced. Minimal disinfection would include chlorination.

**Table D-6 HBMWD Water System Service Goals – Maximum Earthquake (WRF, 2012)**

| Service Category | | Maximum Earthquake |
|---|---|---|
| General | 1 | Minimal secondary damage and risk to the public |
| | 2 | Limit extensive damage to system facilities |
| | 3 | All water introduced into the distribution system minimally disinfected |
| Fire Service | 4 | Provide 50% of average winter level flows to customer meters within 4 hours after earthquake. (Tentative goal for large customers) |
| | 5 | Provide 100% of average winter level flows to all customer meters within 3 days after earthquake. (Tentative goal for large customers) |
| Domestic Water Service | 6 | Potable water via truck or accessible locations within 1 day to meet minimum consumption needs (1 gallon per person per day) |
| | 7 | Impaired service within 7 days |
| | 8 | Normal service within 60 days |
| Raw Water Service | 9 | Impaired service within 7 days |
| | 10 | Normal service within 60 days |

**Table D-7 HBMWD Water System Service Goals – Probable Earthquake (WRF, 2012)**

| Service Category | | Probable Earthquake |
|---|---|---|
| General | 1 | Minimal secondary damage and risk to the public |
| | 2 | Limit extensive damage to system facilities |
| | 3 | All water introduced into the distribution system minimally disinfected |
| Fire Service | 4 | Provide 100% of average winter level flows to customer meters within 4 hours after earthquake. (Tentative goal for large customers) |
| | 5 | Provide 100% of average winter level flows to all customer meters within 3 days after earthquake. (Tentative goal for large customers) |
| Domestic Water Service | 6 | Potable water via truck or accessible locations within 1 day to meet minimum consumption needs (1 gallon per person per day) |
| | 7 | Impaired service within 3 days |
| | 8 | Normal service within 20 days |
| Raw Water Service | 9 | Impaired service within 3 days |
| | 10 | Normal service within 20 days |
| Minimally Disinfected | 11 | Chlorination or better. |
| Impaired Service | 12 | Provide water (adequate to meet winter time demands), possibly at lower pressure than normal. |
| Normal service | 13 | Provide water at the same level of reliability as under "normal" pre-earthquake conditions. |

4. **Provide 50% of Average Winter Level Flows to Domestic Customer Meters within 4 Hours after the Earthquake.** This service goal reflects that after an earthquake, there may be multiple fires in HBMWD's customer service areas. This will be compounded by damage within the customer distribution systems, which will rapidly deplete storage in local storage tanks and reservoirs. If no water can be re-supplied to the customer distribution systems, there can be an

unacceptable high risk of fire spread, especially if it is windy at the time of the earthquake.

The target restoration time for HBMWD to restore water service of four hours should be adequate for McKinleyville. This service goal may vary for other distribution system customers based on their own system needs.

5. **Provide 100% of Average Winter Level Flows to Domestic Customer Meters within 3 Days after the Earthquake.** This service goal reflects that HBMWD should be able to restore its normal wintertime capacity to deliver water to major customer's turnouts at normal pressures and flows, within three days after any earthquake.
6. **Potable Water via truck or Accessible Locations within 1 Day to Meet Minimum Consumption Needs.** It is likely that many Humboldt Bay area residents will be unable to get potable water via their normal water distribution system following large earthquakes. This will include people who are forced out of their homes because of damage to those structures; and due to damage to the underground water distribution networks. In coordination with HBMWD's distribution customers, suitable delivery points for distribution of potable water should be identified as part of an emergency response plan. Suitable facilities should be available to allow water tanker trucks to be filled from reliable sources of potable water.
7. **Impaired Service to all Domestic Water Customers within 7 Days.** Impaired service is defined as the delivery of some amount of water (enough to meet winter time demands, allowing for mandatory curtailment of irrigation if necessary) via the transmission system. Occasional pressure fluctuations or brief outages are possible.
8. **Normal Service to all Domestic Water Customers within 60 Days.** Normal service is defined as the delivery of water at the same level of reliability as under "normal" pre-earthquake conditions.
9. **Impaired Service to Industrial Water Customers within 7 Days.** Impaired service is defined as the delivery of non-potable water to meet low level to average level operations via the transmission system. Occasional pressure fluctuations or brief outages are possible. This level of water should be sufficient for industrial customers to restore operations, albeit at somewhat less than maximum operating day capability.
10. **Normal Service to Industrial Water Customers within 60 Days.** Normal service is defined as the delivery of water at the same level of service as provided prior to the earthquake.

#### D.2.1.4 San Francisco Public Utilities Commission

The San Francisco Public Utilities Commission (SFPUC) is implementing a Water System Improvement Program (WSIP) that involves a broad range of projects varying in size and complexity covering all aspects of the water system—from dams, reservoirs, pipelines, and tunnels to treatment facilities, pump stations, and water storage tanks (SFPUC, 2008, Chapter 3). The goals and objectives for the WSIP were developed based on a planning horizon through 2030. The SFPUC (2008):

> "…selected the year 2030 because published population projections generally do not extend beyond 20 to 25 years, and the agency determined the 2030 forecasts to be the most reasonably foreseeable future condition. The goals and objectives are founded on two fundamental principles pertaining to the existing regional system: (1) maintaining a clean, unfiltered water source from the Hetch Hetchy regional water system; and (2) maintaining a gravity-driven system.
>
> The overall goals of the WSIP for the regional water system are to:
>
> - Maintain high-quality water and a gravity-driven system,
> - Reduce vulnerability to earthquakes,
> - Increase delivery reliability,
> - Meet customer water supply needs,
> - Enhance sustainability, and
> - Achieve a cost-effective, fully operational system.
>
> To further these program goals, the WSIP includes objectives that address system performance. Table 3-2 [reproduced here as Table D-8] presents these objectives as they relate to the WSIP goals. The system performance objectives describe and, in many cases, more specifically quantify, what the regional water system proposes to achieve under the WSIP, and thereby guide the water supply actions, facility improvements, operations, and maintenance requirements included in the WSIP."

### *D.2.2 Performance Criteria and Objectives for Wastewater Systems*[34]

#### D.2.2.1 East Bay Municipal Utility District

EBMUD provides "wholesale" transport and treatment of raw sewage for the cities of Alameda, Albany, Berkeley, El Cerrito, Emeryville, Kensington, Oakland, Piedmont, and part of Richmond California. They have one wastewater treatment plant.

