Report No. 495

MULTIDIMENSIONAL ASSESSMENT OF NORTH CAROLINA COMMUNITY WATER SYSTEM VULNERABILITIES

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UNC-WRRI-495

The research on which this report is based was supported by funds provided by the North Carolina General Assembly and/or the US Geological Survey through the North Carolina Water Resources Research Institute.

WRRI Project No. 20-06-W
January 31, 2022

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Multidimensional Assessment of North Carolina Community Water System Vulnerabilities

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WRRI Final Report

Report date: January 31, 2022

Abstract

Our project, Multidimensional Assessment of North Carolina Community Water System Vulnerabilities, assessed the nature and distribution of vulnerabilities in North Carolina community water systems through achievement of two objectives. First, we developed a network-based method for assessing interrelationships among water system vulnerabilities and used expert information and data from several sources to apply the method to North Carolina water systems. Our measurement of water system characteristics relied on population data estimated from a newly generated digitized statewide map of water system service area boundaries developed in collaboration with the Water Supply Planning Branch at the Division of Water Resources (DWR). Applying our multicriteria approach to 319 North Carolina water systems, we found that vulnerabilities are dispersed: poor performance on one dimension, especially compliance with safe drinking water regulations, does not indicate poor performance on other dimensions. We also found that financial vulnerabilities are correlated with economic conditions in the communities served—in particular, water systems struggling to meet their debt obligations tended to serve disproportionately low-income populations.

Second, we used web scraping and automated data processing to measure and analyze the signals that the public receives about water system performance through news coverage of boil advisories, water main breaks, and other service disruptions. We found that coverage of service disruptions as a proportion of overall news coverage has not increased over time. Although coverage rises during severe weather, the most common news attention to infrastructure failure is not tied to weather, planned disruption, or human error—instead, it seems to signal the deterioration we would expect to see in aging systems.

We carried out our work while the State Water Infrastructure Authority and the Local Government Commission were developing the Viable Utility Program and used much of the same data. Our purpose was different, however: whereas the Viable Utility Program seeks to identify particular utilities in need of assistance, our aim was to identify patterns in vulnerabilities across water systems to inform policy-making that addresses multiple systems. Overall, our results demonstrate the tradeoffs that water systems face in balancing affordability against the capacity to deliver drinking water reliably over the long term, especially in low-income communities. Our findings also indicate that fiscally distressed water systems are performing by other measures similarly to non-distressed small utilities, suggesting that financial support could go far in improving water system performance.

We have maintained ongoing communication with partners in state water agencies about our methods and findings, and we have conducted broader outreach with water systems about the service area maps. Members of our team have met four times with federal officials about applying knowledge from our vulnerability assessment to tools and requirements for the equitable distribution of water infrastructure funding under Justice40. We have produced four articles for academic and practitioner audiences based on our work (two published, one under review, one in preparation).

Acknowledgments

An outstanding team of students and a post-doc contributed to this project and related work. We acknowledge the contributions of Katy Hansen, Emily Bell, Amanda Cabot, Sarwari Das, Rachel Gonsenhauser, Jake Greif, Walker Grimshaw, Shawn Li, Jinghan Luo, Jannette Morris, Carly Osborne, Catherine Otero, Kartik Pathak, Carolyn Rossman, Michael Scott, Sijia Wang, Connie Xiong, and Zoe Yang. We also thank Klaus Albertin at the Water Supply Planning Branch and Lauren Patterson and Kyle Onda at the Internet of Water for their contributions to archiving the water service area map and planning for its maintenance.

1. Introduction

Strong financial and operational underpinnings reduce risk to drinking water systems in the face of changing population, land use, climate, natural events, and regulations, yet decision makers and the public have limited information to assess a water system's overall condition (Mullin 2020). Fragmentation of responsibility among drinking water regulators and funding agencies leads to data gathering and decision making that emphasize a specific aspect of a water system's overall profile—particularly drinking water quality, the only outcome that is subject to federal regulations. Yet, water quality is only one of several important water service outcomes, including reliability, affordability, and the long-term viability of drinking water systems. There have been few efforts to understand how water systems perform across a range of metrics, hampering strategic interventions that can address systemic challenges affecting multiple systems. Meanwhile, it is unclear whether customers are aware of stress on water systems. Without meaningful signals, ratepayers might oppose rate increases, system consolidation, or other interventions that can help manage risk (Hansen et al. 2021).

