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Future of Water Distribution Modeling and Data Analytics Tools

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Future of Homeland Security Research Program's Water Distribution Modeling and Data Analytics Tools

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A portion of the research described here included interviews, which were done in accordance with the Paperwork Reduction Act. In addition, the interviews and the panel workshop were conducted as a peer review effort to obtain comments, suggestions, and new ideas from a broad and diverse group of reviewers.

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Abbreviations

AWWA	American Water Works Association
CWS	contamination warning system
DBP	disinfection byproduct
EPA	U.S. Environmental Protection Agency
EWRI	Environmental and Water Resources Institute
GIS	geographic information system
HSPD	Homeland Security Presidential Directive
HSRP	Homeland Security Research Program
MSX	EPANET Multi-Species eXtension
PPD	Presidential Policy Directive
RTX	EPANET Real-time eXtension
SCADA	supervisory control and data acquisition
TEVA-SPOT	Threat Ensemble Vulnerability Assessment - Sensor Placement Optimization Tool
WNTR	Water Network Tool for Resilience
WST	Water Security Toolkit

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Executive Summary

The U.S. Environmental Protection Agency's (EPA) Homeland Security Research Program's (HSRP) mission is to focus on the research questions, needs, and response capabilities to help communities deal with environmental catastrophes. One research objective is improving the ability of water utilities to prevent, prepare for, respond to and recover from water contamination incidents that threaten public health. To assist in this objective, HSRP has been developing research prototype software tools that can help the drinking water industry in analyzing the security and resilience of water distribution systems to all emergency situations, including both man-made and natural disasters.

In 2016, HSRP conducted a project to help review the existing water distribution system modeling program and identify a path forward for their water distribution system modeling and data analytical tools. The project focused on the state of the science, engagement with the water sector, and functionality improvements for the tools. To assist in outlining a path forward, the project involved conducting interviews with the water distribution system community, reviewing other resources that identified future directions in the drinking water field, and hosting a workshop with experts to obtain their suggestions for the future. Representatives from the drinking water sector, including utilities, professional organizations, software vendors, consultants, academic researchers, and government employees, were included in the interviews and workshop.

The water distribution modeling and data analytical tools that HSRP and their partners have developed to help the water community throughout an emergency include Threat Ensemble Vulnerability Assessment - Sensor Placement Optimization Tool (TEVA-SPOT), CANARY, EPANET Multi-Species eXtension (MSX), EPANET Real-Time eXtension (RTX) libraries, Water Security Toolkit (WST), and Water Network Tool for Resilience (WNTR). Research is also being conducted to better simulate and understand water quality within the plumbing system within buildings. The tools are described in more detail in the report section, Water Distribution System Modeling Tools.

The first step in the review was a series of interviews with subject matter experts from the drinking water community (e.g., drinking water utilities, engineering consultants, software developers/vendors, government, academia) that represented a diverse range of backgrounds, positions, and perspectives within the water industry and the government. The interviewers provided their observations on the barriers and obstacles to using water security and resilience tools, the technical gaps of the tools and/or research needs, and collaboration opportunities between HSRP and the water community. A more detailed summary is presented in the report section, Expert Interviews Prior to Workshop. The following are examples of the provided suggestions:

- Software tools need to be easy to install and use, since water utilities often do not have enough staff or time.
- Water security software tools need to support the day-to-day operations of the utility in addition to water security.
- More basic research on the fate and transport of contaminants within the distribution system is needed.

- A calibrated network model is important to integrate with hydraulic and water quality monitoring data to provide a better understanding of dynamics within the distribution system.
- EPA should connect, talk, and work directly with water utilities to encourage the usage of HSRP's tools.

The second part of the project involved identifying future trends in the industry. This included a series of Environmental and Water Resources Institute (EWRI) committee interviews with water distribution system analysis professionals; a report on trends in water distribution system analysis by an American Water Works Association (AWWA) committee; and an article on a vision for what water distribution systems might look like in the year 2050. These resources identified that aging water infrastructure, infrastructure assessment, real-time modeling and advanced analytics, and research/innovation are topics of interest in this field. In addition, recommendations for the vision and future development of EPANET was collected during the EPANET Visioning Summit held in Reston, Virginia on April 3-4, 2018, since EPANET is an important component of many of HSRP's water security and resilience modeling tools.

The final part of the project involved hosting a workshop with a panel of experts and other participants. On April 9-10, 2018, EPA held the Water Security, Response, Resilience Modeling and Data Analytic Tools Workshop. The purpose of the peer-review workshop was to obtain additional comments, suggestions, and new ideas for HSRP's water security and resilience tools to assist in the development of a path-forward strategy for the tools to support water utility needs. Five drinking water subject matter experts formed the panel, while other water professional experts participated in the discussions. The workshop provided an opportunity to share information regarding the state of the science for drinking water system security and resilience. The workshop included presentations about HSRP's modeling program, discussions on the drinking water industry's future directions and needs, presentations and discussions of HSRP's modeling tools, and suggestions for the future of these tools. A few of the suggestions are listed below, while additional suggestions are provided in the report section, Expert Peer Review Workshop.

- Focus on the day-to-day operation of utilities more than on rare incidents like terrorist acts and natural disasters.
- Seek better input and feedback from different stakeholders (e.g., large utilities, small utilities, consultants) throughout the development process as they have different needs.
- Continue development of fundamental tools that can be adapted by software companies to provide enhancements and roll out to utilities.

Overall, this project highlighted some commonality within the drinking water community. One key message was to ensure the accuracy of the network model since it needs to reflect real operating conditions within the water distribution system. This can often be accomplished by creating a real-time model to depict the actual system dynamics by linking system hydraulic data (e.g., flows, pressures, tank levels) with the network model. The review highlighted that real-time modeling is a direction that the water industry is moving towards. Another key message was the need for accurate representation of the water quality within the distribution system. This can be achieved by collecting more experimental data on the fate of different water constituents to understand how they react with one another, developing more detailed fate/reaction equations, and linking this information with water quality data collected in the distribution. The goal would be providing a more complete understanding of the water quality in the system in real-time. Collaboration was another focus area identified during the project. Experts emphasized that it was important to engage with the water community through all phases of research to understand the problems that the industry is facing, develop solutions for these problems, and transfer the solutions to the industry. In addition, the need for user-friendly modeling and data analytic tools that assist with the day-to-day operation of the water distribution system was highlighted. Specific suggestions for the improvements for each individual tool are provided in the Project Conclusions section of the report.

1 Introduction

National security has been a responsibility of U.S. Environmental Protection Agency's (EPA) for a long time. Executive Order 12656 (signed November 1988), titled "Assignment of Emergency Preparedness Responsibilities," directs EPA to take on two responsibilities: (1) develop guidance on acceptable emergency levels of chemical, nuclear, and biological materials and (2) develop plans to ensure the availability of potable water after a national security incident. Other legislative acts have also shaped EPA's role in responding to national security emergencies, including the Comprehensive Environmental Response, Compensation and Liability Act, the Emergency Planning and Community Right-to-Know Act, and the Clean Water Act, as well as others. Shortly after the events of September 11, 2001, the National Strategy for Homeland Security (OHS, 2002) was developed, which outlined specific objectives for protecting critical infrastructure, defending against catastrophic threats, and preparing and responding to emergencies.

EPA's responsibilities for water security were further mandated in the Public Health Security and Bioterrorism Preparedness and Response Act (Bioterrorism Act) of 2002, and a series of Homeland Security Presidential Directives (HSPDs). Three HSPDs directly affect EPA's role in national emergencies, namely HSPDs-5, 7, and 8, which deal with national incident management system and response, critical infrastructure prioritization and protection, and national preparedness, respectively. HSPD-9, titled "Defense of United States Agriculture and Food," established a national policy to defend the agriculture, food, and water systems against terrorist attacks, major disasters, and other emergencies. HSPD-9 required EPA to develop and support intelligence operations and analysis capabilities for the water sectors. Requirements included support for surveillance and monitoring systems for water quality and new countermeasures for detecting contaminants in the water supply. More recently, Presidential Policy Directive-21 (PPD-21) on Critical Infrastructure Security and Resilience advanced a national effort to strengthen and maintain secure, functioning, and resilient critical infrastructure against all hazards. PPD-21 identifies 16 critical infrastructure sectors and their assigned sector specific agency. EPA is the assigned lead agency for the water and wastewater systems sector.