[34] This information was provided by Don Ballantyne, Principal, Ballantyne Consulting LLC

**Table D-8 SFPUC Water System Improvement Program Goals**

| Program Goal | System Performance Objective |
|---|---|
| Water Quality – maintain high water quality | • Design improvements to meet current and foreseeable future federal and state water quality requirements.<br>• Provide clean, unfiltered water originating from Hetch Hetchy Reservoir and filter all other surface water sources.<br>• Continue to implement watershed protection measures. |
| Seismic Reliability – reduce vulnerability to earthquakes | • Design improvements to meet current seismic standards.<br>• Deliver basic service to the three regions in the service area (East/South Bay, Peninsula, and San Francisco) within 24 hours after a major earthquake. Basic service is defined as average winter-month usage, and the performance objective for the regional system is 229 million gallons per day (mgd). The performance objective is to provide delivery to at least 70 percent of the turnouts (i.e., water diversion connecting points from the regional system to customers) in each region, with 104, 44, and 81 mgd delivered to the East/South Bay, Peninsula, and San Francisco regions, respectively.<br>• Restore facilities to meet average-day demand of 300 mgd within 30 days after a major earthquake. |
| Delivery Reliability – increase delivery reliability and improve the ability to maintain the system | • Provide operational flexibility to allow planned maintenance shutdown of individual facilities without interrupting customer service.<br>• Provide operational flexibility to minimize the risk of service interruption due to unplanned facility upsets or outages.<br>• Provide operational flexibility and system capacity to replenish local reservoirs as needed.<br>• Meet the estimated average annual demand of 300 mgd for 2030 under the conditions of one planned shutdown of a major facility for maintenance concurrent with one unplanned facility outage. |
| Water Supply – meet customer water needs in nondrought and drought periods | • Meet average annual water purchase requests of 300 mgd from retail and wholesale customers during nondrought years for system demands through 2030.<br>• Meet dry-year delivery needs through 2030 while limiting rationing to a maximum 20 percent system-wide reduction in water service during extended droughts.<br>• Diversify water supply options during nondrought and drought periods.<br>• Improve use of new water sources and drought management, including use of groundwater, recycled water, conservation, and transfers. |
| Sustainability – enhance sustainability in all system activities | • Manage natural resources and physical systems to protect watershed ecosystems.<br>• Meet, at a minimum, all current and anticipated legal requirements for protection of fish and other wildlife habitat.<br>• Manage natural resources and physical systems to protect public health and safety. |
| Cost-effectiveness – achieve a cost-effective, fully operational system | • Ensure cost-effective use of funds.<br>• Maintain gravity-driven systems.<br>• Implement regular inspection and maintenance program for all facilities. |

Unlike the water system, EBMUD wastewater does not have a defined post-earthquake Level of Service; they indicate that it would be dependent on the extent of damage. EBMUD only owns the interceptor and treatment facilities, and the collection systems are owned by the cities. Although there is a prioritized restoration plan, time ranges are not associated with it. The plan is to: (1) move raw sewage away from people; (2) move raw sewage to the wastewater treatment plant; and (3) treat sewage with disinfection, primary and secondary, and discharge it to the San Francisco Bay. There is some concern that pipe damage could allow inflow of salt water from the Bay into the interceptors, disrupting the treatment process (D. Ballantyne, personal communication).

#### D.2.2.2 Portland Bureau of Environmental Services

Portland Bureau of Environmental Services provides retail and wholesale service primarily to the residents of the City of Portland. They have two wastewater treatment plants. They were key participants in assembling the Oregon Resilience Plan (OSSPAC, 2013). They intend to develop and employ a resilience strategy with the following target:

> To be resilient enough to "restore 90% of core services within 3 months of a Cascadia Subduction Zone magnitude-9 earthquake by year 2065."

The Bureau of Environmental Services believes and has committed to an approach based on a framework that resiliency planning is best implemented with a phased approach over a number of years that should include, but not be necessarily limited to:

- Understanding the nature and degree of the likelihood and consequence of a Cascadia Subduction Zone magnitude-9 earthquake;
- Committing to determining the Level of Service with regard to the speed of recovery (e.g., "restore 90% of core services within 3 months of a Cascadia Subduction Zone magnitude-9 earthquake by year 2065");
- Using notable GIS capabilities in determining the highest consequence assets in the sewer and storm water systems;
- Determining which of the Bureau's assets are critical to providing the core functions of the Bureau following a natural hazard event;
- Using the Bureau's substantial mapping capabilities, overlaying the condition and geologic information on a map, and looking for those points that are indicating a high likelihood and consequence of asset failure; and
- Enhancing the techniques that may be employed to meet the future level of service standards set by the Bureau/City for the magnitude of the event. Examples include:
    - Adding to standard specifications more earthquake resilient design elements in those areas of the system where a more robust asset is dictated; and
    - Adding a criterion for "earthquake resiliency" to the decision-making formula deciding on the priority, schedule and scope for asset rehabilitation.

The Portland Bureau of Environmental Services use the *International Building Code* for design of their facilities.

### D.2.2.3 San Francisco Public Utilities Commission

The SFPUC adopted a series of level of service goals for its sewer system improvement program (SFPUC, August 28, 2012 Board Meeting). These are provided in Table D-9.

**Table D-9 SFPUC Sewer System Level of Service Goals**

| Sewer System Improvement Program Goals | Levels of Service |
|---|---|
| Provide a Compliant, Reliable, Resilient, and Flexible System that can Respond to Catastrophic Events | • Full compliance with State and Federal regulatory requirement's applicable to the treatment and disposal of sewage and storm water.<br>• Critical functions are built with redundant infrastructure.<br>• Primary treatment with disinfection must be on-line within 72 hours of a major earthquake. |
| Integrate Green and Grey Infrastructure to Manage Storm water and Minimize Flooding | • Control and manage flows from a storm of the three hour duration that delivers 1.3 inches of rain. |
| Provide Benefits to Impacted Communities | • Limit odors to within the treatment facility's fence line.<br>• Be a good neighbor. All projects will adhere to the Environmental Justice and Community Benefits policies. |
| Modify the System to Adapt to Climate Change | • New infrastructure must accommodate expected sea level rise within the service life of the asset. (i.e., 16 inches by 2050, 25 inches by 2070, and 55 inches by 2100).<br>• Existing infrastructure will be modified based on actual sea level rise. |
| Achieve Economic and Environmental Sustainability | • Beneficial reuse of 100% Biosolids.<br>• Use nonpotable water sources to meet 100% of Wastewater Enterprise facilities nonpotable water demands.<br>• Beneficially use 100% of biogas generated by Wastewater Enterprise treatment facilities.<br>• Stabilize lifecycle cost to achieve future economic stability. |
| Maintain Ratepayer Affordability | • Combined Sewer and Water Bill will be less than 2.5% of average household income for a single family. |

After the Commission endorses and validates the goals and levels of service, staff will proceed with the planning, design, and environmental review of Phase 1 of the Sewer System Improvement Program proposed projects.

# Appendix E
# Supplement to Interdependent Infrastructure Analysis

This appendix supplements the material presented in Chapter 8—Interdependent Infrastructure Systems, as well as in Chapter 2—Societal Considerations.

## E.1 Details of Current Research in the Interdependent Infrastructure Field

Research on interdependent infrastructure systems, including both lifeline and information/data systems, has been rapidly increasing since the field gained traction over the past decade, particularly after major disasters and manmade events. From a selection of 140 papers (listed in Section E.4), as a subset of representative interdependent critical infrastructure documents, 74% of the papers have been published in 2010 or later. This indicates there is significant academic and professional interest in interdependent systems and many institutions want to understand such systems in more detail, the benefits from their coupling, and their associated liabilities today.

