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Systems Measures of Water Distribution System Resilience

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List of Acronyms and Abbreviations

ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
CBRN	chemical, biological, radiological and nuclear
CBWR	Community Based Water Resiliency
CIPAC	Critical Infrastructure Partnership Advisory Council
CREAT	Climate Resilience Evaluation and Awareness Tool
DMA	district metered areas
EPA	U.S. Environmental Protection Agency
EPANET	Hydraulic and water quality modeling software for pipe networks
GHG	greenhouse gas
gpm	gallons per minute
HRD	Hydraulic Reliability Diagram
IFRC	International Federation of Red Cross
NAS	National Academies of Science
NEDRA	Network Design and Reliability Assessment
NIAC	National Infrastructure Advisory Council
NPR	node pair reliability
psi	pounds per square inch
PSPF	Percentage of Demand Supplied at adequate Pressure
RAMCAP	Risk Analysis and Management for Critical Asset Protection
SCADA	supervisory control and data acquisition
WDS	water distribution systems
WPR	Water Provision Resilience
WST	Water Security Toolkit

1 Introduction

> "Water security is defined as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."
>
> –United Nations-Water Task Force on Water Security, 2013

Drinking water security is the ability to access an adequate amount of good quality water to support human health, the economy, and the environment. It also means protecting drinking water from a wide variety of hazards including natural disasters, climate change, and terrorist attacks. Building resilience to these hazards is key to improving water security.

U. S. Presidential Policy Directive (PPD) 21 – *Critical Infrastructure Security and Resilience* – establishes national policy to build resilience to hazards. PPD 21 directs federal agencies to work with critical infrastructure owners and operators and state, local, tribal, and territorial entities to "take proactive steps to manage risk and strengthen the security and resilience of the Nation's critical infrastructure, … These efforts shall seek to reduce vulnerabilities, minimize consequences, identify and disrupt threats, and hasten response and recovery efforts related to critical infrastructure." Water and wastewater systems are identified as one of sixteen critical U. S. infrastructure; resilience of the water sector is tightly linked to the resilience of other critical infrastructure such as energy, food and agriculture, healthcare and public health.

Disaster resilience is defined by the National Academies of Science as the ability of a human system (e.g., an individual, community, or the nation) to prepare and plan for, absorb, recover from, and successfully adapt to adverse events (NAS, 2012). The Community and Regional Resilience Institute (CARRI) defined community resilience as "the ability to anticipate risk, limit impacts, and bounce back rapidly in the face of turbulent change" (CARRI, 2014). The National Infrastructure Advisory Council (NIAC) defined infrastructure resilience as "the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event" (NIAC, 2009). Here, infrastructure refers to the facilities and equipment comprising the physical infrastructure, the services provided to a community by the infrastructure, the people using the services, and the organizations that manage the infrastructure. By these definitions, resilience of human systems to natural disasters and other hazards implies a continuous cycle of planning and preparedness activities, response and recovery actions following an adverse event, and adapting and changing to be better prepared for future events based on lessons learned (see Figure 1).

Figure 1 Continuous cycle of building resilience to hazards.

These definitions of resilience also highlight the importance of defining who or what is resilient, and to what they are resilient. In this report, the focus is on the resilience of drinking water systems to natural disasters, terrorist attacks, and other hazards. Resilience of drinking water systems refers to the ability of the human organizations that manage water to design, maintain, and operate water infrastructure (e.g., water sources, treatment plants, storage tanks, and distribution systems) in such a way that limits the effects of disasters on the water infrastructure and the community it serves, and enables rapid return to normal delivery of safe water to customers. Many organizations have written about the resilience of drinking water systems to natural disasters, terrorist attacks, and other emergencies over the last several years (ASCE, 2008; CIPAC Workgroup, 2009; ANSI, 2010; USEPA, 2011 and 2012a) providing useful information on preparedness, response and recovery, case studies and lessons learned, and water sector specific tools.

One of the challenges to using the concept of resilience is determining how to quantify or measure resilience. With limited resources, water utilities must make decisions about which preparedness and adaptation activities will most improve their resilience. Measures of resilience would help in prioritizing such decision making.

This report reviews quantitative performance measures for water distribution systems with a focus on systems measures that can be used to quantify resilience to natural disasters, terrorist attacks, and other hazards. In the next section, literature and tools to support the resilience of drinking water systems are reviewed. Then, resilience characteristics, attributes, and systems analysis approaches are reviewed for their relevance to quantifying the resilience of drinking water systems to hazards. Existing water system performance measures are presented and reviewed. Finally, the advantages of using these measures to quantify resilience to hazards is considered and necessary improvements to systems analysis tools are outlined. This report provides an overview of potential resilience measures, however, additional research is needed to formulate meaningful quantitative systems measures for resilience and incorporate them into tools for water distribution systems.

2 Resilience of Drinking Water Systems

Drinking water systems have been significantly impacted by natural disasters and hazardous releases. Hurricane Katrina, Superstorm Sandy, the West Virginia's 2014 Elk River chemical spill, and the 2014 Lake Erie algal bloom have all significantly impacted drinking water systems and received national attention (Reed et al., 2013; Scharfenaker, 2006; Sewerage and Water Board of New Orleans, 2013; WARN, 2013; DiGiano and Grayman, 2014; Osnos, 2014). This section reviews the many potential hazards facing drinking water systems, guidance on preparedness, and existing drinking water resilience tools.

2.1 Drinking Water Hazards

Across the United States, water systems face multiple challenges on a daily basis. Water systems plan and prepare for natural disasters, hazardous material releases, cyber-attacks, and terrorist attacks. Utilities strive to maintain and retrofit aging infrastructure in an effort to minimize water quality problems, leaks, and pipe breaks. In addition, utilities plan for uncertainty in water supply and demand due to climate change and shifting population centers.

Figure 2 lists a variety of potential hazards to water distribution systems and the resulting impacts to the water system (adapted from CIPAC Workgroup, 2009). Each of the hazards in the first box could result in multiple impacts listed in the second box. For example, a 2011 drought in Texas caused pipes to break because of shifting soils and caused some water sources to dry up (Llanos, 2011), resulting in both pipe breaks and service disruptions. The 2011 Tropical Storm Irene caused power outages, damaged roads and bridges which caused pipe breaks and limited transportation of water treatment chemicals, and released hazardous waste that impacted the quality of water sources (Vermont Department of Natural Resources, 2011). The 2007 Angora Fire near Lake Tahoe damaged tanks, booster stations, hydrants, and valves, and resulted in a power outage (ASCE, 2008). Similarly, the 2014 Elk River chemical spill affected the water quality of the water supply of Charleston, West Virginia, caused a disruption in water service for several days, and affected public confidence in the water system (Osnos, 2014).

Potential Hazards	Potential Impacts
Natural Disasters • Drought • Earthquakes • Floods • Hurricanes • Tornados • Tsunamis • Wildfires • Winter Storms Terrorist Attacks Cyber Attacks Hazardous Materials Release Climate Change	Pipe Break Other Infrastructure Damage/Failure Power Outage Service Disruption (source water, treatment, distribution, or storage) Loss of Access to Facilities/Supplies Loss of Pressure/Leaks Change in Water Quality Environmental impacts Financial impacts (e.g., loss of revenue, repair costs) Social Impacts (e.g., loss of public confidence, reduced workforce)

Figure 2 Potential hazards and impacts to drinking water systems.

2.2 Enhancing Preparedness for Hazards

One component of resilience is preparedness (Figure 1), which involves anticipating risks and planning mitigation strategies. Several recent reports have provided guidance for water utilities on enhancing preparedness to the hazards listed in Figure 2. The Water Sector Critical Infrastructure Partnership Advisory Council's (CIPAC) report on All Hazard Consequence Management Planning for the Water Sector helps to build resilience of water utilities by identifying specific actions that will mitigate the consequences of hazardous events (CIPAC Workgroup, 2009). In the CIPAC report, resilience is defined as "the ability of a utility's business operations to rapidly adapt and respond to internal or external changes (such as emergencies) and continue operations with limited impacts to the community and customers." The report focuses on the potential consequences of hazardous events, which are separated into the following categories: loss of power, loss of communication, loss of supervisory control and data acquisition (SCADA), service disruption, reduced workforce, contamination incidents, and economic disruptions. For each of these consequences, specific preparedness and response and recovery actions are identified.

The Recovery Practices Primer for Natural Disasters (ASCE, 2008; Welter, 2009) also provides guidance on preparedness for natural disasters. General guidelines for disaster planning are presented, as well as hazard-specific guidance for river floods and coastal hurricanes, earthquakes, and wildfires. LeChevalier and Chelius (2014) suggest resiliency planning should include: renewing aging infrastructure, planning for operational continuity, combining new operational solutions with capital improvements, and practicing emergency response plans. Several reports focus on building resilience of the water and energy sectors jointly (The Johnson Foundation, 2013; USDOE, 2014; Ajami and Truelove, 2014).

Preparedness planning guidance is also available for specific types of hazards. Several articles provide lessons learned from Hurricane Katrina and Superstorm Sandy (Reed et al., 2013; Scharfenaker, 2006; Sewerage and Water Board of New Orleans, 2013; WARN, 2013). Other articles address floods (USEPA, 2014a; USEPA, 2014c; Gebhart and Johnson, 2014), earthquakes (Davis, 2013; Oregon Seismic Safety Policy Advisory Commission, 2013; ABAG Earthquake & Hazards Program, 2009), and winter storms (Concho Valley Council of Governments). A number of reports have provided guidance on preparing drinking water systems for terrorist attacks (see for example, USEPA, 2014b and Murray et al., 2010). Recent guidance is available on cybersecurity (AWWA, 2014). USEPA (2012b) and (2013a) provide guidance to water utilities on planning adaptation strategies for climate change.

2.3 Drinking Water Resilience Tools

Tools have been developed to help water utilities improve their resilience to natural disasters, climate change, and other hazards. EPA's Community-Based Water Resiliency (CBWR) electronic tool was developed as part of a broader initiative to increase overall community preparedness by raising awareness of water sector interdependencies and enhancing integration of the water sector into community emergency preparedness and response efforts. The CBWR tool provides over 400 targeted resources to help local communities plan for and respond to drinking water emergencies and includes a resiliency self-assessment tool (USEPA, 2011). The assessment evaluates a water utility's resilience in terms of outreach to interdependent sectors, dedication of resources, security enhancements, vulnerability assessments, emergency response plans, contaminant detection, incident command system training, mutual aid assistance agreements, participation in local emergency response planning, and long-term climate change planning.

Another EPA resilience tool is the Climate Resilience Evaluation and Awareness Tool (CREAT), which helps water utilities assess the impacts of climate change on utility assets (USEPA, 2012). CREAT provides future climate scenarios based on regional climate projections, and helps utilities define threats and vulnerable assets based on these scenarios. For each asset-threat pair, a qualitative determination of the likelihood and consequences is made. A baseline risk assessment takes into account existing climate adaptation strategies and a resilience assessment evaluates additional strategies that could be employed. Resilience adaptation strategies are grouped in three areas: expanded operating flexibility, expanded capacity, and alternative strategies. The results identify the assets most vulnerable to climate change and produce a set of adaptation strategies that minimize risk.

The Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Drinking Water and Wastewater Systems (ANSI, 2010) uses an approach similar to CREAT, but focuses on natural disaster and malevolent acts rather than climate change scenarios. In the RAMCAP methodology, risk is estimated for all threat-asset pairs, and risk management strategies, or specific actions utilities can take, are identified to reduce risk. These strategies are classified as countermeasures (ones that can reduce vulnerability or threat) or consequence mitigating actions (ones that reduce consequences). The strategies can then be ranked by the amount that they reduce risk for the water utility, summed up across all threat-asset pairs.

The Argonne National Laboratory Resilience Index (Fisher, 2010) measures the resilience of critical infrastructure, including drinking water and wastewater systems. It combines more than 1,500 variables into a composite index that measures robustness, recovery and resourcefulness, and produces an overall score from 0 (low resilience) to 100 (high resilience). In contrast to the CREAT and RAMCAP self-assessment tools, this index is designed to be calculated by Department of Homeland Security investigators. The single index allows comparison of water systems across the nation to help prioritize funding and assistance.

EPA has developed multiple tools to help support the design, implementation, and evaluation of contamination warning systems (CWS), which help build resilience to contamination incidents. CWS integrate multiple detection strategies, including online water quality monitoring, customer complaint monitoring, and public health surveillance, to rapidly detect a wide range of potential contamination incidents. The TEVA-SPOT sensor placement optimization tool (USEPA, 2013c; Berry et al., 2012; Murray et al., 2010a) helps to identify sensor locations in a distribution network that minimize one or more objectives. The CANARY event detection software enhances detection by analyzing water quality sensor data in real time and alerting the operator when anomalous data is observed (USEPA, 2012c). The Water Contaminant Information Tool (WCIT) is an online database that provides information about contaminants of interest for water security, including physical properties of contaminants, how they behave in water, analytical methods for detecting contaminants, and potential human health effects (USEPA, 2010). For more information about EPA products supporting CWS, see USEPA 2014b.