As a result of the September 11th terrorist events and the subsequent anthrax attacks in New York City, Washington D.C., and Florida, EPA established the Homeland Security Research Program (HSRP) within the Office of Research and Development in 2002. HSRP conducts applied research by developing systems-based technology solutions to increase the capability of EPA to achieve its homeland security responsibilities as identified in statues and presidential directives. HSRP recognized a thorough understanding of the nature of biologicals, chemicals, and radiological agents, their transport in the environment, and their effects on human health was a critical research need to help ensure critical infrastructure was secure against threats.

In terms of the water sector, a major focus of HSRP has been the development of research prototype software tools that can be used by the water industry to analyze water contamination threats to drinking water distribution systems. The water community recognized the vulnerability of drinking water distribution systems to contamination threats. The initial software tools quantified the potential impacts or consequences to public health from contamination releases within the drinking water distribution system and then used the results to optimally determine where best to place sensor monitoring stations to reduce public health impacts or decrease the detection time of the contamination incident. The consequence and sensor placement optimization software tools provided key capabilities for a water utility to design and implement an online water quality monitoring system as a component of a contamination warning system (CWS) to improve a community's response to a contamination threat. Later, accidental and natural disasters, such as the Deepwater Horizon oil spill in 2010 and Hurricane Sandy in 2012, demonstrated the need for communities to be better prepared for and able to recover from all types of hazards. The "all hazards" approach seeks to provide technical support for dealing with incidents, regardless of the type of contamination or cause (e.g., intentional or unintentional physical disruption). The all hazards approach has been expanded to include improved resilience against man-made and natural disasters. With the broader definition of threats, HSRP expanded its water security tools to include the capability to analyze a broader range of threats.

In December 2016, HSRP undertook a project to conduct an evaluation and technical review of their modeling tools and programs with an eye towards assessing and designing their future research program. The review focused on the state of the science, how to encourage broader use of water distribution system modeling and data analytical tools by the water sector, how to improve the technical functionality of the tools, and how to foster partnerships with the commercial sector. To provide a broad basis of views, the review engaged representatives of the water sector, including water utilities, professional organizations, software vendors, consultants, and academic researchers in this field.

The elements of the evaluation and technical review of modeling tools and programs included the following:

- Conduct external and internal interviews with a variety of professionals in the drinking water industry to gather their comments on HSRP's water modeling program and any research needs associated with improving the operations, water quality, or resilience of drinking water systems
- Review published literature to identify potential future directions within the water distribution system analysis field
- Identify potential enhancements for HSRP's existing water distribution system modeling tools to support improved security and resilience of water systems
- Engage with the EPANET developer and user community to identify overlapping areas of interest since EPANET provides the hydraulic and water quality simulation engines for HSRP's modeling and simulation software tools
- Convene an expert panel to provide additional input to build on the findings from the external and internal interviews
- Summarize the results of the evaluation and technical review
- Develop a path forward strategy for HSRP's water modeling research to continue the advancement and delivery of its tools and methodologies to help improve the security and resilience of the water community

The primary goal for performing the evaluation and technical review, as well as developing this report, is to foster communication and collaborations within EPA and the wider water community to develop a path forward for HSRP's water security and resilience tools.

2 HSRP's Vision for Situational Awareness Tools

To identify research gaps and to better understand potential security issues and concerns of the U.S. water community, EPA engaged with numerous water experts, stakeholders from government, industry, and academia. From these engagements, EPA developed the Water Security Research and Technical Support Action Plan to summarize the needs and define research projects to improve the security of the nation's water and wastewater systems (U.S. EPA, 2004). The needs were organized across the following seven recommended focus areas:

- Protect drinking water systems from physical and cyber threats
- Identify drinking water threats, contaminants, and threat scenarios
- Improve analytical methodologies and monitoring systems for drinking water
- Contain, treat, decontaminate, and dispose of contaminated water and materials
- Plan for contingencies and address infrastructure interdependencies
- Target impacts on human health and inform the public about risks
- Protect wastewater treatment and collection systems

The American Water Works Association (AWWA) collaborated with HSRP to form the Water Utility Users Group (Roberson and Morley, 2005; Morley et. al., 2007; Janke et al., 2011). This group was comprised of utilities interested in developing monitoring systems to detect contamination threats, and they partnered with HSRP in their development of prototype software tools to help design, implement, and evaluate online water quality monitoring systems as a component of a CWS. The partnership helped to ensure that HSRP was focused and grounded in improving the security of water distribution systems by developing relevant tools and methodologies that could be used by the water community (Morley et al., 2007).

Through these engagements, HSRP and the wider water community recognized that to achieve a timely, effective response to contamination threats, a real-time understanding of water system operations across the distribution system during an incident was needed. This capability is called "situational awareness." As a major water contamination incident or significant emergency unfolds, hydraulic and water quality conditions in the distribution system can change quickly and dramatically. Therefore, it is important to accurately understand in real-time the changing hydraulic and water quality behavior of the water distribution system during such emergency events. This understanding or situational awareness requires a continuous collection, assessment and assimilation of critical, real-time data and information.

Because of the complexity of water distribution systems, network models are commonly used to predict flow directions and water quality at different locations and times. Tools using these network models were widely recognized as needed functionality to support situational awareness and response efforts. As such, HSRP developed a plan to develop tools built on top of hydraulic modeling capabilities that could be combined to provide a real-time, situational awareness of drinking water distribution system behavior. The situational awareness tools would support more effective and rapid decision making, and other specific tools would help in planning for incidents ahead of time (e.g., where to locate sensors), collecting and interpreting data during an incident (e.g., analyzing sensor data) or in response to incidents after they had occurred (e.g., where to flush contaminants from the system).

The 2013 Roadmap to a Secure and Resilient Water Sector (CIPAC Water Sector Strategic Priorities Working Group, 2013) identified and prioritized activities needed to improve the security and resilience of the drinking water and wastewater infrastructure. One of the top priority activities listed in the roadmap is to "support the development and deployment of tools, training, and other assistance to enhance preparedness and resiliency" of water infrastructure systems, including the work being developed by HSRP. A revised roadmap, Roadmap to a Secure and Resilient Water and Wastewater Sector (Water and Wastewater Sector Strategic Roadmap Work Group, 2017), provided updates on previous activities and identified priority activity areas for the next five years. These roadmaps helped to extend HSRP's original plans which were focused on contamination incidents to more broadly address resilience to all types of disasters.

3 Water Distribution System Modeling Tools

Since its inception in 2002, HSRP's vision for the water distribution system modeling program was to develop methodologies and tools for the nation's drinking water systems to help make them safer and more resilient. HSRP researchers and their partners have developed systems analysis methodologies including mathematical modeling, simulation, optimization, data analytics, and software engineering that can be applied to drinking water systems. Through these efforts, HSRP has created research prototype software tools to help the water community throughout the continuum of an emergencies. These software tools were developed based on the paradigm that water system security, resilience, and response capabilities are dependent on: (1) identifying threats and vulnerabilities, (2) designing, developing, and implementing engineering systems that can quickly detect such threats, and (3) developing and deploying tools and methodologies that can be used to help minimize the response and recover times following a water system attack and/or disruption. These prototype software tools include the Threat Ensemble Vulnerability Assessment - Sensor Placement Optimization Tool (TEVA-SPOT), CANARY, the EPANET Multi-Species eXtension (MSX), the EPANET Real-Time eXtension (RTX) libraries, the Water Security Toolkit (WST), and the Water Network Tool for Resilience (WNTR). Additionally, efforts are underway to better understand water quality after water leaves the distribution system and enters the premise plumbing systems of the community, such as residences, businesses, schools, and hospitals. The Appendix provides some terms and definitions associated with water distribution system modeling. A short description of each software tool is provided below.

TEVA-SPOT enables users to evaluate threats and consequences from a contaminant release into a drinking water distribution system. Using the results from a site-specific consequence assessment, TEVA-SPOT allows the user to investigate locations within the distribution system where best to place real-time monitoring or sampling stations to help mitigate contamination risk to public health and to support the development of an emergency response plan in the event of a contamination incident. TEVA-SPOT also allows users to evaluate existing site-specific monitoring plans to determine their effectiveness in addressing a wide range of user defined threats through the software (U.S. EPA, 2010a; 2016). TEVA-SPOT's results are dependent on the accuracy and the specific utility operation's snapshot (e.g., maximum, minimum, or average daily water demands) of the network model used in the analysis. TEVA-SPOT includes a graphical user interface, but a significant learning curve for understanding and effectively using TEVA-SPOT is still necessary.