The vast majority of papers analyzed (approx. 90%) study the interconnection between different kinds of systems, being mainly physical, but also economic and social. The most popular systems studied today are power grids at 60% and water systems at 35% (note that studies are not mutually exclusive). Power systems are popular because electricity is used in almost all facets of modern life. Surprisingly, supervisory control and data acquisition (SCADA), telecommunications, and cyber systems are analyzed by only about a fourth of all papers, despite the overwhelming presence of communication and digital technology in today's economy and society (this reflects an urgent need to study such systems today). Also, social, economic and institutional systems represent a fifth of these sample papers, which typically do not discuss user expectations of performance and restoration times. A full breakdown of analyzed systems can be seen in Figure E-1.

Additionally, these systems analyzed have changed over time. As seen in Figure E-2, SCADA, gas, water, and electric power systems have become more popular in the literature in recent years (a welcome trend), while economic, health, and social systems, despite their urgency and relevance, have become less common in the body of publications. The proportion of papers studying interdependent systems, telecommunication, cyber, and transportation has remained relatively constant.

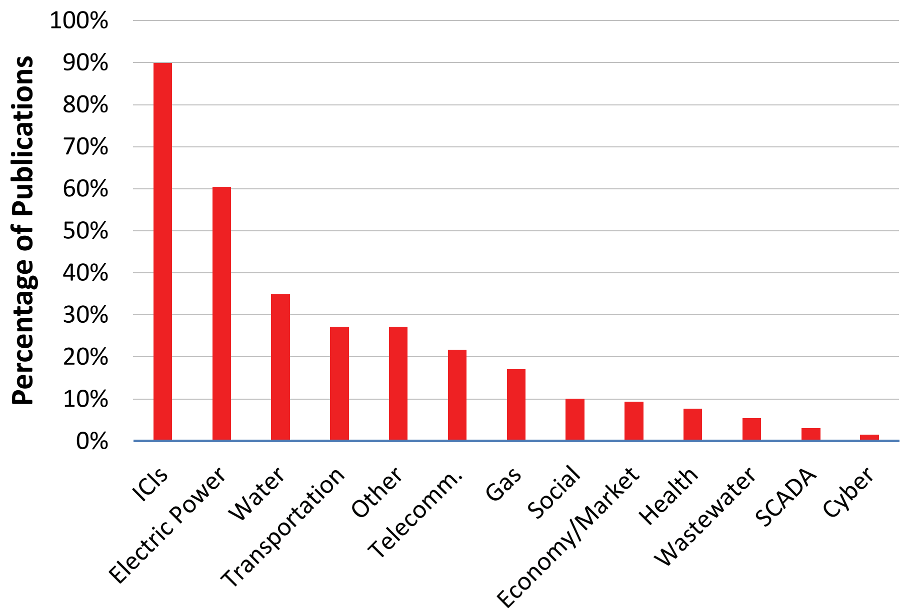



Figure E-1 Types of infrastructure systems prominent in the literature. ICIs: interdependent critical infrastructure systems.

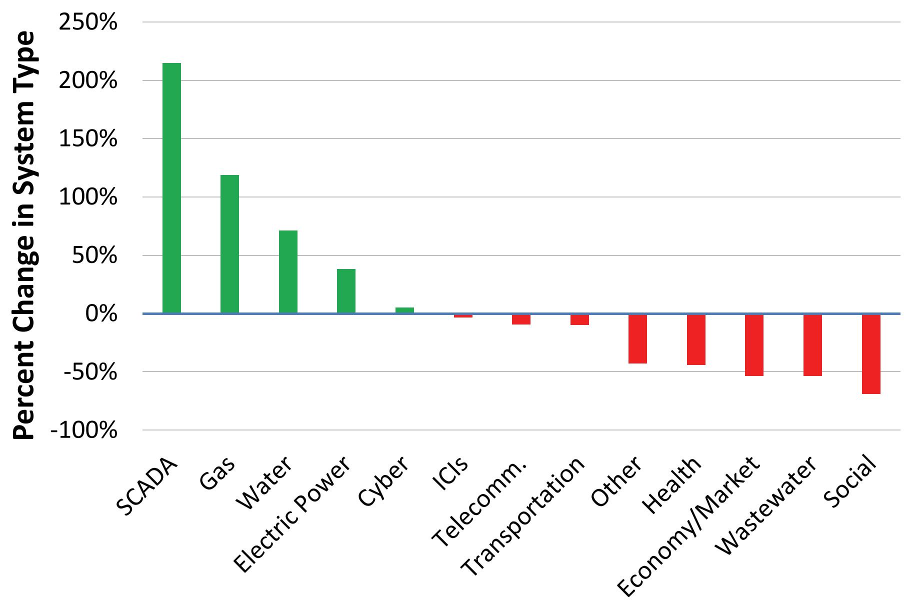



Figure E-2 Percent change in the types of infrastructure systems analyzed between documents published in 2010-2015 relative to 2005-2010. Systems in the “Other” category include ports, nuclear facilities, and emergency systems. ICIs: interdependent critical infrastructure systems.

When analyzing the literature of critical infrastructure, insightful patterns emerge, particularly the joint study of specific infrastructure systems across the literature. That is to say that, whenever a system is studied in a paper, it is likely that another specific system will be studied in the same paper. Table 8-1 in Chapter 8 summarizes the frequency of recurrent pairings of systems across studies.

However, studying not only the infrastructure type, but also the method of interdependent critical infrastructure analysis in the literature unveiled interesting patterns and trends. Of the sample papers, the majority of them modeled their infrastructure systems with a network-based model. Of the papers using network analyses, they favor using probability-based network theory. Empirical models are also popular. Network and system reliability theory are commonly together because they can be abstracted and applied to many systems at once, where the mathematics mirror the physical system topology. Also, other models such as agent-based models and physical models may require industry-specific datasets that researchers cannot access, making them less widespread, yet these approaches offer a significant opportunity for modeling the complexities of socio-technical systems, including performance goal attainment and restoration times with user's constraints. A full breakdown of models can be seen in Figure E-3.