The Water Security Toolkit (WST) is a suite of software tools that help provide the information necessary to help water utilities make good decisions that minimize the human health and economic consequences of contamination incidents (USEPA, 2013). WST is intended to assist in planning and evaluating response actions to terrorist attacks, natural disasters and traditional utility challenges, such as pipe breaks and poor water quality. It includes hydraulic and water quality modeling software and optimization methodologies to identify: (1) sensor locations to detect contamination, (2) locations in the network at which the contamination was introduced, (3) hydrants to remove contaminated water from the distribution network, (4) locations in the network to inject decontamination agents to inactivate, remove or destroy contaminants, (5) locations in the network to take grab samples to confirm contamination or cleanup and (6) valves to close in order to isolate contaminated areas of the network. In combination with a real-time, data-driven hydraulic model as provided by the EPANET-RTX software (USEPA, 2014d), WST could help a drinking water utility respond more quickly and accurately to any type of incident that might impact their distribution network.

3 Measuring Resilience

While attempting to quantify such a broad and diverse concept is difficult, measuring resilience is necessary to prioritize resilience enhancing strategies, to enable cost-benefit analyses, to monitor progress, and to clarify what is meant by resilience (NAS, 2012). In this section, the general concept of resilience is explored further, resilience characteristics are identified, and resilience measurement techniques are reviewed.

3.1 Understanding Resilience

Resilience is a property of a *system* (Resilience Alliance, 2010) whether system is a community, an ecosystem, an industry, or a drinking water system. Figure 3~~Figure 3~~ graphically represents the functional state of a system before, during, and after an event, in a very simplified fashion. The function F(t) can represent any system performance measure (e.g., percentage of customer demand provided by the water utility) as long as higher values represent higher performance. Alternately, F(t) could be a function that represents overall total performance of the system, combining all of the performance measures into a score or index. At time t_e, a disruptive event occurs, and the system performance declines until it reaches a minimum state, the disrupted state, at time t_d. Once response or recovery actions have been implemented at time t_a, the system begins to recover, and reaches a new stable recovered state at time t_r.

Figure 3 illustrates that the goal of a resilient system is to minimize the time that a system is disrupted (t_r - t_e) and the magnitude of the disruption ($F(t_0)$-$F(t_d)$), and also to maximize the performance of the system after recovery, $F(t_r)$. In fact, the National Infrastructure Advisory Council (NIAC, 2009) defines resilience as "the ability to reduce the magnitude and/or the duration of disruptive events." Similarly, a National Institutes of Standards and Technology report (McAllister, 2013) defines disaster resilience as "the ability to minimize the costs of a disaster, return to the *status quo*, and to do so in the shortest feasible time." In many cases, returning exactly to the *status quo* might not be feasible and $F(t_r)$ is likely to be greater than or less than, but is unlikely to be exactly equal to $F(t_0)$ (Chang, 2010). Fiksel et al., (2014) define resilience as "the capacity for a system to survive, adapt, and flourish in the face of turbulent change and uncertainty," highlighting the desire to maximize the state of the system post disruption. Tierney and Bruneau (2007) refer to the resilience triangle in Figure 3 (assuming recovery starts immediately after the event, t_e=t_d=t_a), which represents "the loss of functionality from damage and disruption, as well as the pattern of restoration and recovery over time."

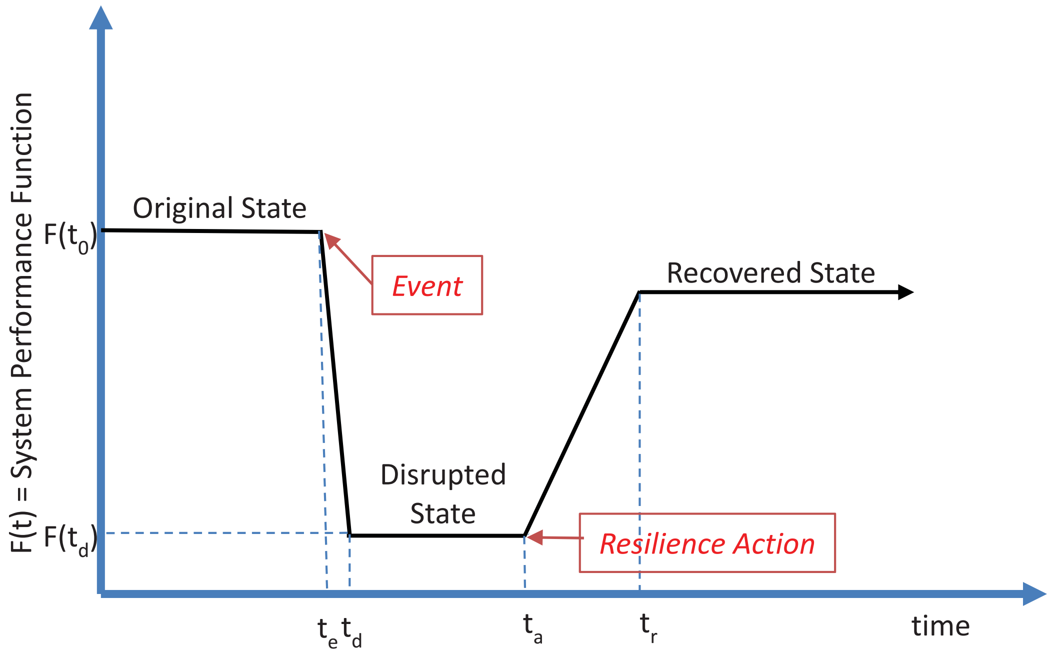

Figure 3 System performance function before, during, and after an event.

3.1.1 Resilience, Risk, Vulnerability, and Preparedness

The literature review on resilience of drinking water systems in Section 2 reveals that many concepts of resilience bear much similarity to the concepts of preparedness, vulnerability assessment, disaster management and risk management. As Figure 1 and Figure 3 imply, resilience involves not just rapid recovery but also preparedness and mitigation activities to help reduce vulnerabilities and the potential impacts of hazards, learning from previous events, managing risk, and adapting to be better prepared for future events. How does resilience differ from these concepts? Is it a distinct concept or is it just a different word for the same activities?

The National Academies of Science says that anticipating and managing risk is one step toward increasing resilience to hazards (NAS, 2012). Disaster risk is "the potential for adverse effects from the occurrence of a particular hazardous event, which is derived from the combination of physical hazards, exposures, and vulnerabilities" (NAS, 2012). Risk is often calculated as the product of the likelihood of a specific hazard and the consequences of that hazard. Sometimes, the likelihood is expressed as the product of the vulnerability and the threat (see for example, ANSI, 2010). Understanding risk enables informed decision making about how to reduce risk (either the likelihood or consequences) and increase resilience.

Vulnerability assessment, risk assessment, and resilience assessment can be quite similar (ANSI, 2010). By reducing vulnerability and risk, resilience is increased. For example, if a water system has important facilities located in flood plains, it is vulnerable to flooding; by moving or protecting the facilities, the system can reduce vulnerability. The water system's resilience is also increased because, as this facility will not be as affected by the flood, the magnitude of disruption to the water system will be decreased, and the utility will be able to return to service more rapidly. But resilience is more than the inverse of vulnerability; resilience can also help explain why systems with similar vulnerabilities to hazards might return to very different recovered states after an event (Figure 3). For example, two water systems might both be equally vulnerable to flooding, but one utility might be more resilient because its highly agile organizational structure enables it to respond more rapidly. Vulnerability helps to explain the causal connections between hazards and resulting negative consequences; resilience, on the other hand, can disable or transform the causal connections (FSIN, 2014).

Preparedness is also a large component of resilience. Resilient systems are prepared to manage hazards with minimal loss of functionality. However, communities can be prepared with emergency response plans in place, and mitigation strategies in effect, and yet not demonstrate resilience during a hazard. Resilience focuses heavily on preparedness, but also requires effective implementation of response and recovery actions, with flexibility, agility, and rapidity.

The Community and Regional Resilience Institute's (CARRI) definition of resilience helps to pull all of these concepts together: resilience means the ability of a system to anticipate risk, limit impacts, and bounce back rapidly (CARRI, 2014). Anticipating risk means identifying and understanding the risks of potential hazards to a system. Limiting impacts means enhancing preparedness, implementing risk management strategies, and reducing vulnerabilities. Bouncing back rapidly means ensuring the ability to respond and recover rapidly through training, planning, and building flexibility and adaptability into the culture of the organization.

In addition, resilience is different in that it implies the ability to manage unexpected events. While risk and vulnerability focus on specific hazards, resilience requires the ability to be flexible, agile, and adaptable in the face of an unforeseen hazard. IFRC (2011) describes resilience as being focused on building capacity to a wide range of hazards under uncertain conditions, rather than the "predict and prevent" paradigm of risk and vulnerability assessment to specific hazards. In the next section, additional attributes of resilient systems are reviewed to further highlight unique aspects of resilience.

3.1.2 Resilience Attributes and Indicators

The International Federation of Red Cross and Red Crescent Societies (IFRC) recently published the report, *Characteristics of a Safe and Resilient Community: Community-Based Disaster Risk Reduction Study* (2011). The report draws on the experience of the organization in responding to hundreds of disasters each year across the world and on current disaster resilience literature to identify common characteristics of resilient communities. The results of the study identified six characteristics of a safe and resilient community.

A safe and resilient community (IFRC, 2011):

1. *Is knowledgeable and healthy. It has the ability to assess, manage, and monitor its risks. It can learn new skills and build on past experiences.*
2. *Is organized. It has the capacity to identify problems, establish priorities, and act.*
3. *Is connected. It has relationships with external actors who provide a wider supportive environment, and who supply goods and services when needed.*
4. *Has infrastructure and services. It has strong housing, transport, power, water, and sanitation systems. It has the ability to maintain, repair, and renovate them.*
5. *Has economic opportunities. It has a diverse range of employment opportunities, income and financial services. It is flexible, resourceful, and has the capacity to accept uncertainty and respond proactively to change.*
6. *Can manage its natural assets. It recognizes their value and has the ability to protect, enhance, and maintain them.*

The IFRC report highlights that resilient communities have the capacity to be resourceful, adaptable/flexible, and learn from past experiences. Such communities also have assets and resources that are strong, robust, well located, diverse, redundant, and equitable. The communities are committed to reducing risk over the long term.

Fiksel (2003, 2014) identifies several indicators of resilience in human systems:

- Diversity – the existence of multiple resources and behaviors in the system.
- Adaptability – the capacity of a system to change in response to new pressures.
- Cohesion – the strength of unifying forces, linkages, or feedback loops.
- Latitude – the maximum amount of change the system can absorb while still functioning.

- Resistance/Stability – the capacity of a system to maintain its state in the face of disruptions
- Vulnerability – the presence of disruptive forces that threaten the system.
- Recoverability – the ability to overcome disruptions and restore critical operations.
- Efficiency/Resource Productivity – the ability of the system to perform with modest resource consumption, or to maximize produced value relative to consumption.

Tierney and Bruneau (2007) present the R4 framework of disaster resilience which identified four major attributes of disaster resilience:

- Robustness – the ability to withstand disasters without significant degradation or loss of performance.
- Redundancy – the ability to substitute system components if significant degradation or loss of functionality occurs.
- Resourcefulness – the ability to identify and prioritize problems and initiate solutions by mobilizing resources.
- Rapidity – the ability to restore functionality in a timely way, containing losses and avoiding disruptions.

Similarly, the National Infrastructure Advisory Council (NIAC, 2009) defined three attributes of resilient critical infrastructure:

- Robustness – the ability to maintain critical operations and functions in the face of a crisis.
- Rapid Recovery – the ability to return to and/or reconstitute normal operations as quickly and efficiently as possible following a disruption.
- Resourcefulness – the ability to skillfully prepare for, respond to, and manage a crisis or disruption as it unfolds.

The RAMCAP Utility Resilience Index (RAMCAP, 2010) measures water system operational resilience in terms of seven indicators:

- Emergency response plan
- National Infrastructure Management Plan compliance
- Mutual aid and assistance agreements
- Emergency power for critical operations
- Ability to meet minimum daily demand when plant is non-functional
- Critical parts and equipment
- Critical staff resilience

There is significant overlap between the attributes and indicators of resilience described in this section. Robustness focuses on the ability to withstand hazardous conditions and includes latitude, resistance, stability, and the ability to meet minimum customer demand even under system failure. Redundancy refers to the ability to substitute system components and includes diversity and access to emergency power sources, critical parts and equipment. Rapid recovery focuses on the ability to return to normal functions as soon as possible and includes rapidity, adaptability, recoverability, and mutual aid and assistance agreements. Resourcefulness focuses on the ability to prepare for, manage and recover from a crisis and includes emergency response plan, National Infrastructure Management plan compliance, cohesion, efficiency, resource productivity, and staff resilience. These characteristics help human systems to anticipate and resist the effects of hazards, but systems can also be designed to be inherently resilient with these characteristics in mind (Fiksel, 2006).

3.1.3 Resilience as a Systems Concept

The definitions of disaster, infrastructure, and community resilience reflect that resilience is a property of a system. A system is composed of interacting parts that operate together to achieve a function. Resilience is used to describe the performance of a system not its individual components. Figure 3 helps to demonstrate resilience as a systems concept. Rather than simply measuring the performance of a single component, resilience measures the state of the entire system. Understanding the performance of individual components is critically important; however, resilience reveals the dynamic interactions among the components in ways that might enhance or hinder preparedness, response, and recovery capabilities.

In a resilient community, the entire community is the "system" with its residents, businesses, governance and institutions, infrastructure, services, natural assets, and external linkages making up its "parts." For a resilient infrastructure, the physical components of the infrastructure, the services provided by the infrastructure, the organizations or institutions that manage the infrastructure, and the individuals and businesses that use the infrastructure services make up its parts.