CANARY is an event detection software that water utilities can use to analyze sensor data, such as chlorine, pH, oxidation reduction potential, total organic carbon, and conductivity, from typical online water quality monitoring sensors and report when a period of anomalous water quality is detected in the distribution system. The software uses several statistical analysis algorithms to evaluate real-time water quality sensor data that is polled every 2 to 15 minutes and to identify outliers from an established baseline. CANARY was designed to be able to interact with a supervisory control and data acquisition (SCADA) database, making it able to work with sensors of any type or brand (U.S. EPA, 2010b; 2012; 2013; 2014a). CANARY can be used with any sensor to analyze any time-series data. CANARY does not have a graphical user interface.

The multi-species extension to EPANET, MSX, allows users to write their own chemical or contaminant fate routines (i.e., reaction rate equations) and to incorporate multiple species (e.g., interacting chemicals) in EPANET's water quality simulation. MSX can be used to simulate the fate and transport of biological and/or chemical contaminants, as well as chemicals associated with disinfection, such as chlorine, chloramine, and disinfection byproducts (DBPs), in a system (Shang et al., 2008; 2011). MSX was released as a stand-alone, command line application, without a user interface. MSX is not easy to use and requires the development of reaction kinetic equations for any species that are to be simulated. Additionally, accurate MSX modeling relies on an understanding of the water quality and character of the water distribution system (e.g., water constituents, extent of biofilms, disinfectants, pipe material) that is difficult to obtain.

RTX is different from the other prototype research tools since it is a set of C++ software libraries that software developers can use to build real-time hydraulic and water quality modeling applications. These applications can help improve water distribution system modeling, planning, and operations. The RTX libraries extend the capabilities of EPANET by integrating the network model with SCADA data to better reflect daily operational activities as well as operational changes (Janke et al., 2011; Uber et al., 2014; U.S. EPA, 2015). One application is, RTX:LINK, which provides utility managers and operators the opportunity to remotely view their streaming real-time SCADA monitoring data and associated analytics. In addition, the RTX libraries were developed to support HSRP's other modeling and simulation tools (e.g., TEVA-SPOT, WST, WNTR) by improving the accuracy of the network models and providing the software infrastructure for real-time response. Deploying RTX software tools to implement real-time modeling within a water utility's operations will require a significant effort and possibly resources. Water utilities will require software development capabilities for the deployment and application of the RTX software tools.

WST is a suite of software codes (i.e., set of separate, command line executable programs) built upon the EPANET platform that can be used to assist water utilities in trying to understand how best to respond to a contamination incident in a water distribution system. WST includes hydraulic and water quality modeling software and optimization methodologies to investigate possible: (1) locations in the system in which the contamination was introduced, (2) locations to flush contaminated water from the distribution system, (3) locations in the system to inject chlorine to inactivate contaminants, and (4) locations in the system to take grab samples to help identify the extent of contamination (U.S. EPA, 2014c). WST does not include a graphical user interface and requires a significant learning curve, but it does not require software development capabilities. WST results are dependent on the specific snapshot network model used in the analysis. WST does not include linkage to real-time models, which would be needed for utility deployment during an emergency.

WNTR is a Python software package that allows the user to design, simulate, and analyze the resilience of water distribution systems given internal or external threats or incidents. The software includes the capability to: (1) create and modify water network models; (2) assign fragility and survival curves to network components; (3) simulate hydraulics and water quality to model disruptive incidents (e.g., power outages, earthquakes, pipe breaks, and contamination incidents) as well as response and repair strategies; and (4) analyze results and generate graphics to evaluate resilience using a wide range of metrics. WNTR extends the capabilities of EPANET by allowing for pressure dependent demand simulations, simulating pipe leaks/breaks of different sizes, changing aspects of the network and/or operations during a simulation (i.e., stop/restart), and enhancing the hydraulic solver to be more robust during extreme failure scenarios (Klise et al., 2017a; 2017b). WNTR is similar to WST in terms of the lack of a graphical user interface and difficulty to use, since it requires some knowledge and experience with Python. Similar to TEVA-SPOT and WST, the results of WNTR are dependent on the specific operation's snapshot of the network model that was used in the analysis.

Premise distribution system modeling represents a new research area within the EPA. The premise distribution system modeling research is focused on extending the capabilities of EPANET to study issues such as lead and *Legionella* (the bacterial causative agent of Legionnaires' disease and Pontiac fever) contamination as well as water age, a factor in water quality degradation, in building premise plumbing systems (e.g., in homes, apartments) (Samuels et al., 2010; Burkhardt et al., 2018). This effort has focused on two main areas: the addition of dispersion modeling to EPANET and a Python-based script tool for scenario management. The Python-based tool includes an agent-based demand generation and analysis component that is used as part of a Monte Carlo based approach to better understand the impact of different factors (e.g., usage patterns, plumbing layout) on exposure within premise plumbing systems. Additional functionality is also being developed to understand flushing efficacy within premise plumbing systems based on different flushing approaches.

4 Expert Interviews Prior to Workshop

A key element of the review process was the collection of ideas and viewpoints through a series of interviews with subject matter experts representing a broad range of interests and perspectives (e.g., drinking water utilities, engineering consultants, software developers/vendors, government, academia). Nine interviews were conducted with external experts and an additional eight interviews with internal experts (EPA staff and some of their working groups). The internal and external interviewees represented a diverse range of backgrounds, positions, and perspectives within the water industry and the government.

The interview questions were tailored to the specific experience and background of the interviewee while structured to gain insight across the following topics: (1) barriers and obstacles preventing water utilities from using the HSRP's water security and resilience tools, (2) technical gaps in the tools or the water security program, and ideas for advancing the tools or the program, and (3) strategies to improve collaboration between the program and water utilities and commercial partners. A sample of the questions asked are provided below.

- What are the barriers/obstacles to using HSRP's software tools (or tools produced by other researchers or vendors)?
- What are the technical gaps in HSRP's water distribution system modeling research program? What improvements can be made to HSRP's software tools, methodologies, or algorithms to address the most pressing needs of the water sector?
- How can HSRP more effectively collaborate with the water sector (i.e., water utilities) and private sector and industry partners?

The interviewees provided a wide variety of responses to the questions. Some of the key messages from the interviews are summarized below in categories of barriers, research needs and capabilities, and collaboration opportunities.

BARRIERS

- Currently there are no regulations or requirements that mandate utilities to use HSRP's water security and resilience tools. Similarly, utilities are not required to develop a network model that is an accurate representation of the water distribution system and its behavior.
- Many utilities do not have the necessary SCADA and asset management systems to adequately support the development and maintenance of a network model or real-time model. Additionally, monitoring equipment is often not adequately calibrated nor reliable. This is especially the case for small utilities.
- At many water utilities, organizational silos exist between engineering, water quality, and operations, which prevents them from effectively communicating and working together. Engineering departments often develop and use the network model for only planning purposes. Operations departments manage distribution system operations but generally without the use or need for the network model.
- Water utilities often do not have enough staff or time to use modeling software.
- Modeling results are often not trusted to assist with making operational decisions due to a lack of trust in the quality and accuracy of the network model to represent operations.
- Water security software tools need to support the day-to-day operations of the utility and not just remain focused on security related concerns.
- Most water systems have not incorporated complex tools like TEVA-SPOT, WST, or WNTR into their risk analysis of operations. Many utilities have not addressed distribution system vulnerability or even water quality modeling.
- Water utilities need software to be easy to install and operate. Good documentation (technical and user guides and tutorials) must also be made available.

NEEDED RESEARCH AND CAPABILITIES

- Foundational research and practical utility case studies demonstrating the application and use of the water security and resilience tools are needed.
- More basic research on the fate and transport of contaminants in the distribution system is needed. The water community is still using basic methods even for predicting the fate of chlorine and DBPs in the distribution system.
- Importance of well-calibrated network models cannot be overstated. Water quality modeling is dependent on a well-calibrated hydraulic model.
- Integration of hydraulic and water quality SCADA data with network models, real-time analytics, and real-time modeling (including smart water technologies) are important advances and technologies to provide a better understanding of what is really happening in the distribution system. However, the selection and adoption of the most appropriate technologies is a difficult task for most water systems.
- Water security and resilience tools need to be enhanced to support normal operations and, therefore, warrant the efforts required for water utilities to implement the software programs into their operations. For example, TEVA-SPOT and WST could be modified to examine and optimize the placement of continuous, online monitors to support routine water quality monitoring and help meet regulatory requirements.

COLLABORATIONS WITH WATER COMMUNITY

- Presence at national and international conferences is important.
- Connecting, talking, and working directly with water utilities is important.
- Publishing practical utility case studies demonstrating the water security and resilience tools and methods would be useful.
- Open source software and community software development projects can be very effective, but they need support and guidance from EPA.
- Water utilities need technologies that provide a return on investment. Utility case studies that quantitatively demonstrate the benefits and cost savings from the use of the water security and resilience tools would be useful.