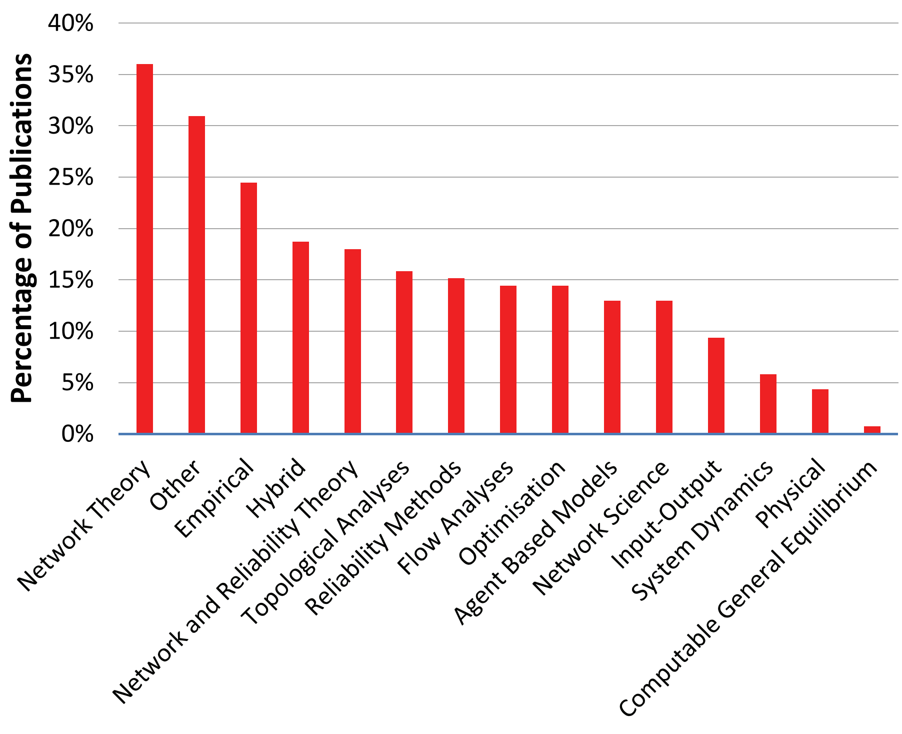



Figure E-3 Percentage of publications per model type in the interdependent infrastructure literature. The "Other" category includes a variety of methods spanning Bayesian networks, Petri-nets, federated simulation, neural networks, game theory, and fuzzy logic, among other approaches, while hybrid approaches involve several tools integrated in custom ways per application.

As with the type of infrastructure system modeled, the type of analysis used has also varied in the last five years. Agent-based models, input/output models, and reliability models have fallen out of favor in the mainstream literature, while network flows, optimization, empirical, and hybrid among other models have gained in popularity since 2010. It is likely that the drop in agent-based models, system reliability models, and input/output models is due to their inclusion in flow-based, physics-based, and a variety of hybrid models. Additionally, discussions in Chapter 8 identified a shift in the use of agent-based models and input/output models towards institutions with large computational centers and national laboratories (Pederson et al., 2006). A full breakdown of the change in model use since 2010 can be seen in Figure E-4.

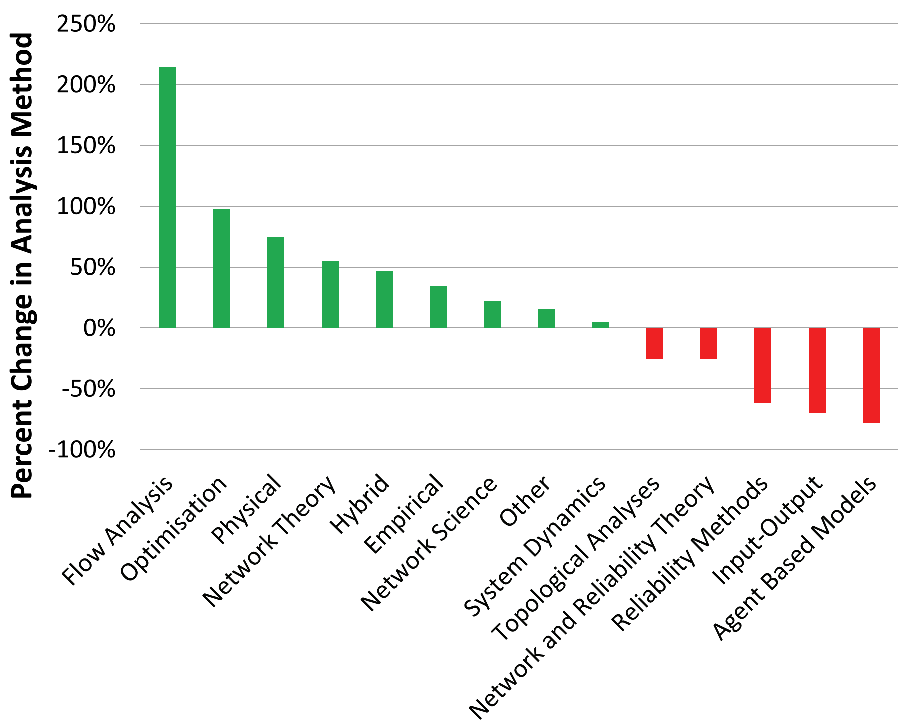



Figure E-4 Percent change in methods of analysis between papers published in 2010-2015 relative to 2005-2010.

Model use can also be tied to specific infrastructure systems. Most systems except for health and economic systems are frequently modeled using some form of network analysis and system reliability theory. Also note that no other system uses network and system theory as frequently as power infrastructure. And most systems strive to inform their modeling with empirical methods.

A full breakdown of model use by infrastructure type can be seen in Table E-1, which also suggests a variety of trends. For example, economic and social systems tend to use a different distribution of models than the more physical systems. Agent-based models mention SCADA systems 30% of the time, while agent-based models and input/output models are often used to simulate economic and social systems (at

**Table E-1 Frequency of Modeling and Analysis Methods in Publications Mentioning Certain Infrastructure Systems**

| | Power | SCADA | Water | Wastewater | Telecomm | Gas | Transport | Health | Cyber | Other | Economy | Social |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ABM | 7% | 30% | 0% | 0% | 6% | 3% | 7% | 23% | 20% | 16% | 24% | 24% |
| Input-Output | 7% | 0% | 8% | 14% | 11% | 14% | 14% | 15% | 0% | 19% | 38% | 24% |
| CGE | 1% | 0% | 0% | 0% | 3% | 3% | 2% | 0% | 0% | 0% | 5% | 0% |
| Empirical | 26% | 10% | 38% | 57% | 36% | 31% | 30% | 31% | 20% | 24% | 14% | 18% |
| System Dynamics | 4% | 20% | 2% | 0% | 3% | 3% | 5% | 15% | 40% | 5% | 10% | 12% |
| Network Theory | 10% | 20% | 8% | 0% | 6% | 3% | 9% | 0% | 20% | 8% | 0% | 12% |
| Probability | 24% | 0% | 25% | 29% | 11% | 21% | 0% | 0% | 20% | 0% | 0% | 0% |
| Topological | 18% | 10% | 15% | 0% | 11% | 7% | 12% | 0% | 20% | 5% | 0% | 6% |
| Flows | 18% | 0% | 17% | 29% | 19% | 14% | 7% | 8% | 20% | 8% | 5% | 6% |
| Physical | 5% | 20% | 2% | 0% | 6% | 3% | 2% | 8% | 20% | 3% | 0% | 0% |
| Reliability | 15% | 20% | 17% | 14% | 8% | 17% | 7% | 15% | 20% | 3% | 5% | 6% |
| Optimization | 17% | 0% | 15% | 29% | 17% | 17% | 9% | 0% | 0% | 8% | 14% | 6% |
| Other | 26% | 50% | 25% | 0% | 31% | 28% | 19% | 0% | 40% | 35% | 14% | 35% |
| Hybrid | 17% | 30% | 19% | 0% | 19% | 21% | 5% | 8% | 20% | 16% | 10% | 29% |

Note: Modeling and analysis methods are noted in the left column; infrastructure systems, including both physical lifelines and information/data systems, are listed in the top row; green shading denotes highest mention frequency and red shading denotes lowest frequency.