For drinking water systems, the system includes: physical components such as water sources, treatment plants, storage tanks, pumping stations, and pipe distribution networks delivering water to businesses and homes (Figure 4); services provided by the water system – the timely delivery of an adequate amount of safe water; the municipality or private company that manages the water; and the businesses, organizations, and individuals that purchase and consume the water.

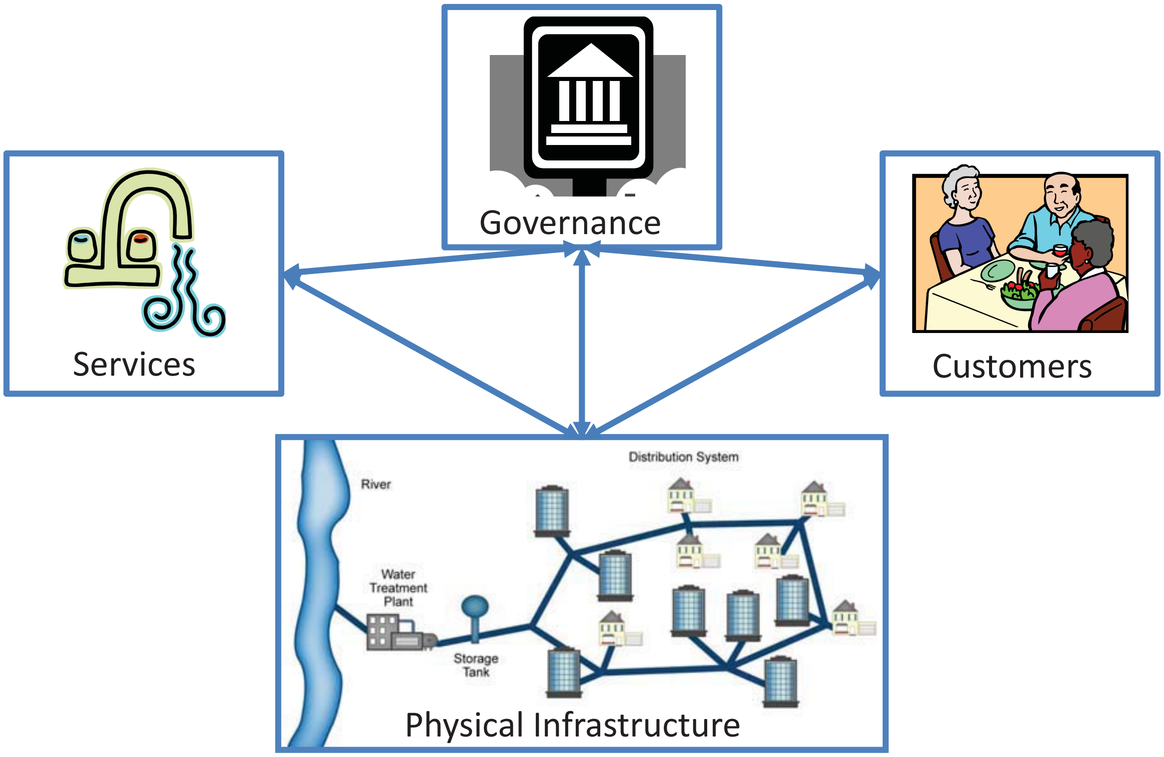

Figure 4 Schematic of a drinking water "system" with all its interacting component parts: the physical components, the services it provides, the organizations that govern it, and the people and industry that consume it.

3.2 Approaches to Measuring Resilience

The National Academies of Science recommends that any approach to measuring resilience address multiple hazards, be adaptable to the needs of specific communities and the hazards they face, and be capable of addressing multiple dimensions of resilience (NAS, 2012). In addition, they recommend that a national resilience scorecard should be built upon both qualitative and quantitative information that, among other things, measures the ability of critical infrastructure to recover rapidly from disasters (NAS, 2012). Many approaches in the literature use a similar qualitative ranking, scorecard, or index to assess resilience (Fiksel, 2003; ANSI, 2010; Fisher, 2010). The benefit of such an approach is that different types of information from distinct fields can be combined; however, such approaches are subjective and are not able to capture the dynamic nature of linkages and feedback loops inherent to systems. An alternative approach is to use systems modeling that directly simulates hazards and their effects on systems. Both approaches are discussed below.

3.2.1 Qualitative Approaches

As resilience is influenced by multiple diverse factors that are difficult to measure quantitatively, a composite index that gives weights to various metrics and combines them into an index or a score is a reasonable approach. Metrics can have numerical values or can be given a ranking such as high, medium, or low. A composite index invites collaboration from diverse stakeholders and subject matter experts; however, it is also subject to bias and lack of knowledge or imagination. Several qualitative ranking methods are described below.

The Resilience Alliance developed a qualitative approach to socio-ecological resilience analysis that uses complex adaptive systems theory to frame the problem (Resilience Alliance, 2010). This approach involves defining the system, identifying thresholds representing breakpoints between different system states, understanding system interactions, and determining actions that will prevent, slow down, or adapt to system changes. Resilience is measured as the distance between the system state and the threshold, revealing how far a system is from a major system change. This approach incorporates uncertainty regarding the hazards, the complexity of systems, and the importance of time scales on actions. Another qualitative approach scores systems on five resilience characteristics (Fiksel, 2003). The characteristics (detailed above in Section 3.1.2) are diversity, adaptability, cohesion, latitude, and resistance. This approach has been applied to industrial systems as well as ecological systems.

The RAMCAP Utility Resilience Index (ANSI, 2010) scores water utilities on operational and financial resilience. The seven operational indicators represent a “utility’s organizational preparedness and capabilities to respond and restore critical functions/services following an incident.” The five financial indicators represent a utility’s financial preparedness and ability to adequately respond to an incident. Each of the indicators is scored with a value from 0 to 1, and the operational and financial indices are multiplied by weighting factors and summed. The maximum value of the index is 100. The Utility Resilience Index takes a high level approach to measuring resilience; however, it is not a true systems measure as it does not account for interconnections between the indicators.

The Argonne National Laboratory Resilience Index uses a scale of 0 to 100 (with 100 being the most resilient) to score infrastructure resilience, including water and wastewater systems, to hazards. The approach involves extensive data collection (over 1,500 variables covering physical security, security management, security force, information sharing, protective measures assessment, and dependencies) and categorization of the variables that contribute to robustness, recovery, and resourcefulness. Robustness combines variables measuring redundancy, prevention, and maintaining key functions. Recovery combines variables measuring restoration and coordination. Resourcefulness combines variables measuring training, awareness, protective measures, stockpiles, response, new resources, and alternative sites. The data is reviewed by subject matter experts who also determine the weights of the variables, which are then combined into the single index. The single index allows comparison of critical infrastructure across the nation to help prioritize funding and assistance (Fisher, 2010).

3.2.2 Systems Modeling Approach

Another approach to measuring resilience is to use systems modeling to calculate the impacts of hazards on specific systems. For example, models could be used to simulate the impacts of a hurricane on a water system as well as response and recovery actions. Systems modeling captures the dynamic relationships between the parts of the system and helps to reveal unforeseen effects of actions in one part of a system on other parts. Such an approach enables examination of the linkages between system components, and the changes in the system due to internal or external forces. Systems modeling can demonstrate the interactions, side effects, and unexpected consequences of actions designed to enhance resilience on a system (Fiksel, 2006).

This approach has the potential to be more scientifically rigorous than the qualitative approaches, to reveal more insight about the complex interrelated parts of the system, and to better assess the benefits and drawbacks of actions designed to enhance resilience. However, there are many technical challenges to using systems modeling to measure resilience, including: the lack of models that can simulate extreme events like the hazards outlined in Figure 2 (in general, such events can push models toward their boundaries of validity); the lack of models to simulate response and recovery actions; and the lack of data at the appropriate scales needed to accurately develop and validate models (e.g., cost or weather data, or impact data from previous disasters).

3.2.2.1 Systems modeling of water distribution networks

While systems modeling and simulation tools that incorporate all components of drinking water systems (as shown in Figure 4) are available. Network models take into account each component shown in Figure 4: the physical infrastructure represents the pipes, tanks, reservoirs, pumps and valves in the system; the customers are represented by demand patterns reflecting how much water they consume and where and when it is consumed; the governance is represented by the set of operating rules for tanks, pumps, and valves; and the services are represented by the amount and quality of water delivered.

Figure 5 is an example of a drinking water network model with two water sources – a lake and a river –three storage tanks, 117 pipes, and 92 nodes. This network serves approximately 62,000 customers, and the nodes represent service connections where water is delivered to these customers at homes, hospitals, schools, or businesses. The distribution network is operated by determining how much water enters the network, when pumps are active, valves are closed, and tanks are filling or draining. This model is a highly simplified representation of the real water system but captures the important behaviors.

Distribution networks are large and spread out, often spanning thousands of miles of pipe that are highly interconnected with multiple flow paths between any two points. Flows in distribution networks vary over space and time and can change directions. Flows are influenced by water pressure and random customer demands (that show trends on hourly to monthly time scales). Overall, drinking water distribution networks are spatially and temporally complex, and these complexities are interdependent.

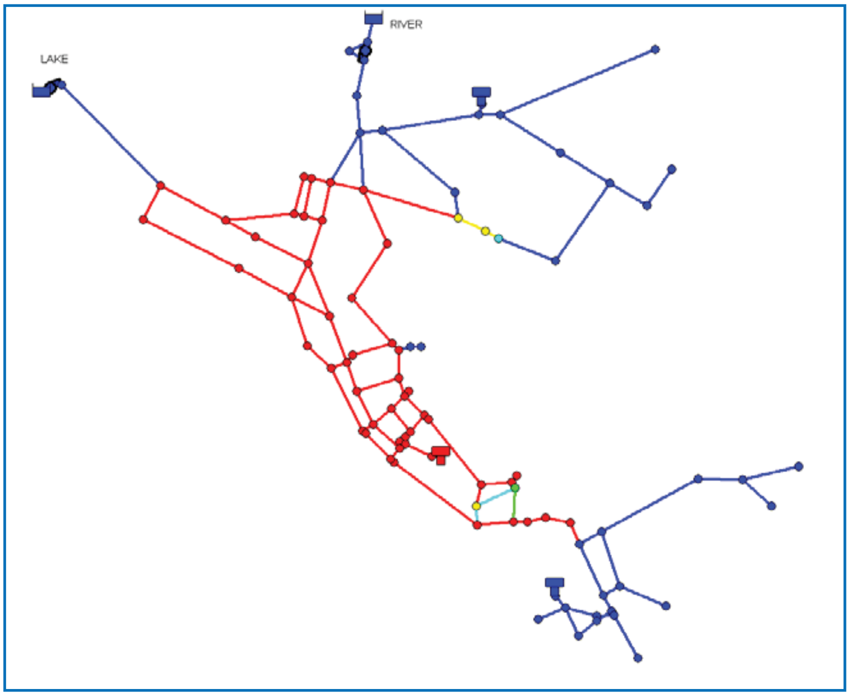

Figure 5 Schematic of a distribution network with two sources (lake and river) and three tanks.

Systems analysis and simulation incorporate these complexities and interdependencies, allowing for an integrated analysis of behavior in water distribution networks. Such an approach is crucial to understanding the potential tradeoffs of resilience enhancement strategies. For example, adding more pipes to form loops in the network can increase reliability by ensuring multiple delivery routes to customers; however, this redundancy can also increase the risk of customer exposure to contaminants.

Systems analysis of water distribution networks typically utilizes software packages that predict hydraulics and water quality over time given a specific water utility network and set of operations. EPANET is a freely available software package that is considered the gold standard in the industry (Rossman, 2000). EPANET was created to support the long term planning and operation of water systems. To support more rapid decision making and more accurate dynamic calculations, extensions to EPANET have been developed such as EPANET-MSX (Shang, Uber, and Rossman, 2008) – which allows for tracking multiple constituents in the water and complex reactions between them – and EPANET-RTX (EPA, 2014d) – which allows for real-time integration of field data into hydraulic and water quality calculations.

In order to use these systems modeling tools to analyze the resilience of distribution networks to hazards, they need to be able to robustly handle failures and stresses on the network. Mays (2000) defines emergency loading conditions that distribution networks are designed to handle on a routine basis: fire-fighting water demands, pipe breaks, pump failures, power outages, control valve failures, and insufficient storage capacities. Resilient networks must be able to deliver required flows to customers at adequate pressure during these emergency conditions. The hazards listed in Figure 2 might result in extreme versions of these emergency conditions, for example, pipe breaks in large mains or multiple conditions at the same time, putting severe stress on the system. In addition, resilient networks must also be able to handle water quality failures. For example, pipe breaks can result in contamination of water with sediments or biological materials. Inadequate pressure can lower flow rates and allow for water quality degradation and chlorine residual loss.

4 Quantitative Performance Measures

The rest of this report focuses on the use of systems modeling techniques to calculate quantitative measures of resilience for drinking water distribution systems (WDS). Many quantitative performance metrics have been developed for WDS. In this section, metrics are presented and their relevance to evaluating the resilience of drinking water systems to hazards is discussed. This is intended to be a comprehensive review and some of these measures might not prove useful for resilience. To date, none of these measures have been validated against a real disaster. Additional research is needed to determine the most useful and informative measures and to incorporate them into a usable tool for water utilities.