5 Future Trends

The 2015 Water and Wastewater Systems Sector-Specific Plan (U.S. DHS and U.S. EPA, 2015) provided the latest blueprint identifying the sector's goals and objectives to help ensure future security and resilience of the sector. The plan outlined the complex governance, management, and institutions that support and help to maintain the nation's water systems. The drinking water community (and the wastewater community) is vast and complex, representing a multitude of stakeholder segments and federal, state, and local government entities.

While the plan identified the sector's goals (e.g., "Goal 1: Sustain protection of public health and the environment") and objectives to meet each goal (e.g., "Objective 1: Encourage integration of both physical and cyber security concepts into daily business operations at utilities to foster a security culture"), it did not specify the technology solutions and business practices that would be needed to address them. Thus, the water community (i.e., water utilities, industry, consultants, and academics) should develop them. This section examines the future trends in technologies and business practices that could help shape the drinking water community into the future and help meet the goals and objectives outlined in the plan.

One recent trend is the establishment of multiple water clusters, which are regional groups of private and/or public organizations focused on innovative water technologies. Examples of the water clusters that focused on drinking water technologies included Colorado Water Innovation Cluster, Confluence, North East Water Innovation Network, and WaterStart. The technologies emphasized by these clusters help address water efficiency, water reuse, water–energy–food nexus, drinking water treatment, water infrastructure, monitoring and modeling, and smart water (Wood et al., 2018). An initiative that is helping the water industry look towards the future is the Utility of the Future Today recognition program that started in 2016. The goal of Utility of the Future Today is help water utilities become more efficient, productive, and sustainable in their operations. Utilities are recognized for implementing innovative programs and technologies that help make them more resilient to challenges in their communities. The recognition categories include water reuse, biosolids reuse, nutrient reduction and materials recovery, partnering and engagement, energy generation and recovery, energy efficiency, and watershed protection (WEF, 2019).

EPA has also outlined ideas to help advance technology innovation in the water industry. In "Promoting Technology Innovation for Clean and Safe Water: Water Technology Innovation Blueprint, Version 2," water scarcity, water quality, aging infrastructure, climate change, and water accessibility are identified as water challenges affecting our world today and into the future. To help address these challenges, technologies are needed to conserve and recover energy, recover nutrients, improve and green infrastructure, conserve and reuse water, enhance water monitoring techniques, increase resilience of water infrastructure to climate change impacts, reduce water usage by energy industry, and improve water quality in watersheds (U.S. EPA, 2014b). Bluefield Research has also identified the top nine trends in 2019 for the water industry. These trends included smart asset management technologies for leak detection, pressure management, and workflow management, solutions to address infrastructure leakage, smart meters that combine water and energy monitoring, decentralized water treatment to reuse water, and real-time control solutions and water quality monitoring to increase resilience of systems to climate change impacts. Bluefield also noticed more interest in the water industry for artificial intelligence and machine-learning solutions as well as software-as-a-service and cloud-based offerings (Tisdale, 2018).

To identify the likely future trends specifically in drinking water distribution system analysis, operation, and design, three additional sources of information were examined. These sources included: a series of interviews available on YouTube with professionals in the field of water distribution system analysis conducted by an Environmental and Water Resources Institute (EWRI) committee (EWRI, 2019); an AWWA committee report on trends in the field of water distribution system analysis (AWWA, 2014); and an article on a vision for what water distribution systems might look like in the year 2050 (Grayman et al., 2012).

Starting in 2015, the EWRI History of Water Distribution System Analysis task committee conducted approximately 50 interviews with professionals who have made significant contributions in the water distribution system analysis field (EWRI, 2019). The interviewees were asked various questions about their background and experiences and, most importantly for this review, about their perceptions of future needs and trends in this field. The interviewees identified a wide range of topics. The categories discussed the most frequently during the interviews included water infrastructure assessment, real-time modeling, advanced analytics, water loss/leakage, research/innovations, monitoring, water quality, economics, and optimization. Other areas that were mentioned include water and cyber security, energy analysis, valve management, uncertainty, mega cities, and intermittent water supplies. Several interviewees emphasized the need for good engineering judgement in addressing issues.

The AWWA Engineering Modeling Applications Committee has regularly conducted surveys on the state of water distribution modeling. In a 2014 article, they summarized their latest findings in terms of trends in water distribution system modeling (AWWA, 2014):

- Utilities will continue to integrate network models with geographic information system (GIS).
- Investment in modeling increases, with a capital improvement program will be the top driver for growth.
- Operations show the greatest increase in anticipated use of the network model.
- Real-time data will influence direction and use of network models.

The committee summarized the current use of modeling as follows. “The current level of a water utility’s interest and activity in using hydraulic models is high, and these models can be a critical tool for addressing the major challenges that many utility’s encounter with the planning, design, and operations of their water distribution systems. With more advanced data systems such as GIS and asset management becoming standard tool sets within water utilities, the hydraulic model has evolved in terms of the level of detail being modeled, integration with these systems, and the use of more advanced hydraulic model applications. With these advancements, there is also added complexity, with hydraulic model calibration shown as the most challenging aspect of hydraulic modeling tasks” (AWWA, 2014).

In a chapter titled “Water Distribution System in 2050” in the EWRI published book, “Toward a Sustainable Water Future – Visions for 2050,” future trends identified for water distribution systems included investigating different types of distribution designs, having more control and monitoring within the distribution system, and managing the assets of system more effectively and efficiently (Grayman et al., 2012). In addition, issues facing distribution systems today and in the future were:

- Degraded infrastructure
- Climate change, resource depletion and increasing demands for water
- Using highly treated water to satisfy lower quality needs
- Providing adequate standby fire-flow needs
- Preventing contamination in distribution systems
- Reducing energy requirements
- Providing centralized systems in developing regions
- Reducing vulnerability to terrorism

The water industry is encountering numerous challenges, such as water scarcity, water quality, aging infrastructure, and climate change. The most commonly identified capabilities to address these challenges include real-time analytics, enhanced modeling and monitoring (e.g., real-time modeling), integrated asset management systems, and smart water hardware and communication technologies. These challenges and capabilities can be used to inform research directions and technology development that HSRP and others pursue in the future to make drinking water systems more resilient.

6 Engagement with EPANET Community

EPANET provides the hydraulic and water quality simulation engines for the HSRP's modeling and simulation software tools. Therefore, an important step in the review of these tools was to engage with the EPANET community on the future vision and development direction of EPANET. EWRI in association with EPA, the National Center for Infrastructure Modeling and Management, and the broad user and open-source software development communities convened an EPANET Visioning Summit in Reston, Virginia on April 3-4, 2018 (Grayman and Travers, 2018). A more detailed summary of the Summit is provided in Murray et al. (2018). The mission of the Summit was to develop a shared vision for the future development of EPANET. Thirty-five participants including representatives from the Summit sponsors, commercial software companies, engineering consultants, water utilities, academia, and professional organizations attended. The Summit addressed the three general questions listed below:

- What is the appropriate structure and style for future EPANET development?
- What additional functionality is needed in EPANET and other water distribution system modeling software?
- How can the various members of the EPANET community work together to best move EPANET forward in the future?

The participants had general agreement surrounding the continued development of EPANET as an open-source project, with strong community contributions and based upon a permissive license. While the general direction of the open source development of EPANET was considered positive, the participants wanted more specific details about EPANET's future development. It was anticipated that continued discussion among the represented groups (e.g., commercial software companies, engineering consultants, water utilities, academia, professional organizations, and government) would further shape the overall development to ensure that the diverse EPANET community can work together effectively to further the advancement of EPANET.