ABM: agent-based model

CGE: computable general equilibrium

SCADA: supervisory control and data acquisition

least 24% of the time), but these models are less frequently used to model other systems. Economic systems use several of the models in the "Other" category including game theory. Social systems differ in that they can be modeled with network theory and hybrid models. This indicates that if one wishes to model social systems with other systems, then using network models and hybrid models would be the best model choice, especially if agent-based models are too expensive or data intensive.

The set of papers of this study were also classified by what type of hazards they considered. The vast majority of papers developed flexible models where several kinds of hazards can be input. This indicates an academic and professional interest to develop general purpose models. Twenty-eight percent of the papers considered the effects of random failures on interdependent critical infrastructure systems, indicating an interest to model the behavior of such systems in normal operating conditions as well. The most popular hazards to model are earthquakes.

The abundance of flexible models shows that similar mathematical principles are used to represent post-hazard hazard impacts and to predict their effects. While these flexible models are useful, caution must be exercised when applying them to a specific hazard. A full breakdown of the modeled hazards can be seen in Figure E-5. The takeaway from this graph is that storm models and cyber-attack models are not common, which is a missed opportunity. This is because the frequency of storms is

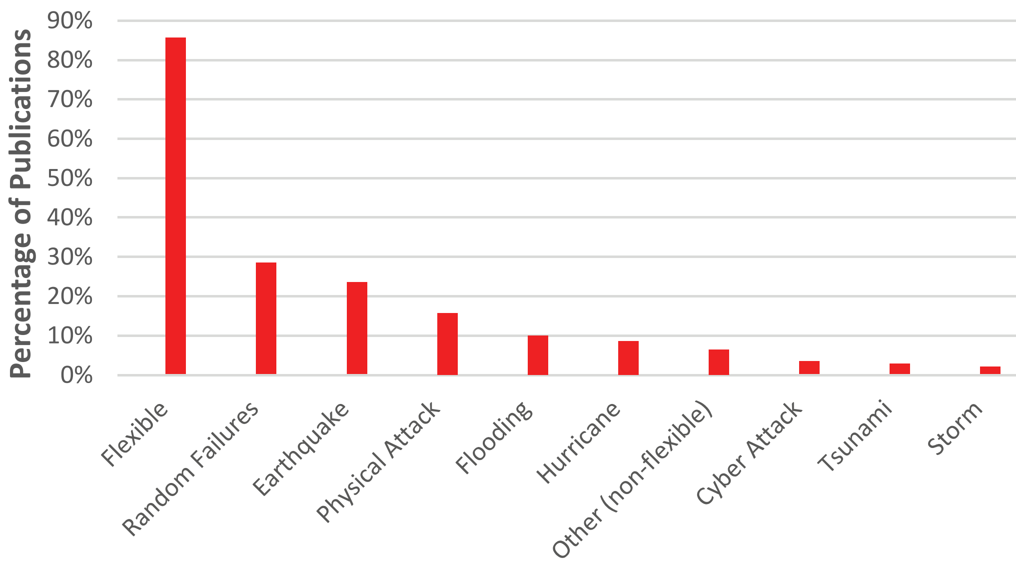



Figure E-5 Percentage of publications per type of hazard modeled. Flexible indicates models that include a variety of hazard events.

high, so that models based on them can be validated and calibrated more easily. Cyber-attacks are a rapidly emerging issue, unlikely to be incorporated into the hazard based flexible models, and yet needed as smart technologies permeate the totality of interdependent critical infrastructure systems in the years to come.

These papers were further categorized by types of analyses covered within a publication. The majority of papers analyzed the risks of interdependent critical infrastructure systems in the face of different hazards. However, only 7% of the papers offered a visualization of their results. Without this visualization it is difficult to communicate effectively or for industry experts to evaluate the accuracy of these models, while making it difficult for individuals and governments to internalize model-based outputs. Also, only 21% of the papers considered interdependent critical infrastructure resilience or recovery processes. This indicates more research is needed to determine how systems respond after parts of them fail, and more importantly, how decision making processes evolve at the intersection of social and physical systems. A full breakdown of the types of analyses covered in the literature can be seen in Figure E-6.

Figure E-7 shows the sources of these papers. Note that 94% of the analyzed papers come from academic sources. The other papers come from industry or governmental sources. This skew may be in part a result of using peer-reviewed databases, which leaves out industry and governmental advances that may be published as reports or in news outlets. However, industry and government collaborations with academia should increase to adopt and test these models, so as to bring together access to real data and advanced mathematical and computational models.

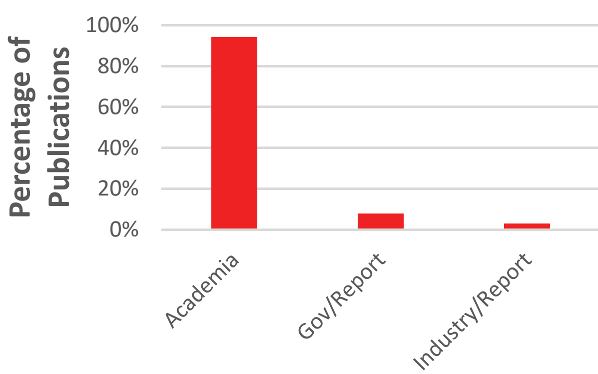



Figure E-7 Percentage of publications per source.

Papers in the interdependent infrastructure literature calibrated and validated their models using various data sources. Over 70% of papers used data from case studies, likely because the data were relatively abundant and publically available. The United States is the most popular data source, probably because of its geographical size and documented material after disasters. Many papers also used artificial case studies. These papers analyzed particular idealized locations, such as rural towns, to generate case examples with properties that mimic the characteristics of such locations.

### E.2 Source Data from Utilities and Cities that Can Serve as "Proxies" for Societal Expectations of Infrastructure Performance and Restoration Times

This section provides source data from utilities and municipalities that can serve as "proxies" for societal expectations of infrastructure performance and restoration times. Table E-2 lists publicly disclosed recovery expectations from utility companies, and Table E-3 lists publicly disclosed recovery expectations from public entities.