4.1 Risk

Risk is a generic term that describes the probability of an event occurring and the resulting consequence if that event occurs. Risk is typically calculated as the product between the probability of an event occurring and the consequence of the event, each of which must be carefully defined for a specific hazard under certain circumstances. The consequence of each event can be computed using a wide range of metrics. In a water distribution network, the incident could be a contaminant that enters the network, a pipe break, or loss of supply. Consequences could be measured in terms of the number of people exposed to harmful levels of the contaminant or the number of service locations without adequate water pressure for a given set of time. Risk is calculated using the following equation:

$$Risk = \sum_{i=1}^{I} \alpha_i M_i$$

where I is the number of events, α_i is the probability of event i occurring, M_i is the metric used to quantify the consequence of the ith event. The units for risk are the same as the units for the consequence, M.

Whether *Risk* is considered a systems measure depends on how the consequence terms, M, are calculated. Several systems applications of the standard risk metric have been used in the drinking water literature. This formulation is used by Ozger (2003) who calculated the risk of not meeting customer demands by computing the “available demand fraction” after a pipe failure and multiplying that value by the probability of the pipe failure occurring (this metric is also referenced later in this report in the section on reliability). Pipe failures are simulated across the network, and the resulting ability of the system to meet demands is calculated.

Berry et al. (2006) and Murray et al. (2010a) use the standard risk equation to calculate the risk of contamination incidents in water distribution systems, and to design sensor networks that minimize such risk. TEVA-SPOT and EPANET are used to calculate contamination concentrations across the network and predict the spatial and temporal impacts on customers.

Impacts are measured in terms of the number of people exposed to harmful levels of contaminants, the number of pipe feet contaminated, or other measures; the probability is the likelihood of a particular contamination event occurring, where the event is defined by the location of the contaminant entering the system, and the quantity and rate of contaminant introduced.

The Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Drinking Water and Wastewater Systems (ANSI, 2010) calculates a similar measure of risk for each threat-asset pair defined for a specific water system. The risk equation is modified to include a term for vulnerability to the threat, and allows for reduced risk if the water utility has hardened their system against a specific threat. For example, floods might occur with some frequency in a region and might potentially damage chemical storage tanks. However, if these tanks are stabilized to prevent damage, their vulnerability to floods is greatly reduced, and the overall risk is reduced. In this way, risk is calculated as:

$$Risk = CVT$$

where *C* is the consequence of a particular threat to a specific asset (e.g., a tank), *V* is the vulnerability of the asset to the threat, and *T* is the threat likelihood. The consequences are measured in terms of the number of fatalities, injuries, financial losses to the utility or the metropolitan region. The vulnerability is the likelihood that the threat will result in the specific consequences. The threat likelihood is the probability that the threat will occur to the specific asset over a given time period. The risk can be summed over a series of threats for each asset.

In the RAMCAP methodology, risk is estimated for all threat-asset pairs, and risk management strategies, or specific actions utilities can take, are identified to reduce risk. These strategies are classified as countermeasures (ones that can reduce vulnerability or threat) or consequence mitigating actions (ones that reduce consequences). The strategies can then be ranked by the amount that they reduce risk for the water utility, summed up across all threat-asset pairs. This approach does not use systems modeling but rather an expert judgment to estimate consequences, vulnerability, and threat likelihood. The RAMCAP method is limited in that risks are estimated for each individual component with no way of tracking the interdependencies among the components; thus, it cannot predict unanticipated tradeoffs between risk management strategies as a true systems analysis approach would.

4.2 Resilience

The term “resilience” is used frequently when describing desired characteristics of critical infrastructure, but a standard mathematical equation for its quantification has not been adopted. The RAMCAP methodology (ANSI, 2010) defines drinking water asset resilience as:

Asset Resilience = DSVT

where *D* is the time duration (in days) of a service outage to a specific asset (e.g., a tank), *S* is the amount of service denied (in gallons per day), *V* is the vulnerability of the asset to the threat, and *T* is the threat likelihood. In this approach, perfect asset resilience results in a score of zero; positive values provide the opportunity for improved resilience. This approach modified the standard risk equation by replacing the consequences term with *DS*, but is not a systems approach as it focuses solely on individual components of a water distribution system.

4.2.1 Time-based Resilience Assessment

Attoh-Okine et al. (2009), Henry and Ramirez-Marquez (2012), Barker et al. (2013), Francis and Bekera (2013), and Ayyub (2013) suggest time-based resilience assessment that is generic enough to be applied to a wide range of infrastructure systems. These metrics compute resilience as a function of time and can track the impact of restorative actions in the system. These methods evaluate the change in system performance between two points in time. This definition is commonly used by the earthquake community. The equation used to measure resilience as a function of time is shown below:

$$R = \frac{\int_{t_0}^{t_1} Q(t)dt}{100(t_0 - t_1)}$$

where *Q(t)* is the quality of infrastructure, t_0 is a time before a hazardous event, and t_1 is a time after the event. The evaluation considers the intrinsic ability of the system to recover or take into account the impact of restorative actions. To perform a resilience assessment, the system of interest must be clearly defined. That system will undergo disruption and recovery, as measured by a specific metric. A wide range of metrics can be used for *Q(t)*; the only requirement is that the metric must be impacted by the disruptive event and the restorative action (if under consideration). The timeframe for the disruption and restorative action also need to be estimated. Attoh-Okine et al. (2009) add to this basic equation by considering the interrelationship between different infrastructure using belief functions.

Henry and Ramirez-Marquez (2012) outline different system states used to compute resilience (similar to Figure 3). The system is assumed to start in an original, stable state. After a disruptive incident, the system transitions to a disrupted state over a period of time. The system will stay at that disrupted state until resilience action is taken. At that point in time, the system begins to recover until it reaches a stable recovered state. The recovered state might not be equal to the original stable state. In a water distribution network, the stable original state is the network itself in normal operations. The disruptive incident could be an earthquake that causes a pipe break, and the resilience action is repair to that pipe. For this case, the metric used to assess resilience could be the percentage of nodes meeting pressure requirements.

Henry and Ramirez-Marquez (2012) calculate resilience as a function of time for a given disruptive event as follows:

$$R(t_r \mid e_j) = \frac{F(t_r \mid e_j) - F(t_d \mid e_j)}{F(t_0) - F(t_d \mid e_j)} \quad \forall e_j \in D, t_r \in (t_d, t_f)$$

where $R(t_r|e_j)$ is the system resilience as a function of time given scenario e_j, D is the set of disruptive events, t_d is the time of the disruption, t_f is some time in the future time, and t_r is any time between t_d and t_f. The numerator is the system recovery at time t_r and the denominator is the system loss at t_d. If recovery is equal to loss, then the system is fully resilient. F, referred to as the 'figure-of-merit', is the value of the performance metric at a specific time for a given scenario and represents $Q(t)$ in the previous equation. For example, $F(t)$ could be pressure in the network as a function of time.

Francis and Bekera (2013) expand upon this concept by adding a speed recovery factor which takes into account the maximum time that the system can be sub-standard, and the time to complete recovery actions. Baker et al. (2013) proposed methods to measure the importance of a specific component to the resilience of the system. The component's importance is based on its vulnerability and recovery speed. Ayyub (2013) suggest a similar method to measure system resilience that includes failure and recovery profiles and accounts for system degradation over time.

This approach to measuring resilience would be suitable for addressing the hazards in Figure 2 if the *Q(t) or F(t)* were calculated using systems analysis methods to account for the interconnectedness of the system. A time-based approach is appealing because it allows for the explicit evaluation of resilience enhancing actions, which could include mitigation actions (such as decentralization of treatment or storage, installation of a contamination warning system, or adding redundant equipment) or response and recovery actions (such as flushing low quality water from the system, repairing pipe breaks, and implementing interim solutions).

4.3 Reliability

Many systems performance measures for water distribution networks have been proposed in the research literature that are closely related to resilience, reliability, robustness, and redundancy. Summaries are provided in Mays (1989, 1996), Ostfeld (2004), and Lansey (2013). Reliability is usually defined as the probability that the system performs its mission within specified limits for a given period of time under certain conditions; or, as the probability that the system can provide the demanded flow rate at the required pressure head under normal, fire flow, and emergency conditions. Certain emergency conditions are routine for WDS, including pipe breaks, pump failures, power outages, and insufficient storage capacity. Robustness is defined similarly but focuses on the ability of the system to maintain function during abnormal conditions. Redundancy is the duplication of critical components in a system with the intention of increasing reliability. In the literature, these terms are often used interchangeably.

Reliability assessment generally falls into three categories: topological reliability, hydraulic reliability, and entropy surrogates (Ostfeld, 2004). Topological reliability refers to the connectivity of the network and focuses on the physical connections between customer service nodes. Hydraulic reliability refers to the ability of a network to deliver the desired water quantity and/or quality to customer service nodes. Entropy is a measure of uncertainty in a random variable; in a water distribution network model, the random variable is flow in the pipes and entropy can be used to measure alternate flow paths when a network component fails. These approaches are described in more detail below.

These metrics are potentially useful for calculating resilience to the hazards listed in Figure 2. Network connectivity can improve resilience to pipe breaks, infrastructure failures, and loss of access to a single source. Hydraulic reliability and entropy can be used to measure resilience to pressure loss, service disruptions, as well as loss of access to sources or other infrastructure.

4.3.1 Topological Reliability

Graph theory can be used to quantify the connectivity of water distribution networks, and topological metrics based on graph theory can be used to assess the reliability of the network. Topological metrics rely on the physical layout of the network system components (i.e., the data contained in an EPANET or GIS file). When the WDS is viewed as a graph, the pipes are the graph edges and the pipe junctions are graph nodes. Topological metrics can be used to understand how the underlying structure and connectivity constrains network reliability. For example, a regular lattice, where each node has the same number of edges, is considered to be the most reliable graph structure. On the other hand, a random lattice has nodes and edges that are placed according to a random process. A real world WDS probably lies somewhere in between a regular lattice and a random lattice in terms of structure and reliability.

Topological metrics use undirected graphs which means that the graph edges have no beginning or ending node. In a WDS, this means that connectivity is defined using the physical layout of the system rather than the direction of flow. In some cases, however, topological metrics can be extended to include flow direction by changing the undirected graph into a directed graph. This can be helpful, for example, when exploring the connectivity between a water source and a customer demand node under specific hydraulic conditions.

Goulter (1987) and Ostfeld (2004) outlined several methods used to measure reliability through topological metrics. Jacobs and Goulter (1988, 1989) compute redundancy that arises from the network layout and explore the use of regular lattices as a way to improve reliability. Wagner et al. (1988a) compute connectivity, defined as the probability that a given demand node is connected to a source, and reachability, defined as the probability that all demand nodes in a system are connected to a source.

Shamsi (1990) measured the probability that any two nodes are connected in a network using a metric termed 'node pair reliability' (NPR) as a way to quantify network reliability. NPR is computed at each customer service (demand) node to see if there are multiple paths from these nodes to water sources (e.g., treatment plant, reservoirs, storage tanks). This method results in a "reliability surface" that can be used to predict areas that need priority for maintenance and repair. Quimpo and Shamsi (1991) use a similar method to quantify reliability.

Watts and Strogatz (1998) suggest using small-world network graph theory to understand connectivity of networks. In a small-world network, regions of highly clustered nodes are connected to other clusters by a direct path. In a WDS, this structure is similar to neighborhoods that are connected by large water mains. The structure of small world networks lies between a regular lattice and a random network. Shen and Vairavamoorthy (2005) demonstrate how to apply small-world network analysis to a WDS and show how this approach can provide information on the efficiency of the network. The graph structure of WDS networks can be compared to regular and random graphs by computing characteristic path lengths and clustering coefficients.

Yazdani and Jeffrey (2011) present several topological metrics and describe how these metrics can be used to quantify network structure, efficiency, redundancy, and robustness. Here network structure refers to the physical arrangement of nodes and links, efficiency refers to minimizing the number of links in a network while still meeting its function, redundancy refers to the existence of multiple paths between nodes, and robustness refers to the existence of paths between nodes even if nodes or links are removed from the graph.   This approach was applied to a WDS network in Ghana to explore different expansion strategies. Results showed the tradeoff between increased redundancy and efficiency using a meshed layout for the expansion and the added costs.

Pandit and Crittenden (2012) provide similar topological metrics for water distribution networks. The metrics include diameter, average path-length, central-point dominance, critical ratio of defragmentation, algebraic connectivity, and meshed-ness coefficient.

Trifunovic (2012) developed the Network Design and Reliability Assessment (NEDRA) computer package, which combines graph theory and hydraulic analysis to compute reliability in water distribution networks. NEDRA includes several topological metrics that can be used to quantify connectivity of the network. NEDRA generates network layouts and computes network reliability. This analysis is displayed as a Hydraulic Reliability Diagram (HRD). A HRD is a plot of available demand fraction (Ozger, 2003) and normalized pipe flow, and displays where the network is connected or disconnected and overdesigned or underdesigned. This level of detail is often hidden by network-wide averaged reliability metrics.

4.3.2 Hydraulic Reliability

Hydraulic reliability metrics are based upon spatially and temporally variable flows and/or pressure; calculation of these metrics require simulation of WDS hydraulics that reflect how the system operates under normal conditions and in response to failures or hazards. Mays (2000) defines emergency loading conditions that distribution networks are designed to handle on a routine basis: fire-fighting water demands, pipe breaks, pump failures, power outages, control valve failures, and insufficient storage capacities. Reliable networks must be able to deliver required flows to customers at adequate pressure during these emergency conditions; however, not all hydraulic reliability metrics explicitly consider all of these conditions. While some hydraulic reliability metrics are calculated over a time interval, others are calculated using flows and pressures at a single time.