We developed a descriptive, network-based method of assessing drinking water system vulnerabilities to identify cross-cutting challenges (Bell et al. n.d.). Our approach recognizes and measures the complex relationships among dimensions of water system *performance*, the accomplishment of desired outcomes, and *capacity*, the resources and capabilities required to achieve those outcomes, and allows regulators to visualize and assess common vulnerabilities across many systems. We applied the method to 319 water systems in North Carolina, using physical, demographic, financial, technical/management and performance data that government agencies and research institutions have made publicly available.

By analyzing how vulnerabilities coincide with one another across systems, we demonstrate that documented compliance with water quality regulations is often unrelated to other measures of performance and capacity. Systems with violations tend to be operationally sound by other measures. Moreover, focusing on violations masks other important sources of vulnerability, including financial vulnerability. Many larger water systems with limited financial capacity are charging low water rates, pointing to a potential for intervention to ensure the long-term viability of these systems. Rate increases need to be carefully designed, however, because low financial capacity is strongly related to the income of the population served by a water system. Together, these results bring to the fore the fundamental dilemma of balancing water affordability against the capacity to deliver drinking water reliably over the long term. Finally, we found that the signals the public receives about water service failure from local news coverage focus mainly on the boil water advisories and water main breaks that are predictable consequences of water infrastructure deterioration (Otero et al. n.d.).

2. Methods

For the multicriteria assessment, we began from a conceptual framework (Figure 1) that recognizes the complex interactions among dimensions of water system performance and capacity. The framework includes service reliability and affordability as desired outcomes in addition to water quality, and it treats water service area demographics, quantity and quality of source water supplies, and physical, financial, and managerial aspects of the water system itself

as measures of capacity to support water system operations. These dimensions of performance and capacity are interdependent upon one another, and not part of a system with structured causal ordering. We introduce an assessment method that uncovers patterns in these complex relationships using data available to decision makers.

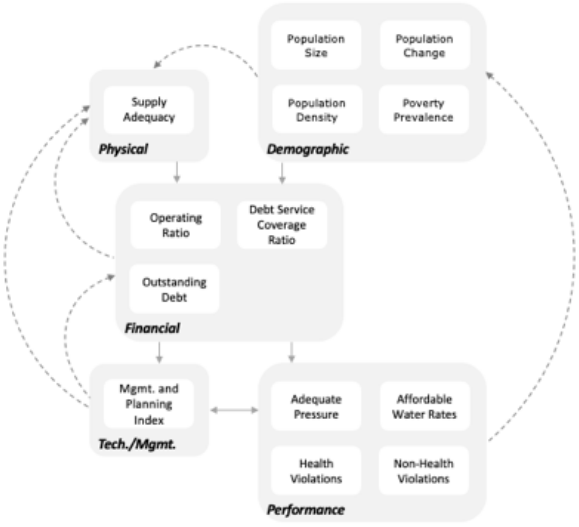

Figure 1. Conceptual framework of water system vulnerability.

We brought together publicly available data from multiple sources to build a profile of water system performance and capacity. For reasons of data availability and regulatory requirements, our sample was limited to community water systems operated by local governments serving any population size and systems operated by entities other than local governments (mostly private operators) serving more than 3,300 people or more than 1,000 connections. Under state law, systems meeting these criteria must submit annual Local Water Supply Plans (LWSPs) in order to support statewide drought and water quantity planning. We used data from 2017, which state agency officials indicated would have the most complete and accurate LWSPs of recent years. In total, 504 water systems submitted plans for 2017. Availability of service area maps and other data further limited our sample to ultimately include 319 North Carolina systems serving approximately 55% of the state's population.

We selected a set of variables measuring aspects of the performance and capacity dimensions in our framework. Included variables do not capture the full scope of these dimensions but instead reflect information that NC decision makers could potentially obtain—a critical consideration for implementing a risk management framework that might extend to other states. For the multicriteria assessment, we identified the water systems that fall outside an acceptable range of capacity or performance on each variable, treating these scores as indicators of system vulnerability. The thresholds for acceptable performance came from water service literature and industry standards.

Measuring a water system's demographic and financial capacity required knowledge of the population and economic characteristics of water system service areas. This research was the first application of a newly created digitized statewide map of water system service area boundaries (Gonsenhauser et al. 2020). Using this map that was developed in partnership with the Water Supply Planning Branch at the Division of Water Resources (DWR), we estimated population characteristics from block- and block group-level decennial Census data. Other data came from LWSPs, the Environmental Finance Center (EFC), and the Safe Drinking Water Information System (SDWIS).