The participants also identified additional functionality that is needed to improve the capabilities of EPANET and support other water distribution system modeling programs. A total of 44 specific areas of needed functionality enhancements were identified. These were categorized into four major themes: user experience, development needs, hydraulics, and water quality. Some of these functionalities could become future research pursuits for HSRP's water distribution system modeling program. A few of the functionalities are summarized below. EPANET should include the ability to:

- Stop and restart simulations after a change to the simulation parameters (e.g., demands, pipe status) of the network model
- Directly integrate extensions like RTX, MSX, and others into one product
- Run the hydraulic and water quality engines in step with each other rather than sequentially
- Run the network model if a portion of the network is disconnected
- Incorporate real-time data streams into the modeling capabilities to support operations
- Isolate portions of the network by closing selected valves within the network model
- Simulate pressure driven demands
- Update leakage equations to be more realistic
- Include prototype multi-species water quality reaction/fate equations that are of interest to water utilities (e.g., chlorine decay, DBP formation and decay, chloramine decay/fate, temperature modeling, and multiple source tracing)
- Simulate dispersion under laminar flow in the network for dead-ends and premise plumbing systems

7 Expert Peer Review Workshop

The three preceding steps (expert interviews, review, and EPANET community engagement) provided a wide overview of the needs in water distribution system modeling and analysis. In order to dig deeper into the subject and to address the specific goals of the review, the final step in information collection was the expert peer review workshop. The workshop on HSRP's Water Security, Response, Resilience Modeling and Data Analytic Tools, was held at the EPA's campus in Cincinnati, Ohio on April 9-10, 2018. The purpose of the workshop was to: (1) review HSRP's water security and resilience modeling goals; (2) obtain additional comments, suggestions, and new ideas through face-to-face discussions on the status of HSRP's water security and resilience tools; and (3) develop a path-forward strategy to improve these tools and increase their usage by water utilities and support their needs. Five drinking water subject matter experts with in-depth knowledge and experience in the field of water distribution systems modeling, operation, or analysis, and at least 10 years of experience were selected to form the panel. They were selected by Versar, Inc., an independent EPA contractor, through a peer review selection process. Additionally, other water professional experts from the water industry sector (e.g., water utilities, professional organizations, software vendors, and consultants), academia, and EPA were in attendance and participated in the discussions. The workshop provided an opportunity to share information regarding the state of the science for water system security and resilience, with the focus on drinking water distribution systems.

7.1 Panel Charge Questions

In preparation for the workshop, the peer review panelists were provided background material including short descriptions of each of the HSRP's water security and resilience tools along with a preliminary set of suggested enhancements prepared by EPA staff (see Appendix for enhancement suggestions). Using this information, the panelists were asked to provide responses for the five charge questions. For the first three questions, responses were requested in terms of general comments as well as specific comments on each tool individually. General comments were requested for the last two charge questions. A preliminary report summarizing the panelists' responses was assembled and were provided to the panelists prior to the workshop. The charge questions are listed below.

1. How could HSRP's software tools or systems modeling and data analytics research be used to support the current and future needs of the water sector? What modifications could be made to these tools to encourage their use in applications beyond drinking water distribution systems?
2. What improvements can be made to HSRP's software tools, methodologies, or algorithms to address the most pressing needs of the water sector and provide multiple benefits? How can HSRP increase the usability and applicability of their tools to meet the needs of the water sector?
3. What other innovative methods are available from the research community that should be evaluated by our systems modeling research program or incorporated into HSRP products? Please describe any such methods and why they should be incorporated.
4. How can systems modeling and data analytics techniques be used in new or different ways to advance water sector research priorities? What new research areas can be identified?
5. With the potential of reduction in resources, how should HSRP focus their efforts on these tools to provide the most benefit to the water sector?

7.2 Workshop Agenda

The 1 ½ day workshop was composed of the following steps:

- Introductions and overview presentations on HSRP's research and modeling program
- Description of the objectives of the review program and structure of the workshop
- Discussion of the future high-level directions and needs of the drinking water industry
- Separate discussions on each of the seven HSRP tools and research areas
- Brainstorming on where the field will go in the next 25 years
- Final suggestions for the future direction of HSRP's water security, response, resilience modeling and data analytic tools

7.3 Workshop Discussions

Highlights of the discussions during the workshop are presented below organized by the following topics:

- Future high-level directions and needs (See Section 7.3.1.)
- Brainstorming on next 25 years (See Section 7.3.2.)
- Experts' suggestions on HSRP's future modeling direction (See Section 7.3.3.)

7.3.1 Future High-Level Directions and Needs

The first discussion topic during the workshop was on future high-level directions and needs, including a summary of the charge question comments submitted by the panelists. The following list highlights future high-level directions and needs relevant to tool development that were identified. Other topics discussed during the workshop included sensors and pressure management.

- Engage utilities and other end users
    - EPA needs to create a plan for the development of their tools, specifically one that includes engaging with customers to understand their needs.
    - Utilities are no longer just an end-user. A recent shift has occurred in which utilities participate in the innovation process. EPA needs to recognize this and bring the utilities in sooner to the development of tools.
- Integrate water security tools into day-to-day tools used by utilities
    - If a tool is designed for water security only, it might not be useful to the end-user when it is needed.
    - Utilities might not be able to justify the costs for tools unless the perceived benefits outweigh the costs. Utilities tend to be more concerned about items such as pipe break assessments, water loss, energy efficiency, pressure management, and age of system, rather than security.
    - Utilities are driven by regulatory requirements (such as for water quality), resources, and customer expectations, and by imminent health and safety issues. Cost benefit comes in play for compliance strategies and non-regulatory initiatives. Tools that address multiple challenges are more useful to the water industry.
- Look to the future
    - For any tool created now, there will be a ramp-up period of up to 10 years before it is fully used by the water industry. EPA needs to include this aspect in their tool design.
    - Forward thinking is challenging, and most utilities have a better understanding of past and current problems.
    - The industry is moving towards consolidated management through regional networks or virtual networks. As such, individual utilities might not have to fully understand all the details of modeling.
    - The future workforce will be more knowledgeable about information technology and these types of tools will be more useful to them. Institutional knowledge will be lost with expected workforce retirements.
    - Utilities should move toward real time operations systems like the electric industry. Tools exist today for the water sector, but they are separate, disconnected system that are not connected.
- Consider approaches to increase the use of tools
    - Analyses could be conducted to compare utility use of HSRP tools with violations/compliance. If results show that use of tools correlates with fewer violations, smaller systems might be more likely to use the tools.
    - A risk assessment scoring system could be developed so that communities could rate themselves in terms of risk. This will encourage lower rated communities to adopt tools that will help them respond to risks.
    - Simplified models could be explored for small systems, since they do not have programmers/modelers on staff and rely mainly on vendors/consultants. This could be accomplished by conducting sensitivity analysis that could be applied to small systems.

7.3.2 Brainstorming Future of the Drinking Water Industry

Another portion of the workshop included brainstorming the future of the drinking water industry. A variety of technologies or changes in water that might influence the field over the next 25 years were identified. Some of these were advancements in infrastructure materials (e.g., smart pipes) and computer resources (e.g., artificial intelligence, cloud computing); changes in water administration (e.g., point-of-use treatment, concept of net zero water and conservation); and shifts in the customer expectations (e.g., real-time communication on water usage and water quality). A detailed list of the brainstorming topics is provided in the Appendix.

7.3.3 Experts' Suggestions for HSRP's Future Modeling Direction

The recommendations of the panel in terms of the water distribution systems modeling and data analytics research program are summarized below.

- Investigate new approaches and technologies for the tools, such as smart phone or tablet-based apps, cloud-based systems, data analytics, and artificial intelligence.
- Focus on the day-to-day operation of utilities more than on rare incidents like terrorist acts.
- Seek more input and feedback from different stakeholders (e.g., large utilities, small utilities, consultants) along the development process as they have different needs.
- Build connections with water utilities, associations (AWWA, Association of State Drinking Water Administrators) and the Water Research Foundation.
- Adapt tools to anticipate potential future changes in EPA regulations.
- Consider the workforce of the future.
- Develop more simplified tools (e.g., real-time, sensor placement) that are plug-and-play and easier to use.
- Conduct field studies to validate the theories and assumptions included in the modeling tools (e.g., complete mixing at pipe junctions, fate models).
- Increase usability and applicability of tools by:
  - Identifying target audience and performing a needs assessment
  - Focusing EPA research in their areas of strength and expand efforts to leverage other government and private sector capabilities for other areas
  - Developing a software sustainability plan that includes all players
  - Making sure that software core (EPANET) is stable and usable
- Update and regularly maintain tools. New tools require additional resources.
- Discontinue several areas of development because commercial providers can incorporate HSRP's developments into mainstream programs.
- Look at the electrical power industry approach as a vision for water utilities – using real time analytics and using links to asset management and to other data for immediate response.

7.4 Experts' Take Away Messages

After the workshop the experts were asked to summarize their recommendations for the future path forward for HSRP tools. This included providing five take away messages that they wanted to share with EPA. Summaries of the experts' take away messages are categorized below into the following three topic areas: tools, collaboration/coordination, and marketing/strategy/vision. As the experts represented various viewpoints (e.g., academia, consulting engineer, utility), the messages could be conflicting.