As mentioned earlier in this report, demand-driven simulation (such as with EPANET) might not be adequate to simulate hydraulic capacity during some disruptive events; pressure driven models are sometimes used instead to predict pressures more accurately. Alternately, pressure corrected demand-driven simulation is sometimes used to overcome this limitation; simulated demand can be corrected based on a minimum pressure threshold (Wagner et al., 1998b) or nodes can be changed to virtual tanks to supply demand when pressure is low (Trifunovic, 2012).

An overview of hydraulic reliability metrics can be found in Ostfeld (2004). Su et al. (1987), Wagner et al., (1988b), Bao and Mays (1990), Fujiwara and Ganesharajah (1993), Ostfeld (2001), and Ostfeld et al., (2002) use stochastic simulation to analyze reliability in WDS networks. By using stochastic simulation, an ensemble of hydraulic scenarios can be defined by sampling from probability distributions of, for example, demand profiles, initial water quality, the time and location of pipe breaks, and the time it takes to repair individual components. This helps to estimate the reliability of a WDS to a wide variety of conditions.

Ostfeld et al. (2002) developed the Reliability Analysis Program (RAP) which uses stochastic EPANET simulations and computes the fraction of delivered volume (FDV), fraction of delivered demand (FDD), and fraction of delivered quality (FDQ). To be able to more accurately calculate demand under failure scenarios using EPANET, simulated demands were corrected based on the pressure and flow rate. In this way, a node is only supplied its fully requested demand when a minimum pressure constraint is met, otherwise only a fraction of the demand is satisfied. FDV is the ratio of total volume delivered to the total volume requested. FDD is the fraction of time periods where demand is met. FDQ is the fraction of time periods where water quality standards are met. These metrics can be calculated at each demand node, j, using the following equations:

$$FDV_j = \frac{\sum_{i=1}^{N} V_{ij}}{V_T},$$

$$FDD_j = \frac{\sum_{i=1}^{N} t_{ij}}{NT},$$

$$FDQ_j = \frac{\sum_{i=1}^{N} tq_{ij}}{NT}$$

where N is the number of stochastic simulations, T is the duration of each simulation, V_{ij} is the volume of water supplied to node j for simulation i, V_T is the total requested volume of water at node j over all simulations, t_{ij} is the total duration where the demand supplied at node j is above a demand threshold for simulation i, tq_{ij} is the total duration where the concentration at node j is below a concentration threshold for simulation i. Ostfeld et al. (2002) use the RAP tool to create reliability maps of water distribution networks based on single component failure events.

In a similar manner, Ozger (2003) measure available demand fraction (ADF) using a pressure dependent correction of EPANET hydraulic simulations. ADF is calculated at each demand node, j, using the following equation:

$$ADF_j = \frac{Q_j}{D_j}$$

where Qj is the available demand and Dj is the requested demand over the simulation timeframe. ADF can be computed for multiple simulations, as in Ostfeld et al. (2002).

Awumah and Goulter (1989) compute the percentage of demand supplied at adequate pressure (PSPF). This metric requires a hydraulic simulation for each pipe removal in the system. For each simulation, the fraction of demand that is supplied when pressure is above a specified threshold is recorded. Wagner (1988b) also measure the number and duration of pipe failures, pump failures, the number and duration of reduced service events, and the between failure time and repair duration.

Another commonly used hydraulic reliability metric is the Todini resilience index (Todini, 2000). The Todini resilience index has been used as an indirect measure of the hydraulic reliability of water distribution networks (Seifollahi-Aghmiuni et al., 2013; Trifunovic, 2012; Murray et al., 2010b). This index is related to the capability of a system to overcome failures while still meeting demands and pressures at the nodes. The Todini Index defines resilience at a specific time as a measure of surplus "power" at each node and measures "relative energy redundancy". The metric can be computed using demands and pressures calculated from EPANET. If failure events are considered, pressure driven or pressure corrected hydraulic simulations should be used.

The metric assumes that availability of surplus power at a node is an indicator that alternative pathways to deliver water to customers are present. In the case of network failure, the surplus will be dissipated internally to maintain function. The total available power that enters the network and the power delivered to users are computed using the following equations:

$$P_{tot} = \gamma \sum_{r=1}^{R} Q_r H_r \quad \text{and} \quad P_{ext} = \gamma \sum_{n=1}^{N} q_n h_n$$

where P_{tot} is the total available power entering the network and P_{ext} is power delivered to users. The specific weight of water, γ, is the product of density and gravity. *Q* is the discharge from reservoir *r*, *H* is the pressure head at reservoir *r*, *q* is the demand at node *i*, *h* is the pressure head at node *i*. *R* is the number of reservoirs in the network and *N* is the number of nodes.

The Todini resilience index is the ratio between the surplus power delivered to consumers and the maximum power that can be dissipated in the network when meeting demand and head design criteria. The Todini index is computed as follows:

$$I_r = 1 - \frac{P^*_{\text{int}}}{P^*_{\text{max}}} = 1 - \frac{\gamma \sum_{r=1}^{R} Q_r H_r - \gamma \sum_{n=1}^{N} q^*_n h_n}{\gamma \sum_{r=1}^{R} Q_r H_r - \gamma \sum_{n=1}^{N} q^*_n h^*_n} = \frac{\sum_{n=1}^{N} q^*_n \left(h_n - h^*_n\right)}{\sum_{r=1}^{R} Q_r H_r - \sum_{n=1}^{N} q^*_n h^*_n}$$

where P_{int} is the power dissipated in network while satisfying demand criteria and P_{max} is the maximum power that would be dissipated internally in order to satisfy demand and head criteria. The demand criteria at each node is q^*_n and the head criteria at each node is h^*_n. Power introduced into the network from pumps can be added to the equation for Todini index.

Typically, the resilience index takes on values between 0 and 1, and higher values indicate higher resilience.

Prasad and Park (2004) later modified the resilience index to add a weighting factor based on the diameter of connecting pipes. The hydraulic reliability diagram is compared to the Todini index and the weighted Todini index in Trifunovic (2012).

A related metric, the Todini failure index, can be used to evaluate and compare the effects of pipe failures (Todini, 2000). While the resilience index allows some nodes with surplus power to compensate for nodes with deficient power, the failure index highlights the nodes incapable of providing enough power. The failure index is defined as follows:

$$I_f = \frac{\sum_{n=1}^{N} I_{fn}}{\sum_{n=1}^{N} q_n^* h_n^*} \quad \text{where} \quad I_{fn} = \begin{cases} 0 & \forall i : h_n \geq h_n^* \\ q_n^*\left(h_n - h_n^*\right) & \forall i : h_n < h_n^* \end{cases}$$

A smaller failure index indicates better performance. Seifollahi-Aghmiuni et al. (2013) use the failure index to evaluate network performance.

4.3.3 Entropy Reliability

The concept of entropy can be used as an indirect reliability metric to measure the number of alternate paths between source and demand nodes in a water distribution network in the presence of failed pipe(s). A network that carries maximum entropy flow is considered reliable with multiple alternate paths. Awumah et al. (1990, 1991), Awumah and Goulter (1992), and Tanyimboh and Templeman (1993, 2000) use entropy as a way to measure reliability in water distribution networks.

These methods modify the standard entropy equations for use with water distribution networks. A path parameter is added to count the number of independent paths from the water source to the customer node at a specific time. The number of independent paths is less than or equal to the total number of paths, which could be found using path enumeration. Entropy can be computed using flows calculated from EPANET. If failure events are considered, pressure driven or pressure corrected hydraulic simulations should be used. Entropy analysis can be used to track how the number of redundant paths changes over a wide range of hydraulic scenarios. Redundancy at any one node in the network depends on the redundancy of upstream nodes. Flow reversal, especially in light of a link failure, also contributes to redundancy of a node. This effect can be included in the entropy computation.

Awumah et al. (1990) define entropy using the following equation:

$$S'_j = -\sum_{i\in U_j}\left(\frac{q_{ij}}{Q'_j}\ln\frac{q_{ij}}{a_{ij}Q'_j}\right) - \sum_{k\in L_j}\left(\frac{q_{jk}}{Q'_j}\ln\frac{q_{jk}}{a_{jk}Q'_j}\right) \text{ where } a_{ij} = ND_{ij}\left[1-\sum_{k=1}^{MD_{ij}}(d_k-1)\Big/\sum_{k=1}^{MD_{ij}}d_k\right]$$

Here, S'_j is redundancy at node *j*, U_j is the set of nodes on the upstream ends of links connected to node *j*, L_j is the set of outflow links connected to node *j* in which the link *k* belongs to a loop containing j, q_{ij} is flow in link from node *i* to node *j*, Q'_j is the total of all flow leaving and entering node *j*, a_{ij} is the path parameter between nodes *i* and *j*, ND_{ij} is the number of independent paths through the link from node *i* to demand node *j*, MD_{ij} is the number of links in the ND_{ij} path, and d_k is the number of paths in which link *k* is a member. Average network entropy, *S*, is the average node redundancy over every demand node.

Maximizing average network entropy is equivalent to maximizing the ability of the network to supply flow to each node (maximizing redundancy). Average network entropy has been compared to node pair reliability (Quimpo and Shamsi, 1988) and percentage of demand supplied at adequate pressure (PSPF) (Awumah and Goulter, 1989). Results from this comparison show strong correlations, especially with PSPF. The authors note the relative ease of computing entropy compared to PSPF, which requires hydraulic simulation for each pipe removal. More recently, entropy and the resilience index were compared to exact calculations of reliability and the resilience index was shown to be a more accurate indicator of reliability than entropy (Creaco et al., 2014).

4.4 Standard Performance Measures

In water distribution systems analysis, additional common performance metrics include cost, pressure, and water quality. Such metrics might also be useful when calculating resilience. These metrics are defined below, and their relevance to evaluating resilience to hazards is discussed.

4.4.1 Cost

Water utilities operate on tight budgets to build and maintain water distribution systems. For that reason, cost is an important consideration when designing a new or retrofitting an existing water distribution system. The Battle of Water Networks II (BWN-II), a network optimization competition held at the Water Distribution Systems Analysis Conference in 2012, used cost, along with water quality, and greenhouse gas emissions metrics, to evaluate the performance of various network designs (Salomons, 2012). To evaluate cost, both the capital and operational costs associated with any change to the system have to be considered. Capital costs are related to purchases of new components and are dependent on the component size, labor, transportation, and installation. Operational costs are related to the energy costs associated with operating pumps and generators. Operational costs could also include maintenance costs.

In Salomons, 2012, cost was calculated using the following equation:

$$Cost = \sum_{c=1}^{C} \left(CC_c + OC_c \right)$$

where *Cost* is the total cost associated with system changes, CC_c is the capital cost of new component c and OC_c is the operational cost for new component c. Some components, like pipes, have no operational cost. BWN-II supplied capital and operational cost estimates for network components. The capital cost of pipes and valves increases with diameter and the capitol cost of tanks increases with volume. The operational cost of generators and pumps increases with the desired power output. Both capital and operational costs are annualized to reflect the total cost of maintenance and replacement associated with each component for one year.

For many of the water distribution system hazards listed in Figure 2, cost would be an important metric to use to account for upgrades required to enhance resilience to a given hazard, or to repair the system following an event.

4.4.2 Water Quality

Another metric used to evaluate performance of water distribution networks is water quality. Water quality was used to evaluate network design optimization in BWN-II (Salomons, 2012) and by Murray et al. (2010a) to compare design and retrofit strategies. In both instances, water age was used as a proxy for water quality. Water age is the time that a specific volume of water is in the water distribution system after leaving the treatment plant or reservoir. Water utilities try to minimize water age (also called residence time) as chlorine residuals are known to decay and disinfection byproducts increase over time. EPANET has a built in function to calculate water age at all nodes in the distribution system.

Murray et al. (2010b) compute the average water age in the network as follows:

$$A = \frac{1}{NT} \sum_{n=1}^{N} \sum_{t=1}^{T} A_{nt}$$

where *A* is the average water age, A_{nt} is the water age at junction *n* at time step *t* , *N* is the number of junctions, and *T* is the number of time steps. Murray et al. (2010a) simulated water quality under normal operating conditions over multiple days and averaged water age over the last 24 hours in the water quality simulation to compute water age.

BWN-II uses a modified water age metric in which water age is only meaningful if it is above a specified threshold that indicates potential water quality problems. Additionally, water age is weighted by demand to reflect that high quality water is needed at customer service nodes. If demand at a specific node and time is zero, then no water is consumed and water age at that node-time pair is not used in the calculation. More weight is given to water age as demand increases, which implies that the risk increases with consumption. Since water is not consumed at tanks and reservoirs, water age at those junctions is not included in the calculation. For BWN-II, average water age, weighted by demand, is computed as follows:

$$A = \frac{\sum_{n=1}^{N}\sum_{t=1}^{T} k_{nt} Q_{dem,nt} A_{nt}}{\sum_{n=1}^{N}\sum_{t=1}^{T} Q_{dem,nt}} \text{ where } k_{ij} = \begin{cases} 1 \text{ if } A_{nt} \geq A_{th} \\ 0 \text{ if } A_{nt} < A_{th} \end{cases}$$

where A is the average water age, A_{nt} is the water age at junction n at time t (tanks/reservoirs excluded), A_{th} is a water age threshold which is used to set k_{nt}, $Q_{dem,nt}$ is the demand at junction n and time step t, N is the number of junctions, and T is the number of time steps. For BWN-II, A_{th} was set to 48 hours and the water quality simulation was run for 1 week on an hourly time step. The water age metric was calculated over the entire simulation period and assessed during normal system operations.