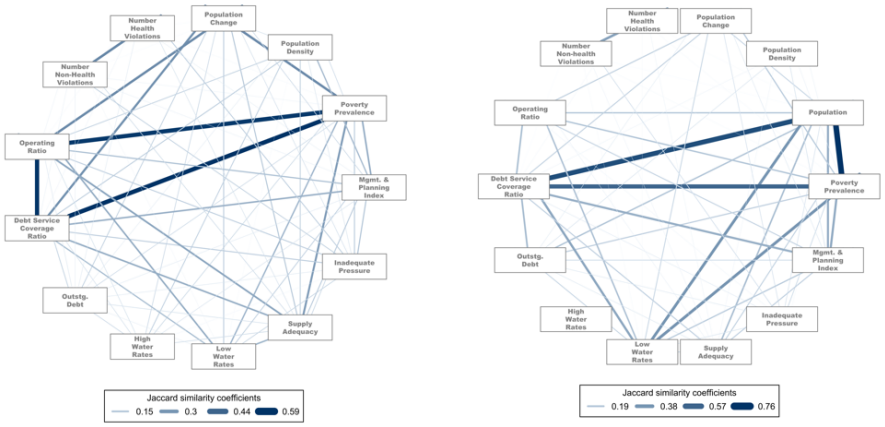

Figure 2. Multicriteria assessments of systems with service populations of 3,300 or less (left; n = 193) and 3,301 or more (right; n = 126).

We analyzed patterns of vulnerabilities using descriptive network analytic techniques. Networks comprise objects of interest, or "nodes," and the relations these objects share, or "ties." In our case, the nodes represent our vulnerabilities of interest; ties show us the Jaccard index, or sum of systems that exhibit two types of vulnerabilities in proportion to all possible systems that could have both vulnerabilities (accounting for overlap. We constructed separate networks for the smallest systems (serving 3,300 or fewer customers) and larger systems (serving more than 3,300 customers), based on the consistent finding that very small systems face particular challenges in managing drinking water and therefore may have vulnerability profiles that look different from their larger system counterparts. All 319 water systems in our analysis demonstrated vulnerability on at least one of the 14 threshold criteria.

3. Results and Discussion

Our analyses demonstrate the demographic foundations of many water systems' struggles. For both small (Figure 2; left) and larger (Figure 2; right) systems, the strong relationships between two of the vulnerabilities—debt service coverage ratio and poverty prevalence—indicate that systems with low-income customer bases are more likely to be collecting revenue at levels inadequate to cover operations and debt. In the graph of larger systems, these vulnerabilities also have high co-occurrence with population, suggesting a problem that exists predominantly among medium-sized systems serving populations of less than 10,000. (Population is a vulnerability for all small systems and therefore omitted from the small-system vulnerability profile.)

The graph of larger systems displays a moderate co-occurrence between low water rates and revenue shortfalls. None of the large water systems in our sample charge extremely high rates, indicating that rate increases could be an important step toward bringing systems with low financial capacity toward sounder long-term viability. However, rate increases would need to be

carefully designed to protect affordability to the large low-income segments of these vulnerable systems' customer bases. For systems that have adequate supply, selling water to neighboring systems may be another way to improve financial capacity.

Rate increases are not an advisable umbrella solution for the financially struggling systems serving populations less than 3,300, many of which have experienced population loss. Small systems with revenue shortfalls are not systematically charging low water rates, and some with financial vulnerabilities are charging rates higher than the recommended range. Rate increases for these systems are likely to threaten affordability for the small, often low-income, customer bases. Small systems with high debt loads are more likely to require state financial assistance in the short term, as their low operating ratios indicate immediate shortfalls in covering expenses. For the small systems in our analysis, supply inadequacy is also moderately tied to financial vulnerabilities. Water systems with limited financial capacity struggle to invest in infrastructure to secure, store, and transport adequate water supply, or to finance capital costs such as integrated water resource solutions. The analyses suggest different types of financial intervention for systems of different size.

The criteria that are not strongly connected to others in either of the vulnerability profiles are also important to note. Although health- and non-health-based SDWA violations overlap with one another, non-compliant systems are rarely vulnerable on other dimensions—a surprising result in light of the strong regulatory emphasis on TMF capacity for improving compliance. Correspondingly, systems in our data with supply and financial vulnerabilities do not have SDWA violations. The strongest relationships are with systems experiencing inadequate pressure events. Consequently, exclusive emphasis on SDWA in analysis of water system performance carries the risk of missing vulnerabilities that could put water availability at risk, especially in the presence of external stressors such as drought or a pandemic.