**Table E-2 Publicly Disclosed Recovery Expectations from Utility Companies**

| | Utility | | |
|---|---|---|---|
| City | *Name* | *Estimation* | *URL (Uniform Resource Locator)* |
| Houston, Texas | Centerpoint Energy | 7-10 days to 6-8 weeks (Hurricane Categories 1 to 5) | http://www.ci.clute.tx.us/doc_center/E-Forms-Documents/CenterPoint%20-%20Hurricane%20Utility%20Info.pdf |
| Orlando, Florida | SECO | 7 days | https://issuu.com/secoenergy/docs/seco_storm_guide_02c9473a4136b6 |
| New York, New York | NYSEG | None Provided | http://www.nyseg.com/MediaLibrary/2/5/Content%20Management/Shared/UsageAndSafety/PDFs%20and%20Docs/Combo%20Weathering%20Storm%20Emerg%20Broc.pdf |
| Pittsburgh, Pennsylvania | Penn Power | None Provided | https://www.firstenergycorp.com/content/dam/customer/get-help/files/Tips%20for%20Power%20Outages.pdf |
| Los Angeles, California | LA Depart. of Water and Power | 3 days | https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-inourcommunity/a-ioc-yoursafety/a-ioc-ys-earthquakepreparedness?_adf.ctrl-state=eg49cz8xw_104&_afrLoop=1101342393827134 |
| San Francisco, California | PG&E | 7 days | http://www.pge.com/en/safety/preparedness/kit/index.page |
| Washington, D.C. | Pepco | None Provided | http://www.pepco.com/uploadedFiles/wwwpepcocom/PepcoStormPreparationHandbook.pdf |
| New Orleans, Louisiana | Entergy | 3 days | http://www.entergy-neworleans.com/your_home/safety/preparing_outages.aspx |
| Portland, Oregon | Portland General Electric | 3-10 days | https://www.portlandgeneral.com/outages/backup-generators |
| Seattle, Washington | Seattle City Light | None Provided | http://www.seattle.gov/light/sysstat/powerOutage.asp |
| Miami, Florida | Florida Power and Light | 14 days | https://www.fpl.com/storm/pdf/storm-guide.pdf |
| Jacksonville, Florida | Jacksonville Electric Authority | Links to many resources | https://www.jea.com/Outage_Center/Storm_Safety/Before_the_Storm/ |
| Baton Rouge, Louisiana | Entergy | 3 days | http://www.entergy-neworleans.com/your_home/safety/preparing_outages.aspx |
| Charleston, South Carolina | SCE&G | None Provided | https://www.sceg.com/docs/librariesprovider5/default-document-library/emergency_kit.pdf |

**Table E-2 Publicly Disclosed Recovery Expectations from Utility Companies (continued)**

| | Utility | | |
|---|---|---|---|
| City | *Name* | *Estimation* | *URL (Uniform Resource Locator)* |
| Boston, Massachusetts | EverSource | None Provided | https://www.eversource.com/Content/ct-e/residential/outages/storm-preparedness/before-a-storm |
| Oklahoma City, Oklahoma | OG&E | None Provided | https://oge.com/wps/portal/oge/outages/storm-prep/!ut/p/a1/pZLNDoIwDICfhivrNjTE2wRDkMR_FHcxaHCSADOA8voO4oUoYGJvbb4vbdoijgLEs_AZi7CMZRYmdc7HJ5OABa5B5ktqG8AsvF3u6YwAwQo4KgA6gkHbdzwyA-bZ9nq0srFLx2-_C1gYv_Xv8qd_-mrAto99rHzYLYBssGN9-J9An-_BgO_B0PwHxBuk7wK9N6hX3AuoHc4RF4k8N_9wZNmZmgLxPLpGeZTrj1yVb2V5LyYaaFBVlS6kFEmkX2SqwTflJosSBW0S3VO_jgDiVXowC_YC_DLlVQ!!/dl5/d5/L2dJQSEvUUt3QS80SmlFL1o2XzgyMEMwSTQySk8xVTEwQUMwVE4wMllxR0Mx/ |
| Kansas City, Missouri | Kansas City Power and Light | None Provided | http://www.kcpl.com/outages-and-weather/weather-center/how-you-can-prepare |
| Minneapolis, Minnesota | Xcel energy | Several days | http://www.xcelenergy.com/Outages_and_Emergencies/Outages_FAQ |
| Denver, Colorado | Xcel energy | Several days | http://www.xcelenergy.com/Outages_and_Emergencies/Outages_FAQ |
| Montreal, Quebec | Hydro-Quebec | None Provided | http://poweroutages.hydroquebec.com/poweroutages/be-prepared-for-power-outage/before-an-outage/ |
| Toronto, Ontario | Toronto Hydro | 3 days | http://www.torontohydro.com/sites/electricsystem/PowerOutages/Pages/beprepared.aspx |
| Vancouver, British Columbia | BC Hydro | 3 days | https://www.bchydro.com/safety-outages/power-outages/prepare-for-outages/prepare-your-home.html |

**Table E-3 Publicly Disclosed Recovery Expectations from Public Entities**

| | Public Entity | | |
|---|---|---|---|
| City | *Name* | *Estimate* | *URL (Uniform Resource Locator)* |
| Houston, Texas | City of Houston's Office of Emergency Management and Harris County Office of Emergency Management | 7 days | http://www.houstonoem.org/external/content/document/4027/2168878/1/COH-DPG2015-ENG-WEB.pdf |
| Orlando, Florida | Orange County Office of Emergency Management | 3-7 days | http://flgetaplan.com/Reports/ReportOutputFiles/ |
| New York, New York | New York City Office of Emergency Management | 3 days | http://www.nyc.gov/html/oem/html/get_prepared/supplies.shtml |
| Pittsburgh, Pennsylvania | Pittsburgh Office of Emergency Management and Homeland Security | 3 days | http://apps.pittsburghpa.gov//72_Hour_Kits.pdf |
| Los Angeles, California | LA Office of Emergency Management | 3-10 days | http://www.lacoa.org/PDF/EmergencySurvivalGuide-LowRes.pdf |
| San Francisco, California | San Francisco Department of Emergency Management | 3 days | http://www.sf72.org/home |
| Washington, D.C. | Homeland Security and Emergency Management Agency | 3 days | http://hsema.dc.gov/page/72-hours |