For many of the water distribution system hazards listed in Figure 2, water age might not be a suitable metric. Water age would not capture changes in water quality due to contamination, cross-connections, or system intrusions. Using EPANET, a water quality metric could calculate chlorine residuals at each node in the network over time and report out the number of nodes not meeting a minimum concentration threshold. Or, the fate and transport of specific contaminants that enter the system could be modeled (e.g., total coliforms, hazardous release agents). The systems measure could be the total quantity of the contaminant that enters the system, or the number of hours the contaminant was present in the system. Both of these approaches would require detailed knowledge about mechanisms within the distribution system that affect the chlorine residual, for example, presence of biofilms on the pipe walls, presence of natural organic matter in the bulk water, the type and age of pipe materials, and the reaction kinetics of chlorine and specific contaminants. EPANET-MSX would be required to calculate these new water quality metrics.

4.4.3 Water Pressure

Water distribution networks must maintain adequate water pressure throughout the network to ensure continuity in service and for fire suppression. Low water pressure can result in flow reductions and high water pressure can cause leaks and damage to system components. Water pressures vary by communities, however, water pressure is typically maintained between 25 and 75 psi (Mays, 2000). Pressure is controlled in the network by pumps and the elevation of reservoirs and tanks. Aside from pipe leaks and water consumption, pressure is lost in the system due to pipe friction.

A systems analysis can be performed to ensure that a specific network meets pressure range requirements under normal operating conditions and when the system is stressed by component failure or changes to operations. EPANET can be used to calculate pressures at all nodes in the system. The number of nodes that satisfy the pressure requirement over the entire specified time period can be computed using the following equation:

$$N_p = \sum_{n=1}^{N} k_n \text{ where } k_n = \begin{cases} 1 \text{ if } \mathrm{P_L} \le p_{nt} \le \mathrm{P}_H \text{ for } 1 \le \mathrm{t} \le \mathrm{T} \\ 0 \text{ otherwise} \end{cases}$$

where N_p is number of nodes in the network that satisfy the pressure requirement, p_{nt} is the water pressure at junction *n* at time step *t* (tanks/reservoirs excluded), k_n is a binary variable set to 1 if the pressure requirement is satisfied at node n at time *t*, *N* is the number of junctions, and *T* is the number of time steps. Similarly, the average percentage of nodes over the entire specified time period that meet the pressure range requirement could be calculated.

Another important pressure measure indicates the ability of a system to provide an adequate amount of pressure to fight fires. Under fire-fighting flows, large amounts of water are pulled from a water distribution system; in residential areas, fire flows might range from 500-3,000 gallons per minute (gpm) while in commercial areas, fire flows might range from 2,500-10,000 gpm (Mays, 2000). The system must be able to maintain enough pressure to deliver the flow rate needed to fight the fire. Typically, pressures must be above 20 psi at hydrants to deliver adequate flow.

Murray et al. (2010b) measure the ability of the network to meet fire flow requirements as a means to compare design and retrofit strategies. Networks were tested under a maximum day demand pattern superimposed with a fire flow of 1,400 gpm. The number of nodes in each network able to maintain pressures above 20 psi during firefighting was calculated as:

$$N_F = \sum_{n=1}^{N} k_n \text{where } k_n = \begin{cases} 1 \text{ if } p_{ntf} \ge 20 \text{ psi for } \mathrm{t}_1 < t < \mathrm{t}_2, \text{for some f where } \mathrm{f}_1 < f < \mathrm{f}_2 \\ 0 \text{ otherwise} \end{cases}$$

where N_F is the number of nodes that meet fire flow pressure requirements during the time period of the fire flows, p_{ntf} is the water pressure at junction *n* at time step t for fire flow *f,* k_n is a binary variable that is set to 1 if the pressure at a specific node and time step meets fire flow regulation, otherwise, k_n is set equal to 0, t_1 and t_2 are the beginning and end of the firefighting period, and f_1 and f_2 are the minimum and maximum flow rates.

For many of the water distribution system hazards listed in Figure 2, the pressure range requirement might be a suitable metric. The concern would be that pipe breaks or other system failures would result in pressures that are too low. The fire flow pressure metric might be useful for measuring resilience to wildfires, earthquakes, and potentially chemical, biological, radiological and nuclear (CBRN) attacks or other hazards.

4.5 Other Performance Metrics

Other systems metrics have been proposed for water distribution systems for various purposes, and these might also be useful for measuring resilience. These metrics are defined below, and their relevance to evaluating resilience to hazards is discussed.

4.5.1 Greenhouse Gas Emissions

The BWN-II competition used greenhouse gas (GHG) emissions as a metric to evaluate network performance (Salomons, 2012). GHG emissions are important to consider given that water utilities might need to adhere to regulations that limit emissions in the future. GHG emissions are calculated by adding the capitol emissions associated with production, transport, and installation of pipes, tanks, and pumps with the operational emissions resulting from fossil fuel sources to operate pumps and generators. For BWN-II, GHG emissions is computed as follows:

$$\mathrm{GHG} = \sum_{c=1}^{C} \left(CE_c + OE_c \right)$$

where *GHG* is the GHG emissions of the network, CE_c is the capitol emissions from component *c* and OE_c is the operational emissions from component *c*. BWN-II supplied annualized CO_2 equivalent emissions to manufacture specific pipes which shows that GHG emissions increase with diameter. Operational GHG emissions is computed as the product of total annual pump energy in the network and an emission factor of 1.04 kg-CO2-e/kWh. Just as with the cost equation given in Section 4.4.1, some components have no operational cost. This metric is particularly relevant to measuring resilience to climate change.

4.5.2 Water Security

Metrics that evaluate how a network performs in the event that contamination enters the system have been used extensively to design sensor placement locations and response action plans (Murray et al. 2010a, Murray et al. 2010b, USEPA, 2013b). Water security metrics can be used to evaluate how potential contaminant incidents impact the population and the network. The impact of contamination in a network depends on several factors, including the contaminant type and strength, injection location and duration, fate and transport of the contaminant, the dose and response to that dose by the population, the time needed to detect and confirm contamination, and additional time needed to notify the public and implement corrective actions. Based on this uncertainty, water security metrics should be evaluated using an ensemble of possible contaminant scenarios and response times. Several water security metrics can be computed using the Water Security Toolkit (WST) Impact Assessment Module (USEPA, 2013b). These equations are summarized below. The water security metrics are particularly useful for measuring resilience to hazards causing contamination of drinking water: CBRN attacks and potentially floods, environmental emergencies, and others. The water security metrics defined above can be cast as a measure of risk if the probability of individual incidents is estimated.

4.5.2.1 Extent of Contamination

The extent of contamination, measured in length of contaminated pipe, for a particular scenario when contaminant is detected by a sensor at time *t'* is calculated using the following equation:

$$EC = \frac{1}{I}\sum_{i=1}^{I}\sum_{n=1}^{N} L_{\mathrm{int}'} \quad \text{if } C_{\mathrm{int}'} > C_{th}$$

where *EC* is the average extent of contamination across the entire network for a set of contamination incidents *I* when detected by a sensor at time t_i', $L_{int'}$ is the length of all pipes starting at node *n* that are contaminated at the time of detection, $C_{int'}$ is the contaminant concentration at node *n* at time t_i', and C_{th} is a contaminant threshold. *N* is the number of junctions. An entire pipe is considered contaminated once the contaminant enters the pipe. This metric is often used as a surrogate for the economic impacts of a contamination incident as it indicates the length of pipe that will need to be cleaned or decontaminated.

4.5.2.2 Mass and Volume Consumed

The average mass of contaminant consumed in the network (i.e. the mass of contaminant that leaves the water distribution network through customer demand nodes) and the average volume of contaminant consumed (i.e., the volume of contaminant that leaves the network through customer demand nodes) over a set of contamination incidents *I* when contaminant is by a sensor at time t_i', is calculated using the following equations:

$$MC = \frac{1}{I}\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{t=1}^{t'} C_{\mathrm{int}} q_{\mathrm{int}} \Delta T$$

$$VC = \frac{1}{I}\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{t=1}^{t'} q_{\mathrm{int}} \Delta T \ \text{ if } C_{\mathrm{int}} > C_{th}$$

where *MC* is the average mass of contamination consumed across the entire network when detected at a sensor at time t_i' and *VC* is the volume of contamination consumed across the entire network when detected at a sensor at time t_i'. C_{int} is the concentration of contaminant at node *n* and time step *t* for incident *i*, q_{int} is the demand at node *n* and time step *t*, and ΔT is the length of the time step. C_{th} is a contaminant threshold. *N* is the number of nodes, and *T* is the number of time steps. Concentration is typically expressed in units of milligrams per Liter (mg/L). This could also be a count of cells for a biological contaminant, where the units are cells/L.

4.5.2.3 Time to Detection

The time to detection is the time from the beginning of a contamination scenario until the contaminant is first detected at a sensor, averaged over all incidents, calculated by:

$$TD = \frac{1}{I}\sum_{i=1}^{I} t_i' \Delta T$$

where t_i' is the time step when concentration is first detected and ΔT is the length of the time step. The scenario is not detected if the concentration never goes above a specified threshold.

4.5.2.4 Population Health Impacts

The population-based human health metrics require dose and response information for each contaminant of interest. A disease progression model is used to predict the number of people at each node susceptible to illness from the contaminant, exposed to a lethal or infectious dose, experiencing symptoms of disease, and being fatally impacted. Population dosed *(PD)* is the average number of individuals that received a cumulative dose of contaminant above a specified threshold over a set of contamination scenarios *I*. Population exposed *(PE)* is the average number of individuals exposed to harmful level of contaminant over a set of contamination scenarios *I*. Population killed *(PK)* is the average number of individuals killed by a contaminant over a set of contamination scenarios *I*. The equations for these health impacts metrics are detailed in USEPA, 2013b.

4.5.3 Social Welfare Functions

Social welfare functions can be used to evaluate how well a water distribution network meets the needs of its water customers or the community at large. Social welfare functions use qualitative measures to evaluate a wide range of benefits to a society. To compute social welfare functions, metrics have to be explicitly defined and data is collected using surveys or through expert judgment. For example, social welfare functions can be used to measure the perceived value of the water system to the community, or how much the water users are willing to invest in infrastructure upgrades. Standard social welfare functions fall into one of three categories: the utilitarian social welfare function, the Bergsonian social welfare function, or the Rawlsian social welfare function. These functions differ in how stakeholders are weighted. Amit and Ramachandran (2009) suggest the use of social welfare functions to measure performance in water distribution networks. Hansen (2009) use social welfare functions to determine water scarcity pricing to combat water shortages.

Milman and Short (2008) proposes a Water Provision Resilience (WPR) indicator to assess the resilience of urban water systems. Their analysis estimates the ability of a water provider to provide access to safe drinking water in the future. The WPR indicator uses a qualitative survey of water utility experts to assess critical aspects of urban water system supply, infrastructure, service population, water quality and governance.

These social welfare functions do not currently utilize systems analysis methodologies and are therefore not recommended as resilience measures; however, some aspects of these approaches could be incorporated into resilience systems measures.

5 Discussion

While there is no single systems approach calculation to predict resilience of water distribution systems to a wide range of hazards, a large number of performance metrics for water distribution systems are available that might be helpful to quantitatively assess resilience to hazards. While some of these metrics might only be useful for certain hazards, many of the metrics might be useful for multiple types of hazards. It is important to note that none of these performance metrics have been validated or tested against recent disasters to date.

Resilience measures: The time-based resilience measures are promising as they provide detailed information about the benefits of resilience-enhancing actions. Such an approach allows a user to explicitly calculate the effects of response and recovery actions or other resilience-enhancing actions on all the system components and interactions. Much work is needed to develop usable time-based resilience measures for WDS. Approaches to model some response actions have already been developed (e.g., flushing hydrants, activating booster stations), but new modeling approaches will need to be developed for other, more complex and realistic actions. In the real world, response actions will include multiple actions at different times, and models will need to be able to account for this. Other resilience enhancing strategies might be undertaken in the mitigation phase rather than the response phase (e.g., decentralization of treatment and storage), and models need to be developed for such actions. Hazard scenarios need to be developed to incorporate the effects of natural disasters, terrorist attacks, and hazardous materials releases. Simulation software needs to be upgraded to more gracefully handle failures. Given the range of possible response scenarios, multiple realizations of responses will need to be simulated, perhaps using stochastic simulation approaches. Simulation software will need to be improved to minimize computational time and memory usage, especially for large water distribution system models.

Reliability measures: Currently, these are designed to measure the reliability of a WDS to pipe failures by ensuring multiple flow paths. Some of the measures are indirect (e.g., topological and Todini resilience index), while entropy is a direct calculation of flow paths. Some of the methods also consider additional stresses on systems, such as maximum day demands or fire flow conditions. As pipe breaks are a common outcome of many of the hazards listed in Figure 2, some of the reliability metrics, especially entropy, might prove to be useful. However, these measures will need to be extended to additional stressor scenarios more representative of conditions following a hazard (e.g., multiple pipe breaks throughout a WDS, failures of pumps or valves, loss of access to storage tanks or sources). Stochastic simulation methods will need to be developed to simulate these scenarios. To support the use of these reliability measures, the simulation software will need to be extended to more gracefully handle failures by continuing to produce results even under abnormal conditions. Separately, the topological reliability metrics might be useful as a screening step, prior to more in-depth analyses.