TOOLS

- Continue supporting the updates and improvements to EPANET to ensure that it is stable and useable as it is a very important tool for utilities and the water industry. Additional features could include uncertainty and/or calibration modules.
- Develop and modify tools in steps, initially focusing on including capabilities that could be of most value to the water utilities, e.g., assist with automated valve isolation and simplified real-time modeling.
- Integrate tools into one product rather than separate codes/modules.
- Tools should be modified and geared towards direct application by the end users (utility staff and consultants) and incorporate the latest advances in user interfaces.
- Modify and update tools for direct application by the end users (e.g., utility staff and consultants), which primarily rely upon modern graphical user interfaces. In small drinking water utilities, staff is often limited to just an operator that is mainly familiar with plug-and-play tools rather than an engineer who understands code and compiling libraries.
- Provide maintenance and support of these tools to ensure continued and expanded use by utilities.
- Support premise plumbing research and model development, since it could assist with understanding *Legionella,* lead, and other public health and design questions within homes and other buildings.

COLLABORATION/COORDINATION

- Collaborate and engage with utilities in the planning, development, and adoption of the tools, since utilities are central to advancements in the water sector.
- Work through existing programs (like the Partnership for Safe Water) to extend participation in the tool development.
- Increase coordination with organizations, such as AWWA and Water Research Foundation, and states to understand the daily challenges at the average utility, such as main breaks and DBP compliance, and identify how the tools can be used to support these challenges in addition to planning for system security.
- Develop a sustainability plan for the tools that includes all the players.
- Explore the creation of a panel that includes utility staff for actively guiding the tool development from initial phases through beta testing.

MARKETING/STRATEGY/VISION

- Encourage adoption of software tools for utilities that could most benefit from the tools but are not aware or trained on how to use them. This serves the core mission of supporting water systems to prepare and recover from disasters, and more importantly, to protect public health and the environment.
- Obtain better data on tool usage and examine any correlation between compliance violations for utilities that do and do not use tools. More simply demonstrate how the use of network models might provide a business case for determining the level of future support for tools.
- Gain wider acceptance and usage of the tools by improving them to address pressing utility needs and focusing on day-to-day operations of a utility, such as main breaks and regulatory needs.

- Develop a full-scale strategic plan/vision for the future of these tools that includes addressing contamination threats and system resilience.
- Promote technology transfer of the tools to the water modeling industry.
- Market directly to utilities, particularly progressive ones, by applying the tools to real systems and presenting the results at AWWA conferences.
- Focus on the areas that EPA does well (e.g., EPANET, fate and transport modeling) and leverage others for their expertise (e.g., user interfaces).
- Identify the target audiences for the research/tools and perform a needs assessment.

8 Project Conclusions for HSRP Tools

Overall, this project highlighted some commonality between the different perspectives (e.g., academia, government, engineering practitioner, utility) within the drinking water community. A major theme was the accuracy of the network model itself. All parts of the review highlighted that the underlying network model needs to accurately reflect the water distribution system and its operation. A more accurate representation is obtained by collecting data (e.g., flows, pressures, tank levels) more frequently within the system and then linking it to the network model to create a real-time model that depicts the actual system dynamics. In addition to the hydraulics of the system, a more accurate representation of the water quality in the system is needed. One step towards this could involve more experimental data on the fate of different water constituents to understand how they react with one another. These data would provide more detailed reaction equations, which could be linked to water quality data collected in the distribution system. This second step would provide a more complete understanding of the water quality in the system in real-time.

Another focus area identified during the project was collaboration. The majority of the subject matter experts emphasized that it was important to engage with the water community through all phases of research and development to understand the problems that water utilities are facing, develop solutions for these problems, and transfer the solutions to the commercial industry for refinement, maintenance, and dissemination. An additional highlight of the project was that modeling and data analytic tools need to assist utilities with the day-to-day operation of the water distribution system rather than the relatively rare occurrences related to security or contamination incidents. Tools focused on the day-to-day operation would provide utilities with a better understanding of the system dynamics, which would be beneficial during emergency situations. The discussions also highlighted that most of the water community needs user-friendly tools that are easy to understand and implement as water utilities have many competing priorities and limited staff and resources.

In terms of HSRP's future steps in upgrading and developing water distribution modeling and data analytics tools, this project has illustrated that it is a complex, multi-dimensional task. It should be influenced by the specific criteria to be used in prioritizing future actions, by the overall available resources, and by the development costs and time associated with each potential action. The following discussion identifies ideas for the future development of HSRP's water distribution modeling and data analytics tools.

Needed future tasks could be as follows:

- Apply existing or modified tools to case studies
- Perform basic research on the processes associated with the tools
- Improve the interface and usability of the tools
- Expand the capabilities of existing tools
- Develop "best practices" for application of tools
- Inform/educate the modeling community about modeling advances
- Champion the future development and application of specific modeling technologies

HSRP has been involved in all these categories of tasks in the past. Based on suggestions from the review process, specific emphasis and tasks for each of the seven areas have been identified and described below.

8.1 TEVA-SPOT

Since its inception over 15 years ago, TEVA-SPOT has been the sensor placement tool most used for water security related issues. The research community has continued to develop alternative optimization routines for determining best sensor locations, but these routines generally have not been incorporated into tools or have not provided user friendly interfaces. However, the use of TEVA-SPOT in recent years has declined since the emphasis on security-only related monitoring has decreased. A potential future direction suggested by the review was expanding the optimal sensor placement tool to design monitoring systems used for routine and regulatory water quality monitoring (in addition to the security-oriented goals) within the water distribution system. The information from these optimally located monitoring locations would be used to improve the day-to-day operation of water distribution systems. TEVA-SPOT has the potential to help reduce the capital, operational, and maintenance costs of sensor deployments for monitoring the distribution system.

8.2 CANARY

CANARY was developed to analyze water quality data collected at online monitoring locations to alert water utilities of abnormal conditions within the distribution system. The review process highlighted opportunities for CANARY to be used beyond its original design purpose. HSRP presented other CANARY applications, such as detecting illicit events in rivers. Based upon the review, future opportunities likely exist with the continued and broader application of CANARY to time-series data. However, resources would be needed to develop a more user-friendly interface. As the water industry continues to collect more data, methods to analyze and evaluate the data are needed to assist in the identification of any issues with the water being monitored.

8.3 EPANET Multi-Species eXtension (MSX)

MSX was developed over a decade ago by EPA. It has been directly incorporated into most of the widely used commercial water distribution system software packages. However, both the EPANET version and commercial versions of MSX have found only limited use outside of the research environment. To expand its use in the water industry, EPA could conduct basic research to develop a library of chemical fate routines for the most widely modeled parameters (e.g., chlorine and DBPs). With more accurate representations of the reaction dynamics of water constituents, a water utility would have a better understanding of how changes in the treatment process and/or source water would affect the water quality within the distribution system.

8.4 EPANET Real-Time eXtension (RTX)

The review process affirmed that real-time modeling and use of real time data in the operations of water systems was at the top of the list for areas of future modeling and analysis of water distribution systems. It also showed that the work that HSRP has done in the development of RTX has been in the forefront in this field and that it has significantly spurred development and applications in this area. However, the review also suggested that commercial entities (software developers, vendors, consultants) are better positioned to develop and apply future software in this field and that HSRP should take a secondary, support role with real-time modeling. Future EPA research directions in this area could be assisting utility partner(s) with the integration and use of real-time technologies to improve routine, day-to-day operations and response to emergency situations. The goal of this work would be to advance adoption of real-time modeling and analytics into the daily operations of drinking water utilities.

8.5 Water Security Toolkit (WST)

Following a contamination incident within a distribution system, a utility implements response actions to mitigate the effects. WST was developed to assist with the evaluation of these responses. The review process suggested that the focus of HSRP tools should be more aligned with day-to-day utility operations (e.g., flushing programs) rather than with security incidents. In addition, the review process found that WST would not be useful during a real emergency due to time constraints required to run the analysis. Future directions for WST would require the linkage with a real-time water distribution model to evaluate the effectiveness of different response strategies available (e.g., source identification, flushing, chlorine disinfection, sampling) in real-time.

8.6 Water Network Tool for Resilience (WNTR)

Resilience has become an important concept within the water industry and other infrastructure systems. WNTR was viewed favorably within the review process as a tool that could be used to support future research. Since WNTR is a relatively new tool, additional case study applications could be pursued to understand the consequence and resilience response results it provides (e.g., effects of different operations' scenarios). A better understanding of WNTR results and findings is needed to help ensure the production of useful analysis and information, and support analysis of critical importance to utilities (e.g., aging infrastructure, natural disasters). In addition, to make the tool more user-friendly, WNTR functionality could be incorporated into future versions of EPANET using the Python-based, new user interface. These future directions could assist drinking water utilities of all sizes to use WNTR to gain a better understanding of how infrastructure (e.g., pipe, tank, or pump) failures could affect operations and the delivery of water to customers.