**Table E-3 Publicly Disclosed Recovery Expectations from Public Entities (continued)**

| | Public Entity | | |
|---|---|---|---|
| City | *Name* | *Estimate* | *URL (Uniform Resource Locator)* |
| New Orleans, Louisiana | New Orleans Office of Homeland Security and Emergency Preparedness | 3 days | http://www.nola.gov/ready/hurricane/supplies/ |
| Portland, Oregon | Portland Bureau of Emergency Management | 3 days | http://www.portlandoregon.gov/pbem/article/409950 |
| Seattle, Washington | Seattle Office of Emergency Management | 7-10 days | http://www.seattle.gov/emergency-management/what-can-i-do/prepare-yourself |
| Miami, Florida | Miami-Dade County Emergency Management | 3-14 days | http://www.miamidade.gov/fire/emergency-supply-kit.asp |
| Jacksonville, Florida | Duval County Emergency Management | 7 days | http://www.coj.net/departments/fire-and-rescue/docs/emergency-preparedness/2015-16-emergency-preparedness-guide.aspx |
| Baton Rouge, Louisiana | Baton Rouge Office of Emergency Preparedness | 3 days | http://brgov.com/dept/oep/pdf/FamilyDisasterPlan.pdf |
| Charleston, South Carolina | Charleston County Emergency Management Department | 3 days | http://www.charlestoncounty.org/departments/emergency-management/emergency-kit.php |
| Boston, Massachusetts | Mayor's Office of Emergency Management | 3 days | http://maps.cityofboston.gov/preparedness_planner/Default.aspx |
| Oklahoma City, Oklahoma | Oklahoma Department of Emergency Management | 3-5 days | http://www.ok.gov/OEM/Programs_&_Services/Preparedness/Preparedness_-_Create_an_Emergency_Plan.html |
| Kansas City, Missouri | Greater Kansas City region's Metropolitan Emergency Managers Committee | 3 days | http://www.preparemetrokc.org/Be_Prepared/supplykit.asp |
| Minneapolis, Minnesota | Minneapolis Office of Emergency Management | 3 days | http://www.ci.minneapolis.mn.us/www/groups/public/@regservices/documents/webcontent/convert_282425.pdf |
| Denver, Colorado | Denver Office of Emergency Management | 3 days | https://www.denvergov.org/oem/OfficeofEmergencyManagement/EmergencyPreparedness/tabid/391460/Default.aspx |
| Montreal, Quebec | Montreal Emergency Preparedness Centre | 3 days | http://ville.montreal.qc.ca/portal/page?_pageid=7637,82421604&_dad=portal&_schema=PORTAL |
| Toronto, Ontario | Toronto Office of Emergency Management | 3 days | http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=e0d36cbd2b95a410VgnVCM10000071d60f89RCRD |
| Vancouver, British Columbia | North Shore Emergency Management Office | 3-7 days | http://nsemo.org/preparedness/emergency-kits-supplies |

## E.3 Sample Base for Interdependent Infrastructure and Restoration Times Array

| | | Energy | | | | Water | | | Telecom. | | | | Transport. | | | | | Financial | | | Security | | | Waste Disp. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Electricity | Coal | Gasoline/Petroleum | Natural Gas | Potable Water | Irrigation Water | Storm Water | Postal Service | Satellite Comm. | Cable/Fiber Optic | Radio Communication | Roadways | Railways | Airports | Water Ports | Spaceports | Banks/Capital | Investment Funds | Insurance | Shelter | Comm. Security/Cyber | Health | Wastewater/liquid | Solid disposal/landfills |
| Waste Disp. | Solid disposal/landfills | | | | | | | | | | | | | | | | | | | | | | | | |
| | Wastewater/liquid | | | | | | | | | | | | | | | | | | | | | | | | |
| Security | Health | | | | | | | | | | | | | | | | | | | | | | | | |
| | Communication | | | | | | | | | | | | | | | | | | | | | | | | |
| | Shelter | | | | | | | | | | | | | | | | | | | | | | | | |
| Finan. | Insurance | | | | | | | | | | | | | | | | | | | | | | | | |
| | Investment Funds | | | | | | | | | | | | | | | | | | | | | | | | |
| | Banks/Capital | | | | | | | | | | | | | | | | | | | | | | | | |
| Transport. | Spaceports | | | | | | | | | | | | | | | | | | | | | | | | |
| | Water Ports | | | | | | | | | | | | | | | | | | | | | | | | |
| | Airports | | | | | | | | | | | | | | | | | | | | | | | | |
| | Railways | | | | | | | | | | | | | | | | | | | | | | | | |
| | Roadways | | | | | | | | | | | | | | | | | | | | | | | | |
| Telecom. | Radio Communication | | | | | | | | | | | | | | | | | | | | | | | | |
| | Cable/Fiber Optic | | | | | | | | | | | | | | | | | | | | | | | | |
| | Satellite | | | | | | | | | | | | | | | | | | | | | | | | |
| | Postal Service | | | | | | | | | | | | | | | | | | | | | | | | |
| Water | Storm Water | | | | | | | | | | | | | | | | | | | | | | | | |
| | Irrigation Water | | | | | | | | | | | | | | | | | | | | | | | | |
| | Potable Water | | | | | | | | | | | | | | | | | | | | | | | | |
| Energy | Natural Gas | | | | | | | | | | | | | | | | | | | | | | | | |
| | Gasoline/Petroleum | | | | | | | | | | | | | | | | | | | | | | | | |
| | Coal | | | | | | | | | | | | | | | | | | | | | | | | |
| | Electricity | | | | | | | | | | | | | | | | | | | | | | | | |
| Commercial | Restaurants | | | | | | | | | | | | | | | | | | | | | | | | |
| | Entertainment | | | | | | | | | | | | | | | | | | | | | | | | |
| | Shopping Centers | | | | | | | | | | | | | | | | | | | | | | | | |
| | Consulting | | | | | | | | | | | | | | | | | | | | | | | | |
| | Software | | | | | | | | | | | | | | | | | | | | | | | | |
| Manufacturing | Specialty Chemicals | | | | | | | | | | | | | | | | | | | | | | | | |
| | Polymer Chemicals | | | | | | | | | | | | | | | | | | | | | | | | |
| | Maintenance/repair | | | | | | | | | | | | | | | | | | | | | | | | |
| | Electronics | | | | | | | | | | | | | | | | | | | | | | | | |
| | Machinists | | | | | | | | | | | | | | | | | | | | | | | | |
| | Carpenters | | | | | | | | | | | | | | | | | | | | | | | | |
| | Construction | | | | | | | | | | | | | | | | | | | | | | | | |
| | Textiles/clothing | | | | | | | | | | | | | | | | | | | | | | | | |
| Raw Materials | Mining | | | | | | | | | | | | | | | | | | | | | | | | |
| | Lumber/Paper Mill | | | | | | | | | | | | | | | | | | | | | | | | |
| | Ceramics/Glass | | | | | | | | | | | | | | | | | | | | | | | | |
| | Masonry | | | | | | | | | | | | | | | | | | | | | | | | |
| | Plastics/rubber | | | | | | | | | | | | | | | | | | | | | | | | |
| | Steel/Metals | | | | | | | | | | | | | | | | | | | | | | | | |
| | Cement | | | | | | | | | | | | | | | | | | | | | | | | |
| Agriculture | Fishing | | | | | | | | | | | | | | | | | | | | | | | | |
| | Forestry | | | | | | | | | | | | | | | | | | | | | | | | |
| | Livestock | | | | | | | | | | | | | | | | | | | | | | | | |
| | Fabrics | | | | | | | | | | | | | | | | | | | | | | | | |
| | Other Foods | | | | | | | | | | | | | | | | | | | | | | | | |
| | Staple Foods | | | | | | | | | | | | | | | | | | | | | | | | |
| Health | Health | | | | | | | | | | | | | | | | | | | | | | | | |
| | Manufacturing/Pharm. | | | | | | | | | | | | | | | | | | | | | | | | |
| Indiv. | Religious Organizations | | | | | | | | | | | | | | | | | | | | | | | | |
| | New Outlets | | | | | | | | | | | | | | | | | | | | | | | | |
| | Homeowners | | | | | | | | | | | | | | | | | | | | | | | | |
| Government | Higher Education | | | | | | | | | | | | | | | | | | | | | | | | |
| | K-12 Educations | | | | | | | | | | | | | | | | | | | | | | | | |
| | Fire Departments | | | | | | | | | | | | | | | | | | | | | | | | |
| | Police Departments | | | | | | | | | | | | | | | | | | | | | | | | |
| | Legal | | | | | | | | | | | | | | | | | | | | | | | | |

Figure E-8 Array example to accelerate the study of interdependent critical infrastructure systems and processes. Select services/processes shown in rows and enabler/utilities in columns.