Other measures: Cost is always an important metric that is needed in order to prioritize actions and plan for expenditures. Cost information will need to be collected and updated on a regular basis in order for this to be a useful metric. Water quality is critical to a water utility's mission and, therefore, this is an important measure to include to ensure that any resilience actions or upgrades do not negatively impact water quality. Accurate water quality modeling can be difficult as there is little data available from within WDS about biofilms, natural organic matter, sediments and other substances that interact with disinfectant residuals; improved water quality models and data are needed to support this measure. The water security measures are useful for understanding the effects of CBRN releases, other hazardous materials releases, and other hazards that cause the release of contaminants into the WDS. Some of the water security measures require information about specific contaminants, their behavior in WDS, and their health effects. Finally, GHG emissions is a useful measure for climate change scenarios.

In order to investigate the utility of each of these measures to calculating the resilience of WDS to hazards, EPA and Sandia National Laboratories have partnered to develop a prototype software tool to support resilience research. This tool uses water distribution network models (in EPANET format) to compute a wide range of WDS performance metrics. The tool leverages the EPANET toolkit (Rossman, 2000), third-party software designed to analyze and visualize the structure of complex networks (Hagberg, 2008), and custom algorithms to compute resilience in water distribution networks. This tool is being expanded to address some of the weaknesses in WDS systems modeling tools described above. Ultimately, this tool is intended to support water utilities, as a customizable way to investigate the resilience of their WDS to a wide range of hazardous scenarios, and to evaluate resilience-enhancing actions.

Extensions to existing systems modeling approaches are necessary to enable analysis of all of the hazards listed in Figure 2 . Many of the hazards are likely to result in pipe breaks, causing an abrupt change in flow patterns and pressures. EPANET is considered a "demand-driven" model, but pressure-driven models and pressure-corrected models are available that might be better suited to handle pipe breaks. With demand-driven simulation, customer water demand must be met even if the pressure in the network decreases. When the demand condition cannot be met, the simulation results are no longer meaningful. To get around this limitation, simulated demand can be corrected based on a minimum pressure threshold (Wagner et al., 1988b) or nodes can be changed to virtual tanks to supply demand when pressure is low (Trifunovic, 2012). Alternatively, pressure-driven simulation methods have been proposed. Pathirana (2010) used an emitter based algorithm for pressure-driven simulations to develop an add-on to EPANET. WaterNetGen also includes an EPANET extension for pressure driven analysis (Muranho, 2012). Laucelli et al. (2012) compared the use of demand-driven and pressure-driven simulation under different scenarios including climate uncertainty and asset deterioration and conclude that pressure-driven simulation should be used to estimate the hydraulic capacity of the network under these scenarios.

In addition, simulation tools need to be adapted to allow them to fail more gracefully; in other words, rather than stopping a simulation when certain required demands or pressures cannot be met, parts of the system could be allowed to fail, while other parts remain operational. Additionally, models will need to be able to incorporate uncertainty in hazard scenarios and in utility response strategies. Such changes and more will need to be made to water distribution system models in order to allow for accurate modeling of hazardous events.

To summarize, systems modeling approaches need the following enhancements to adequately address resilience of water systems to hazards:

- Improvements to hydraulic and water quality software
    - Ability to alter hydraulics mid simulation to better represent response scenarios
    - Ability to compute reasonable results during abnormal operating conditions and system failure
    - Ability to support fast initialization from previous results, as well as “snap-shots” from which a series of scenarios could be run
    - Mathematical models of reaction dynamics for accurate water quality analysis
    - Use of pressure driven or demand driven models when most appropriate
    - Connections to field (SCADA) data to enable real time application of results
    - Ability to propagate uncertainty through a single simulation (rather than requiring separate scenario runs)
- Improvements to network models
    - Updated, validated utility network models to ensure accuracy and usability of results
    - Access to field (SCADA) data in order to improve model predictions
- Improvements to model applications
    - Set of scenarios to represent realistic disaster impacts and responses, including pipe breaks, pump failures, power outages, control valve failures, insufficient

storage capacity, multiple stresses occurring at the same time, fire-fighting conditions, and water quality failures

- Incorporation of uncertainty

6 Conclusions

Resilience is a concept that is being used increasingly to refer to the capacity of infrastructure systems to be prepared for and able to respond effectively and rapidly to hazardous events. In Section 2 of this report, drinking water hazards, resilience literature, and available resilience tools are presented. Broader definitions, attributes and methods for measuring resilience are presented in Section 3. In Section 4, quantitative systems performance measures for water distribution systems are presented. Finally, in Section 5, the performance measures and their relevance to measuring the resilience of water systems to hazards is discussed along with needed improvements to water distribution system modeling tools.

Drinking water systems are subject to a range of hazards, from natural disasters to man-made disasters such as terrorist attacks or hazardous material releases. The impacts of such events on drinking water systems can include pipe breaks, service disruptions, power outages, loss of public confidence, and more. Recent literature has focused on providing guidance to water systems on increasing preparedness for disasters and guidance to planning for emergency response and recovery. In addition, several tools have been developed for the water sector, including the Community Based Water Resiliency (CBWR) tool and the Climate Resilience Evaluation and Awareness Tool (CREAT). The Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Drinking Water and Wastewater Systems presents an approach for measuring resilience. The Argonne National Laboratory Resilience Index helps to measure resilience of water systems but is intended to be conducted by the Department of Homeland Security rather than being used as a self-assessment tool.

Resilience is a broad concept and is used widely across many fields. Disaster resilience incorporates many similar concepts such as reducing risk or vulnerability, enhancing preparedness, and response; however, resilience differs from these concepts in that it also includes the ability to effectively and rapidly recover from unforeseen events. Resilience is a property of a system, and common attributes of resilient systems include redundancy, robustness, rapid recovery, resourcefulness and adaptability. Methods of measuring resilience include developing a composite index incorporating diverse information from multiple fields or using systems modeling approaches to explicitly calculate the effects of hazards on a system and its interacting components. Systems modeling tools are available for water distribution systems, and this report investigates the use of these models.

Although there is not a single measure suitable for measuring the resilience of water systems to hazards, multiple performance measures might be useful. Resilience measures include risk-based qualitative approaches and systems-based quantitative approaches. Time-based resilience measures simulate the system before, during, and after an event and allow for the explicit evaluation of the impacts of resilience-enhancing actions. Reliability measures calculate the ability of a water distribution system to meet pressure and flow requirements under normal and emergency conditions, and fall into three categories: topological, hydraulic, and entropy-based. Other performance measures, such as cost, water quality, and water security are also useful measures.

Finally, these measures are evaluated for their ability to inform resilience. In particular, the time-based resilience measure, the entropy measure, cost, water quality, and water security measures are likely to be effective. All of these measures, however, will require modifications to existing systems analysis modeling tools in order to be used to inform resilience. New scenarios need to be developed to allow for the explicit modeling of hazards and their effects on water systems, especially natural disasters. Existing software, like EPANET, needs to be modified to allow for failure of components in some parts of a system, while remaining operational in other parts. These tools need to incorporate uncertainty inherent in the disaster scenarios and in the utility response, using Monte Carlo or stochastic simulation approaches. By enhancing systems-modeling tools and enabling network models to robustly handle failures and stresses, a comprehensive evaluation of the benefits of each resilience metric can be conducted, and improved resilience tools can be provided to the water sector.

References

ABAG Earthquake & Hazards Program. (2009). Water Systems and Disasters. San Fransico, CA: ABAG Earthquake & Hazards Program.

Ajami NK, Truelove C. (2014). A water-energy research agenda: building California's policy foundation for the 21st century. Stanford, CA: Water in the West, Stanford University. Accessed September 19, 2014, http://waterinthewest.stanford.edu/sites/default/files/Water-Energy%20Agenda-%20final-042514.pdf

American Water Works Association (AWWA), 2014. Process Control System Security Guidance for the Water Sector. American Water Works Association.

Amit RK, Ramachandran P. (2009). Optimal design of water distribution networks: A review. The Selected Works of R K Amit. Accessed September 19, 2014, http://works.bepress.com/rkamit/7

ANSI. (2010). Risk Analysis and Management for Critical Asset Protection (RAMCAP®) Standard for Risk and Resilience Management of Water and Wastewater Systems, 2010, ANSI/ASME-ITI/AWWA J-100-10.

ASCE. (2008). Recovery Practices Primer for Natural Disasters. Produced under the Water Infrastructure Security Enhancements (WISE) Initiative by the American Society of Civil Engineers (ASCE), American Water Works Association (AWWA), and the Water Environment Foundation (WEF).

Attoh-Okine NO, Cooper AT, Mensah SA. (2009). Formulation of resilience index of urban infrastructure using belief functions. *IEEE Systems Journal*, 3(2), pp. 147-153.

Awumah K, Goulter I, Bhatt SK. (1990). Assessment of reliability in water distribution networks using entropy based measures. *Stochastic Hydrology and Hydraulics*, 4(4), 309-320

Awumah K, Goulter I. (1989). Redundancy and reliability of water distribution networks: An entropy based approach. Presented at the 1989 National Conference on Hydraulic Engineering; August 14-18, 1989, New Orleans, Louisiana, United States. In: Ports, M., ed., Proceedings of 1989 ASCE National Conference on Hydraulic Engineering, pp. 768-773.

Awumah K, Goulter I. (1992). Maximizing entropy defined reliability of water distribution networks. *Engineering Optimization*, 20(1), 57-80.

Awumah K, Goulter IC, Bhatt SK. (1991). Entropy-based redundancy measures in water distribution networks. *Journal of Hydraulic Engineering*, 117(5), 595-614.

Ayyub BM. (2013). System resilience for multihazard environments: Definitions, metrics, and valuation for decision making. *Risk Analysis*, 34(2), 340-355.

Bao Y, Mays LW. (1990). Model for water distribution system reliability. *Journal of Hydraulic Engineering*, 116(9), 1119–1137.

Barker K, Ramirez-Marquez JE, Rocco CM. (2013). Resilience-based network component importance measures. *Reliability Engineering and System Safety*, 117, 89–97.

Berry J, Hart WE, Phillips CA, Uber JG, Watson JP. (2006). Sensor placement in municipal water networks with temporal integer programming models. *Journal of Water Resources Planning and Management*, 132(4), 218-224.

Berry J, Boman E, Riesen L, Hart WE, Phillips CA, Watson JP, and U.S. Environmental Protection Agency. TEVA-SPOT Toolkit and user's manual- version 2.5.2. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/041B, 2012.

CARRI. (2014). Community and Regional Resilience Institute. Accessed September 19, 2014, http://www.resilientus.org/about-us/what-is-community-resilience/

Chang SE. (2010). Urban disaster recovery: a measurement framework and its application to the 1995 Kobe earthquake. *Disasters* 34(2), 303-327.

CIPAC Workgroup. (2009). All Hazard Consequence Management Planning for the Water Sector. Produced by the Preparedness, Emergency Response, and Recovery CIPAC Workgroup of the Water Sector Critical Infrastructure Partnership Advisory Council (CIPAC). Accessed September 19, 2014, http://www.wef.org/uploadedFiles/Access_Water_Knowledge/Water_Security/Water_Security_PDFs/All-HazardCMPNovember2009FINAL.pdf

Concho Valley Council of Governments, Section 11 – Winter Storm. In: Hazard Mitigation Plan Update, 2012-2017, Concho Valley, Austin, TX: Concho Valley Council of Governments.

Creaco E, Fortunato A, Franchini M, and Mazzola, MR. (2014) Comparison between entropy and resilience as indirect measures of reliability in the framework of water distribution system design, *Proceedings of the 12th International Conference on Computing and Control for the Water Industry* (CCWI), Procedia Engineering 70(2014): 379-388.

Davis CA. (2013). Water System Seismic Resilience & Retrofit Strategies. In: *Water Utility Infrastructure Management Conference*, July 17, 2013, Costa Mesa, CA.

DiGiano F, and Grayman W. (2014).Can we better protect vulnerable water supplies? JAWWA, April 2014, 28-30.

Fiksel J. (2003). Designing resilient, sustainable systems. *Environmental Science & Technology*, 37(23), 5330-5339.

Fiksel J. (2006). Sustainability and Resilience: toward a systems approach. Sustainability: Science, Practice, and Policy. Volume 2 (2): 14-21

Fiksel J, Goodman I, Hecht A. (2014) Resilience: Navigating a Sustainable Future. *Solutions*, Vol. 5, Issue 5, September/October 2014.

Fisher RE et al. (2010) Constructing a Resilience Index for the Enhanced Critical Infrastructure Recovery Program. Lemont, IL: Argonne National Laboratory. ANL/DIS-10-9.

Francis R, Bekera B. (2013). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety*, 121, 90-103.

FSIN. (2014). Resilience Measurement Principles: Toward an Agenda for Measurement Design. World Food Program's Food Security Information Network.

Fujiwara O, Ganesharajah T. (1993). Reliability assessment of water supply systems with storage and distribution networks. *Water Resources Research*, 29(8), 2917-2924.

Gebhart BJ, Johnson S. (2014). The 500 Year Flood, One Year Later, Nine Lessons (Re)Learned. *Stormwater*, July/August 2014.

Gilbert, SW. (2010). Disaster Resilience: A Guide to the Literature, NIST Special Publication 1117. Gaithersburg, MD: U. S. Department of Commerce, National Institute of Standards and Technology (NIST).