8.7 Premise Plumbing

Premise plumbing has become a significant issue of interest in the water distribution field due to water quality and security concerns. Currently it is an active area of research driven by several contamination incidents that have occurred following wildfires (e.g., Camp Fire in Paradise, California), distribution system contamination (e.g., 2014 Elk River [West Virginia] chemical spill), and water treatment modifications (e.g., Flint [Michigan] water crisis, Pittsburgh [Pennsylvania] water crisis). Thus, the reviewers identified premise plumbing as a research area to pursue. One future task that EPA could undertake in this area would be convening a workshop on the status, the needs, and the potential future directions of water quality research and modeling in premise plumbing systems. This would be similar to when EPA sponsored a workshop on water quality modeling in distribution systems in 1991 that kickstarted development in that area. A better understanding of the fate of water constituents would help to improve water quality in premise plumbing systems.

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10 Appendix

The Appendix provides definitions of the terms used for modeling distribution system, and more detailed information on the potential tool enhancements that were provided to the panelists before the 2018 Water Security, Response, Resilience Modeling and Data Analytic Tools Workshop. In addition, the detailed list of brainstorming topics discussed during the workshop is also presented.

10.1 Modeling Terms and Definitions

The drinking water distribution system infrastructure is the principle asset of a community water system. Drinking water distribution systems are designed to deliver water from a source (e.g., treatment facility) to the customer at the required quantity, quality, and pressure to meet their needs. EPANET is a software application developed by the U.S. Environmental Protection Agency (EPA) to simulate the hydraulics, operations, and the fate and transport of water constituents in drinking water distribution systems. The most popular commercial water distribution system modeling software packages were built using the EPANET solvers for hydraulics and water quality.

In the context of water distribution systems, the term *network model* is used to describe the operation of the water distribution system (e.g., times of day when valves open/close, tank levels to trigger pump operations, times of day when pumps turn on/off) and the characteristics of its infrastructure components (e.g., pipes, pumps, valves, tanks, reservoirs, service connections). The term is often used to describe the input file format required for EPANET. The network models for drinking water distribution systems can vary greatly in the level of detail used to describe the water system (e.g., number and size of pipes included in the network model). Often a less detailed network model has a greater level of skeletonization (i.e., only transmission pipes are represented and not service connections). Additionally, network models generally describe the water distribution system infrastructure from the point just after treatment (e.g., finished water reservoir or clearwell) to an aggregated set of customers service connections. Most network models do not include every customer's service connection individually. The number of customers aggregated can vary greatly, with greater aggregation leading to more skeletonization of the network model.

The network model is usually developed to represent a specific snapshot of the water utility's operation (e.g., maximum, minimum, or average daily water demands). These network models are not connected with real-time sensor data, and, therefore, they might not accurately represent the distribution system behavior during an emergency incident (e.g., pipe break or contamination). A real-time model represents a network model that is continuously fused with real-time data, in sufficient quantity and quality, to more accurately predict the current conditions of the water distribution system operations. With a historical record of operations data (e.g., a SCADA [supervisory control and data acquisition] historian record of operations data for a period of one year or longer), a real-time model could also be capable of examining past operational practices and incidents (e.g., pipe break) to analyze how different practices could be implemented to minimize the consequences or to improve the response times. In addition, the ability to accurately predict customer demands, flows, pressures, and other system parameters is critical for determining how best to respond during an emergency.

The primary developer of the water distribution system network model is the community water utility or their consultant. From the utility's perspective, their responsibility for the piping infrastructure stops at the customer's curb stop, while the customer service line and interior plumbing are the homeowner's responsibility. Thus, utility network models do not include the customer's piping and infrastructure, which is also known as the *premise plumbing* or *premise distribution system*. The design, attributes, and operational practices (i.e., customer's behavior and use of water using appliances) describing the premise distribution system is incredibly varied.

10.2 Potential Tool Enhancements

EPA's Homeland Security Research Program (HSRP) prepared a list of potential future upgrade tasks associated with each of the seven existing HSRP water distribution system modeling tools. These proposed tasks are delineated below.

10.2.1 Threat Ensemble Vulnerability Assessment – Sensor Placement Optimization Tool (TEVA-SPOT)

- Evaluate lessons learned from past applications of the TEVA-SPOT. TEVA-SPOT has been used to determine the optimal locations for monitors in a few dozen water systems. In each case, a detailed analysis was performed that integrated the software with an in-depth understanding of the water system. The method recognized that each water system was a unique entity with different characteristics and operations that would result in a different set of locations for monitors. The purpose of this task is to use the knowledge gained from these past applications of TEVA-SPOT to try to develop some generalized rules/guidelines for determining the best locations for monitors.
- Conduct a utility case study application for emergency preparedness. This work area would include performing a utility threat, consequence, and security improvement case study to demonstrate the capabilities within TEVA-SPOT to assist utilities in their consequence assessment and emergency preparedness efforts. This would be a full immersion utility case study whereupon HSRP representatives would work closely with the partnering utility representatives to apply the TEVA-SPOT methodology to their water system and then work with water utility representatives or their consultants to understand and implement the results for improved monitoring and security.
- Examine methods for extending TEVA-SPOT capabilities to include routine water quality monitoring. TEVA-SPOT was originally designed as a mechanism to investigate the vulnerability of a specific water utility to a wide variety of contamination incidents and to help design a real-time monitoring system to quickly detect contaminants in the distribution system. The purpose of this work area would be to examine how the TEVA-SPOT capabilities could be modified and extended to include the design of monitoring systems used for routine and regulatory water quality monitoring (in addition to the security-oriented goals).
- Investigate an alternate monitoring paradigm involving continuous monitors. This work area would involve partnering with a drinking water utility to use TEVA-SPOT to identify a small number of optimized sampling locations that could be used for more

frequent monitoring of routine water quality parameters. The TEVA-SPOT approach of selecting sampling locations for routine monitoring would be compared to the current approach of identifying sampling locations. Typically, water utilities sample from many locations with single or only a few grab samples. For large utilities, driving around collecting samples is difficult due to traffic issues and logistical concerns. A dedicated continuous monitoring station could be considerably less costly. This work would evaluate the technical (i.e., demonstrate improved public health protectiveness) and business cases for optimized sampling and continuous monitoring.

- Study multiple simultaneous contaminant threat scenarios to water systems. The purpose of this work area would be to investigate the consequences associated with multiple, simultaneous contamination injections. Better understanding of and quantification of consequences associated with such scenarios is needed to not only better identify the magnitude of consequences that water utilities could actually face but the ease at which multipronged attacks could be perpetrated. A better understanding of such threats and their consequences will help our partners and stakeholders to be better prepared and to be able to assist and respond to such threats.

10.2.2 CANARY

- Continue exploratory testing and case studies. The purpose of this work area would be to further explore the capabilities of the current version of CANARY in different applications with different types of sensor data. As sensors become cheaper and more abundant, the need for tools to perform robust analysis is increasing. Having a tool like CANARY that is capable of providing anomaly detection on a wide variety of sensors is also increasingly valuable. Continued research in new and different areas would assist the community by helping them determine if CANARY is appropriate for their application and what type of benefits can be achieved from monitoring.
- Expand CANARY's usability. The purpose of this work area would be to improve usability and reduce the learning curve related to using CANARY. The focus would be to expand the capabilities of CANARY to include the following features: (1) introduce easy set up feature, or attempt to provide a more seamless interaction with SCADA/data sources (i.e., smart features, or wizards); (2) provide more visual information during analysis (i.e., live graphs); and (3) integrate an auto parameterization tool into the user interface that would streamline the process of integrating data from a new source/application.
- Expand CANARY's functionality to include additional algorithms. The purpose of this work area would be to expand functionality to include some additional simple analytics and modify current analytics to be more customizable to improve overall functionality. This work could look at adding some simple algorithms (e.g., mean or median based approaches) and multiple simultaneous algorithms, or automatic confirmatory analysis, to help reduce false alarms (e.g., comparison of multiple algorithms to provide a best two-out-of-three type analysis). This could also include expanding how different signals are analyzed or allow for two different sets of parameters to be applied to different sets of signals in the data stream (i.e., turbidity has one set, while conductivity has another).
- Expand CANARY's functionality to include advanced algorithms. The purpose of this work area would be to identify, test, and add advanced machine learning algorithms (e.g., artificial intelligence approaches) to CANARY. Some approaches have been reported in

the literature, but these methods would require a significant amount of testing and validation before including them in CANARY. Generally, artificial intelligence approaches would require a re-parameterization for each type of signal set (i.e., one set of parameters would not work in two different applications), which would require support from some type of automatic parameterization tool.