## E.4 Literature Reviewed in the Study of Interdependent Infrastructure Trends and Models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# List of Acronyms

| | |
|---|---|
| AAA | Authentication, authorization, and accounting |
| AASHTO | American Association of State Highway and Transportation Officials |
| ABM | Agent-based model |
| AC | Advisory circular |
| ACI | American Concrete Institute |
| AISC | American Institute of Steel Construction |
| ANSI | American National Standards Institute |
| API | American Petroleum Institute |
| AREMA | American Railway Engineering and Maintenance of Way Association |
| ARRA | American Recovery and Reinvestment Act |
| ASCE | American Society of Civil Engineers |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATC | Applied Technology Council |
| ATM | Automated teller machine |
| AWWA | American Water Works Association |
| BPU | Board of Public Utilities |
| BRT | Bus rapid transit |
| CAIDI | Customer average interruption duration index |
| CAIFI | Customer average interruption frequency index |
| Caltrans | California Department of Transportation |
| CCWD | Contra Costa Water District |
| CBC | *California Building Code* |
| CDC | Center for Disease Control and Prevention |
| CDE | Contingency design earthquake |

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|---|---|
| CEATI | Centre for Energy Advancement through Technological Innovation |
| CFR | Code of Federal Regulations |
| CGE | Computable general equilibrium |
| CGS | California Geological Survey |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COWs | Cells on wheels |
| CPUC | California Public Utilities Commission |
| CRISP | Critical Resilient Interdependent Infrastructure Systems and Processes |
| CSRIC | Communications Security, Reliability, and Interoperability Council |
| DHHS | U.S. Department of Health and Human Services |
| DHS | U.S. Department of Homeland Security |
| DIRS | Disaster Information Reporting System |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| DSL | Digital Subscriber Line |
| EAP | Energy assurance plan |
| EAS | Emergency Alert System |
| EBMUD | East Bay Municipal Utility District |
| EDC | Electric distribution companies |
| EEI | Edison Electric Institute |
| EMS | Emergency monitoring system |
| ENEA | Italian National Agency for New Technologies, Energy, and Sustainable Economic Development |
| EPA | U.S. Environmental Protection Agency |
| ERDIP | Earthquake Resistant Ductile Iron Pipe |
| FAA | Federal Aviation Administration |
| FCC | Federal Communications Commission |
| FEMA | Federal Emergency Management Agency |

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|---|---|
| FFE | Fire following earthquake |
| FHWA | Federal Highway Administration |
| GDP | Gross domestic product |
| GETS | Government Emergency Telecommunications Service |
| GIS | Geographic information system |
| GTI | Gas Technology Institute |
| HBMWD | Humboldt Bay Municipal Water District |
| HCA | High consequence areas |
| HFC | Hybrid fiber-coax |
| HVAC | Heating, ventilation, and air conditioning |
| HVL | Highly volatile liquid |
| IBC | *International Building Code* |
| ICS | Incident Command System |
| IEEE | Institute of Electrical and Electronics Engineers |
| IO | Input-output models |
| IOU | Investor-owned utility |
| IP | Internet protocols |
| IPS | Inundation protection system |
| IRD | Infrastructure Resilience Division |
| ISO | International Organization of Standards |
| ISP | Information Service Providers |
| IT | Information technology |
| KJC | Kennedy/Jenks Consultants |
| LAX | Los Angeles International Airport |
| LMR | Land mobile radio |
| LRFD | Load and Resistance Factor Design |
| LTPO | Long-term power outage |
| MAOP | Maximum allowable operating pressure |
| MCEER | Multidisciplinary Center for Earthquake Engineering |
| MILP | Mixed integer linear programming |

| | |
|---|---|
| MOP | Manual of Practice |
| MOTEMS | Marine Oil Terminal Engineering and Maintenance Standards |
| MRE | Manual for Railway Engineering |
| MSC | Mobile switching centers |
| MSS | Manufacturers Standardization Society for Valve and Fitting Industry |
| MTTR | Mean time to repair |
| NACE | National Association of Corrosion Engineers International |
| NASEO | National Association of State Energy Officials |
| NCA | National Climate Assessment |
| NCS | National Communications System |
| NEBS | Network Equipment Building Systems |
| NERC | North American Electric Reliability Council |
| NESC | National Electric Safety Code |
| NFPA | National Fire Protection Association |
| NFV | Network function virtualization |
| NHC | National Hurricane Center |
| NISAC | National Infrastructure Simulation and Analysis Center |
| NIST | National Institute of Standards and Technology |
| NMC | Northridge Medical Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NPMS | National Pipeline Mapping System |
| NS/EP | National security and emergency preparedness |
| NTSB | National Transportation Safety Board |
| OPS | Office of Pipeline Safety |
| PATH | Port Authority and Trans-Hudson |
| PCBs | Polychlorinated biphenyls |
| PDE | Probable design earthquake |
| PE | Polyethylene |
| PG&E | Pacific Gas and Electric Company |

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|---|---|
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PIANC | World Association for Waterborne Transport Infrastructure |
| PIPA | Pipelines and Informed Planning Alliance |
| PPI | Plastics Pipe Institute |
| PRCI | Pipeline Research Council International |
| PSAP | Public safety answering points |
| PURA | Public Utilities Regulatory Authority |
| PVC | Polyvinylchloride |
| QoE | Quality of experience |
| RUS | Rural Utilities Service |
| SAIDI | System average interruption duration index |
| SAIFI | System average interruption frequency index |
| SCADA | Supervisory control and data acquisition systems |
| SDN | Software-defined networks |
| SEI | Structural Engineering Institute |
| SFPUC | San Francisco Public Utilities Commission |
| SGIP | Smart Grid Interoperability Panel |
| SLA | Service level agreement |
| SMS | Short Message Service |
| TAPS | Trans-Alaska Pipeline System |
| TCLEE | Technical Council on Lifeline Earthquake Engineering |
| TDM | Time-division multiplexing |
| TEU | Twenty-foot-long equivalent unit |
| TSP | Telecommunications Service Priority |
| TTX | Long-term power outage tabletop exercise |
| UAV | Unmanned Autonomous Vehicles |
| UBC | *Uniform Building Code* |
| UPS | United Parcel Service |
| USDA | U.S. Department of Agriculture |
| VoIP | Voice over Internet Protocol |

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|---|---|
| WEA | Wireless Emergency Alert |
| WEF | Water Environment Federation |
| WHO | World Health Organization |
| WPS | Wireless Priority Service |
| WRF | Water Research Foundation |
| WSIP | Water System Improvement Program |
| WTC | World Trade Center |

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