Goulter I. (1987). Current and future use of systems analysis in water distribution networks design. *Civil Engineering Systems*, 4(4), 175-184.

Grayman WM, Murray R, Savic DA. (2009). Effects of redesign of water systems for security and water quality factors. In: Proceedings of the World Environmental and Water Resources Congress 2009, Kansas City, MO, May 17-21, pp. 1-11.

Hagberg AA, Schult DA, Swart PJ. (2008). Exploring network structure, dynamics, and function using NetworkX. In: G Varoquaux, Vaught T, Millman J, eds., Proceedings of the 7th Python in Science Conference (SciPy2008), Pasadena, CA, August 19-24, pp. 11-15.

Hansen JK. (2009). Estimating impacts of water scarcity pricing. In: 27th International Conference of the System Dynamics Society, July 26-30, 2009, Albuquerque, New Mexico.

Henry D, Ramirez-Marquez JE. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering and System Safety*, 99, 114–122.

International Federation of Red Cross (IFRC). (2011). Characteristics of a Safe and Resilient Community: Community Based Disaster Risk Reduction Study. 1224200 E 5/2012.

Jacobs P, Goulter I. (1988). Evaluation of methods for decomposition of water distribution networks for reliability analysis. *Civil Engineering Systems*, 5(2), 58-64.

Jacobs P, Goulter I. (1989). Optimization of redundancy in water distribution networks using graph theoretic principles. *Engineering Optimization*, 15(1), 71-82.

The Johnson Foundation. (2013). Building Resilient Utilities: How Water and Electric Utilities Can Co-Create Their Futures. Racine, WI: The Johnson Foundation at Wingspread. Accessed on September 19, 2014, http://www.johnsonfdn.org/sites/default/files/reports_publications/CNW_ResilientUtilities.pdf

Lansey K. (2013). Sustainable, robust, resilient, water distribution systems. In: WDSA 2012: 14th Water Distribution Systems Analysis Conference, Sept 24-27, 2012 in Adelaide, South Australia 1-18.

Laucelli D, Berardi L, Giustolisi O. (2012). Assessing climate change and asset deterioration impacts on water distribution networks: Demand-driven or pressure-driven network modeling? *Environmental Modelling and Software*, 37, 206-216.

Le Chevallier MW, Chelius JJ. (2014). Resiliency Planning Ensures Better Outcomes, *Opflow,* 40(1), 16-18.

Llanos M. (2011). 700 water main breaks in Houston - a day. Today – NBC News, 16 August 2011. [Online]. Accessed 6 June 2014, http://www.today.com/id/44160515/ns/today-weather/t/water-main-breaks-houston-day/#.U57mtfldU1I.

Mays LW. (1996). Review of reliability analysis of water distribution systems. In: Xu IC, Tickle KS, Wasimi S (eds.), Stochastic Hydraulics '96, Seventh IAHR International Symposium, Mackay, Queensland, Australia, pp 53-62.

Mays LW. (1989). Reliability Analysis of Water Distribution Systems. Reston, VA: ASCE Publications.

Mays LW. (2000). Water distribution systems handbook. New York: McGraw-Hill Professional.

McAllister T. (2013). Developing Guidelines and Standards for Disaster Resilience of the Built Environment: A Research Needs Assessment, NIST TN 1795, 2013. Gaithersburg, MD: National Institutes of Standards and Technology (NIST). Accessed on September 19, 2014, http://www.nist.gov/manuscript-publication-search.cfm?pub_id=912299

Milman A, Short A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change*, 18(4), 758-767.

Muranho J, Ferreira A, Sousa J, Gomes A, Sá Marques A. (2012). WaterNetGen - an EPANET extension for automatic water distribution networks models generation and pipe sizing. *Water Science and Technology: Water Supply*, 12(1), 117-123.

Murray R, Haxton T, Janke R, Hart WE, Berry J, Phillips C. (2010a). Sensor network design for drinking water contamination warning systems: A compendium of research results and case studies using the TEVA-SPOT software. [Technical Report] Cincinnati, OH: U. S. Environmental Protection Agency. EPA/600/R-09/141

Murray RE, Grayman WM, Savic DA, Farmani R. (2010b). Effects of DMA redesign on water distribution system performance. In: Boxall J, Maksimovic C, eds., Proceedings of the 10th International on Computing and Control for the Water Industry, CCWI 2009, University of Sheffield, UK. CRC Press: Boca Raton, FL, pp. 645-650.

National Academy of Sciences (NAS). (2012). Disaster Resilience: A National Imperative, prepared by the NAS Committee on Science, Engineering, and Public Policy. Washington, DC: The National Academies Press.

National Infrastructure Advisory Council (NIAC). (2009). Critical Infrastructure Resilience, Final Report and Recommendations, U.S. Department of Homeland Security, Washington, D.C., Accessed September 20, 2014.
http://www.dhs.gov/xlibrary/assets/niac/niac_critical_infrastructure_resilience.pdf.

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

Osnos, E. (2014). Chemical Valley: the coal industry, the politicians, and the big spill. *The New Yorker*, April 7, 2014.

Ostfeld A, Kogan D, Shamir U. (2002). Reliability simulation of water distribution systems – single and multiquality. *Urban Water*, 4, 53-61.

Ostfeld A. (2001). Reliability analysis of regional water distribution systems. *Urban Water*, 3(4), 253-260.

Ostfeld A. (2004). Reliability analysis of water distribution systems. *Journal of Hydroinformatics*, 6, 281-294.

Ozger SS. (2003). A semi-pressure-driven approach to reliability assessment of water distribution networks, PhD Dissertation. Tempe, AZ: Department of Civil and Environmental Engineering, Arizona State University.

Pandit A, Crittenden JC. (2012). Index for network resilience (INR) for urban water distribution systems. 2012 Critical Infrastructure Symposium, Session 1A: Infrastructure Network Analysis. April 23, 2012, Arlington, VA.

Pathirana A. (2011), EPANET2 Desktop Application for Pressure Driven Demand Modeling. In: Lansey KE, Choi CY, Ostfeld A, Pepper I (eds.), Proceedings of the 12th Annual Conference of Water Distribution System Analysis 2010 - WDSA2010, Sept. 12-15, Tucson, AZ.

Prasad TD, Park NS. (2004). Multiobjective genetic algorithms for design of water distribution networks. *Journal of Water Resources Planning and Management*, 130(1), p 73–82.

Quimpo RG, Shamsi U. (1988). Network reliability for water distribution system management. In: Proceedings of the 5th IAHR Symposium on Stochastic Hydraulics, University of Birmingham, U.K, August 2-4.

Quimpo RG, Shamsi UM. (1991). Reliability based distribution system maintenance. *Journal of Water Resources Planning and Management*, 117(3), 321–339.

Reed D, Stephenson R, Hyland S. (2013). Recovering from Hurricane Sandy: Coordination, planning bolster storm response, *Opflow,* 39(5), 10-14.

Resilience Alliance. (2010). Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners. Version 2.0, 2010, Resilience Alliance.

Rossman LA. (2000). EPANET 2 Users Manual. [Technical report] Cincinnati, OH: U. S. Environmental Protection Agency. EPA/600/R-00/057

Salomons E, Ostfeld A, Kapelan Z, Zecchin A, Marchi A, Simpson A. (2012). The battle of the water networks II – Adelaide 2012 (BWN-II). In: Proceedings of the 2012 Water Distribution Systems Analysis Conference, September 24-27, Adelaide, South Australia, Australia.

Scharfenaker M. (2006). Katrina stories highlight new realities of disaster planning, *Journal of the American Water Works Association,* 98(6),16-30.

Seifollahi-Aghmiuni S, Bozorg Haddad O, Mariño MA. (2013). Water distribution network risk analysis under simultaneous consumption and roughness uncertainties. *Water Resources Management*, 27(7), 2595-2610.

Sewerage and Water Board of New Orleans. (2013). Katrina 8 Years Later, Progress, Recovery, Restoration and Rebuilding. New Orleans: The Sewerage and Water Board of New Orleans.

Shamsi UM. (1990). Computerized evaluation of water-supply reliability. *IEEE Transactions on Reliability*, 39(1), 35-41.

Shang F, Uber J, Rossman L. (2008). EPANET multi-species extension user's manual. Technical Report. Cincinnati, OH: US Environmental Protection Agency. EPA/600/S-07/021

Shen Y, Vairavamoorthy K. (2005). Small world phenomena in water distribution network. *Computing in Civil Engineering*, pp. 1-7.

Su YC, Mays LW, Duan N, Lansey KE. (1987). Reliability-based optimization model for water distribution systems. *Journal of Hydraulic Engineering*, 113(12), 1539-1556.

Tanyimboh TT, Templeman AB. (1993). Maximum entropy flows for single-source networks. *Engineering Optimization*, 22(1), 49-63.

Tanyimboh TT, Templeman AB. (2000). A quantified assessment of the relationship between the reliability and entropy of water distribution systems. *Engineering Optimization*, 33(2), 179-199.

Tierney K, Bruneau M. (2007). Conceptualizing and Measuring Resilience: A Key to Disaster Loss Reduction. *TR News*, National Academies, Transportation Research Board, May-June 2007.

Todini E. (2000). Looped water distribution networks design using a resilience index based heuristic approach. *Urban Water*, 2(2), 115-122.

Trifunovic N. (2012), Pattern Recognition for Reliability Assessment of Water Distribution Networks, PhD Dissertation, Delft University of Technology, Delft, Netherlands.

UN-Water Taskforce on Water Security. (2013). Water Security and the Global Water Agenda: A UN-Water Analytical Brief. Hamilton, Ontario, Canada: United Nations University, Institute for Water, Environment & Health.

US Department of Energy. (2014). The Water Energy Nexus: Challenges and Opportunities. Washington, DC: U.S. Department of Energy. Accessed on September 19, 2014, http://energy.gov/sites/prod/files/2014/06/f16/Water%20Energy%20Nexus%20Report%20June%202014.pdf

US Environmental Protection Agency (USEPA). (2010). Water Contaminant Information Tool (WCIT): A Robust Tool for the Water Sector. U. S. Environmental Protection Agency, Office of Water: Washington, DC. EPA 817/F-10/016.

USEPA (2011). Community Based Water Resiliency Electronic Tool. U. S. Environmental Protection Agency, Office of Water: Washington, DC. EPA 817/C-11/001. Accessed September 20, 2014, http://water.epa.gov/infrastructure/watersecurity/communities.

USEPA. (2012a). Climate Resilience Evaluation and Awareness Tool (CREAT). Washington, DC: U. S. Environmental Protection Agency, Office of Water. Accessed September 19, 2014, http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm

USEPA. (2012b). National Water Program 2012 Strategy: Response to Climate Change. Washington, DC: U. S. Environmental Protection Agency, Office of Water.

USEPA. (2012c). CANARY User's Manual version 4.3.2. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/040B, 2012.

USEPA. (2013a). Adaptation Strategies Guide for Water Utilities. Washington DC: U. S. Environmental Protection Agency. EPA 817/K-13/001. Accessed September 19, 2014, http://water.epa.gov/infrastructure/watersecurity/climate/upload/epa817k13001.pdf

USEPA. (2013b). Water Security Toolkit User Manual Version 1.1. [Technical Report]. Washington, DC: U.S. Environmental Protection Agency. EPA/600/R-13/353.

USEPA. (2013c). THREAT ENSEMBLE VULNERABILITY ASSESSMENT- SENSOR PLACEMENT OPTIMIZATION TOOL (TEVA-SPOT) GRAPHICAL USER INTERFACE. (2013c). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-13/014, 2013.

USEPA. (2014a). Planning for Flood Recovery and Long-Term Resilience in Vermont: Smart Growth Approaches for Disaster-Resilient Communities. Washington, DC: U. S. Environmental Protection Agency. EPA 231-R-14-003.

USEPA. (2014b). Water Security Home Website. U. S. Environmental Protection Agency. Accessed September 19, 2014, http://water.epa.gov/infrastructure/watersecurity/index.cfm

USEPA (2014c). Flood Resilience: A Basic Guide for Water and Wastewater utilities. Washington, DC: U. S. Environmental Protection Agency. EPA 817-B-14-006.

USEPA. (2014d). EPANET-RTX Libraries. EPANET-RTX 1.1. Accessed on September 20, 2014, http://openwateranalytics.github.io/epanet-rtx/index.html,.

Vermont Agency of Natural Resources. (2011). Tropical Storm Irene by the Numbers. Accessed Feb. 6, 2014, http://www.anr.state.vt.us/anr/climatechange/irenebythenumbers.html

Wagner JM, Shamir U, Marks DH. (1988a). Water distribution reliability: Analytical methods. *Journal of Water Resources Planning and Management,* 114(3), 253-275.

Wagner JM, Shamir U, Marks DH. (1988b). Water distribution reliability: Simulation methods. *Journal of Water Resources Planning and Management,* 114(3), 276-293.

WARN (Water/Wastewater Agency Response Network). (2013). Superstorm Sandy After-Action Report. Denver, CO: American Water Works Association.

Watts DJ, Strogatz SH. (1998). Collective dynamics of 'small-world' networks. *Nature*, 393, 440-442.

Welter, G. (2009). Natural disasters: Are you prepared? *Opflow,* 35(6), 12-16.

Yazdani, A. and Jeffrey, P. (2011). Complex network analysis of water distribution systems. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 21(1), 016111.