- Build a framework for integration of CANARY and real-time modeling. The purpose of this work area would be to study the potential integration of CANARY analysis as part of a real-time model/monitoring (RTX) framework to better leverage the capabilities of both platforms. The first step would be to investigate the use of CANARY in monitoring real-time modeling efforts. This could potentially reduce false alarms from CANARY and provide additional information to the real-time modeling effort related to model accuracy. Integration with a real-time model would likely require some type of automatic time shifting algorithm to account for temporal variations between the model and the sensor data.

10.2.3 EPANET Multi-Species eXtension (MSX)

- Incorporate MSX into EPANET user interface. As MSX is a command-line program, it is not currently connected with the EPANET user interface. To enhance viewing of the MSX simulation results, an EPANET user interface version with MSX would need to be developed and released.
- Modify the MSX code and process to accommodate/support a library of MSX fate models. The development of a specific MSX fate model requires both domain knowledge on the specific water quality processes being modeled, and some level of experience/knowledge of the MSX software. Modifications to the MSX code to access and utilize the library of fate models in EPANET and development of additional fate models could expand the use of this software.
- Implement the full-scale MSX library. A mechanism for managing and supporting the MSX library could be developed to include available fate models and methods to update the models as needed. Additionally, fate models and parameter sets could be expanded as needed. HSRP could serve the dual role of developing the new fate models and/or evaluating fate models developed by outside groups.

10.2.4 EPANET Real-Time eXtension (RTX)

- Extend RTX software and documentation. This potential work area would evaluate and implement RTX's prototype demand forecasting tool into an RTX library. In addition, this work could investigate the inclusion of RTX libraries within newer versions of EPANET development to provide a better interface and to support real-time modeling. The RTX libraries and RTX:LINK software need improved documentation to help further the development and deployment of the technologies at water utilities.
- Develop an RTX virtual test application. This work area would create an RTX software application that uses a utility distribution system model, generates synthetic SCADA data, and demonstrates threat, consequence, and response strategies (water security and resilience tools) in a real-time framework to potential utility partners.
- Conduct additional real-time modeling case study applications. In partnership with additional drinking water utilities, this work area would examine the application of RTX-based tools. It would involve designing and deploying cloud-based real-time data

analytics (RTX:LINK) and real-time modeling at partnering utility(ies). The purpose of this work would be to assist utility partner(s) with the integration and use of these technologies to improve routine, day-to-day operations and response to emergency situations. The goal of this work area would be to advance adoption of real-time modeling and analytics into the daily operations of drinking water utilities.

10.2.5 Water Security Toolkit (WST)

- Test and exercise the current WST package. WST would be further tested and applied under a wide range of situations, primarily using small network models found in the literature. These applications will serve the purpose of exercising the software and identifying any issues, and providing additional understanding of the characteristics of responding to a contamination incident.
- Conduct one or more large-scale case study applications. The primary focus of this work would be the use of WST on one or two critical case study applications. These case studies could use either the re-creation of recent actual contamination incidents (e.g., West Virginia or Corpus Christi, Texas) or the creation of realistic, hypothetical contamination incidents. These re-creations would serve as a verification/validation that the WST components are functioning properly, and thus, provide greater confidence that it could be used for future incidents.
- Evaluate WST application for routine utility operations. Water utilities perform a variety of daily activities to ensure that water of high quality is delivered to consumers. This work would evaluate the application of WST to routine utility operations, such as flushing and sampling. These applications could use WST to evaluate and design effective flushing and sampling programs.
- Develop a response best practices report. This potential work area could help to identify common response action trends by completing case-study applications with a range of water utility systems. These trends could be related to pre-defining locations to flush and/or take samples, to evaluating how effective response actions are without knowing the source of the contamination, and to exploring the combination of different response actions.
- Examine the simulated usage of WST in conjunction with a real-time model. A real-time network model could be linked with WST to provide a near real-time response tool. The process could be simulated by using a network model derived from a real-time network model linked with SCADA data as input to WST. This could then be used to compare how the response actions differ if the response was occurring in real-time.
- Modify WST to include additional functionality and interface improvements. Future development of additional functionality in WST could be a future work area. This could include building a more user-friendly interface, modifying specific response actions, and adding new response action options.

10.2.6 Water Network Tool for Resilience (WNTR)

- Conduct additional case study applications. A series of case study applications of the WNTR software could be completed in order to validate WNTR, ensure the results produce useful information to water utilities, and determine the path forward for the software and documentation. This work could be done in collaboration with EPA regions, states, water utilities, consultants, nonprofits, or other interested organizations. The following scenarios could be pursued: hurricane, flooding, wildfire, tornado, and cyber.

- Enhance WNTR to include prioritizing infrastructure repair and replacement. In support of the Administration's goals to invest in infrastructure upgrades, WNTR could be enhanced to support analysis and prioritization of drinking water infrastructure repair and replacement. WNTR would be modified to incorporate failure probabilities due to aging infrastructure, material types, and other factors. Scripts could be written to optimize the order of repairs based on a variety of criteria. Costs of repairs could be included as well as metrics to measure the benefits of improvements. In addition, methods could be developed to allow for the comparison of different repair and replacement strategies. Finally, methods could be extended to incorporate resilience analysis into the prioritization process (i.e., make decisions about repair and replacement not just based on age of materials and failure rates but also on benefit provided for improved security and resilience to disasters).
- Transfer WNTR to consultants, water utilities, EPA regions, and states. Using information collected from case study applications of WNTR, guidance on the best practices for applying WNTR to assess resilience of water systems to disasters could be developed. This could also include a series of demo scripts and outputs, and a series of training sessions at conferences or via webinars. The training would be intended for consultants who might apply WNTR in support of contracts with water utilities, states, and EPA regions.
- Integrate WNTR with EPANET. To make the capabilities of WNTR more widely accessible, this work would be directed towards integrating WNTR capabilities within the new EPANET user interface (through the Python plug in) as well as future versions of EPANET. A beta version of EPANET 2.2 includes some of the capabilities of WNTR – pressure dependent demands and pipe leak models. This work could extend this new EPANET version to incorporate some of the other advances included in WNTR. Alternately, the use of WNTR through the new EPANET user interface Python plug-in could be demonstrated to show others how to use WNTR through EPANET.

10.2.7 Premise Plumbing

- Develop risk assessment tool for lead in homes. This work would include enhancements to EPANET to incorporate dispersion, validation of the EPANET model with laboratory data, and development of a risk assessment framework in a Python based tool that builds on the models. This work would continue the 30+ week validation study in a real-scale home plumbing system simulator at EPA, validate results, and develop a Python-based demand simulator.
- Develop a risk assessment tool for *Legionella* in large buildings. This work would investigate the use of EPANET for modeling *Legionella* in buildings, such as hospitals. A long-term study of *Legionella* within the home plumbing system simulator has also been underway, and data from that can be leveraged to support the modeling effort. In addition, EPA researchers have been working with several hospitals to mitigate risks and add treatment, and at least one hospital is willing to share the data needed to develop an EPANET model of their drinking water infrastructure.
- Develop home and building "calculators." This potential work area would investigate and develop premise plumbing "calculators" that run EPANET under the hood and provide

information useful to homeowners or building operators, similar to EPA's National Stormwater Calculator which uses Storm Water Management Model. These calculators could provide information about expected lead concentrations in water given homeowner information, or expected benefits from flushing prior to drinking, or using filters, or other mitigation techniques. In addition, operators of large buildings could use the tool to minimize *Legionella* or other risks.
- Promote the scientific study of water quality in premise plumbing. Premise plumbing has become an important issue in the water distribution field due to water quality and security concerns. In this work area, EPA would take an active role in studying and promoting the scientific investigation of premise plumbing with special emphasis on modeling premise plumbing.

10.3 Future of Drinking Water Brainstorming List

- Artificial intelligence
- Intelligent water networks: cyber communication networks, smart pipes
- Cloud computing
- Point-of-use treatment
- Real-time response
- Prescriptive analytics
- Predictive rather than reactive
- Net zero water
- Conservation
- Changing workforce
- Changing behavior patterns
- More engaged consumer/customer expectations
- Paradigm shift in the way we look at innovation
- Prioritization for replacement of aging infrastructure
- New infrastructure materials
- Valuation of water - use of bottled water
- Message on water quality of water supply
- Fuel cells as water supply
- Drivers for change
- More technology
- Drinking water vs fire protection water, changes in firefighting techniques
- Future design criteria
- Dual systems
- Improvements in hydrants, sensors, meters
- Proliferation of sensors
- Full tracking and accounting of water
- Integrated water and waste water systems
- Calibrated models, full system models
- Decentralized treatment
- Increase in cyber security
- Redundant control systems

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