Among financial criteria, outstanding debt per capita has little overlap with other vulnerabilities. This finding demonstrates the utility of multicriteria assessment for illuminating the broader picture of water system operations. Even among small water systems, high debt per capita is not strongly linked with fiscal or operational robustness. More important is a water system's ability to manage its debt, which is associated more strongly with revenue policies and population characteristics than with debt burden. Credit raters or state fiscal agencies may treat high debt load on its own as an indicator of water system distress, but our results suggest that debt may instead be a positive signal of asset management and infrastructure investment. State officials might instead treat it as a supplement to our planning and management index, which corresponds only modestly with other vulnerabilities.

4. Public signals of water system vulnerability

To understand information the public receives on water system vulnerability, we used Python to web scrape text from a curated list of 153 NC newspapers over the period 2010-19. We searched for the keywords "boil water advisory," "boil advisory," "boil water," "boil notice," "water main break," and "water outage," producing a total combination of 918 queries. We used Google's SERP GoogleSearch API that returns searches, URLs and metadata for any given query. On searching for all 918 combinations, the API returned a total of 467 search results

for our reference period of 2010-2019. After many rounds of data cleaning and data-processing, we were left with 285 articles that were relevant to our search terms. These 285 URLs were checked manually to ensure that they referred to a water service disruption. Then, using BeautifulSoup, we extracted the actual article text for these newspaper articles. The text was further processed to record the type of disruption, the cause of the incident, and whether the incident was primary or secondary focus of the article. Wherever this process could not be automated, this information was fed in manually after examining the text of the article.

We found that news coverage of water service disruptions is rare—we estimate it comprises 5-10 articles out of 20,000 NC news articles each year—and did not increase over time. Although coverage rises during severe weather, the most common news attention to infrastructure failure is not tied to weather, planned disruption, or human error—instead, it seems to signal the deterioration we would expect to see in aging systems.

5. Summary

We developed an inductive, network-based method for multicriteria assessment of community water system performance and capacity. Applying our approach to 319 North Carolina water systems, we found that vulnerabilities are dispersed: poor performance on one dimension, especially compliance with safe drinking water regulations, does not indicate poor performance on other dimensions. Yet we found high correlation among financial vulnerabilities—in particular, systems struggling to meet their debt obligations tended to serve disproportionately low-income populations. Our results demonstrate the tradeoffs that water systems face in balancing affordability against the capacity to deliver drinking water reliably over the long term. They also point to interventions that may be appropriate in different circumstances: some large water systems with heavy debt obligations have unusually low water rates, indicating opportunity for increased revenue collection, but the same was not true among the small systems in our analysis. Our analysis of news coverage indicates that public signals of water system vulnerability are rare, adding to the challenge of garnering public approval for increased local investment in water infrastructure.

6. Conclusion

A multicriteria assessment offers promise for theory-testing across various empirical contexts and can furnish actionable information to decision makers and managers seeking guidance in making strategic policy decisions within multi-agency settings. We carried out our work while NC's State Water Infrastructure Authority and the Local Government Commission were developing the Viable Utility Program and used much of the same data. Our purpose was different, however: whereas the Viable Utility Program seeks to identify particular utilities in need of assistance, our aim was to identify patterns in vulnerabilities across water systems to inform policy-making that addresses multiple systems. We have maintained ongoing communication with partners in state water agencies about our methods and findings, highlighting what can be learned from our research about the distribution of vulnerabilities across different-sized water systems, and we have conducted broader outreach with water systems about the service area maps (Mullin 2021). Members of our team have met four times

with federal officials about applying knowledge from our vulnerability assessment to tools and requirements for the equitable distribution of water infrastructure funding under Justice40.

Our analysis underscores how focus on any single dimension may be insufficient to improve overall system sustainability. Using multiple criteria to test theory and to inform decision making will be increasingly important, especially under dynamic and uncertain social, ecological, and climate conditions. Future work that builds on knowledge of vulnerability profiles across different systems will be essential for achieving this end.

7. Recommendations

- Regulators and researchers should not draw overly broad conclusions from any one measure of water system vulnerability, as it may be weakly related to other vulnerabilities.
- Policy interventions to improve water systems' fiscal viability need to consider economic conditions in the communities served. Water rate increases can threaten affordability for systems serving small, low-income customer bases. In some cases, state assistance could help local water systems design rates that generate adequate revenue without jeopardizing affordability. In other cases, reaching viability may require state policies to share revenue and resources across water systems or to promote system consolidations.
- In evaluating water systems' fiscal viability, overall debt burden is a less informative measure than indicators that incorporate revenue generation.
- Multicriteria assessment can distinguish isolated water system vulnerabilities from those that signal more systemic challenges and help agencies responsible for water system compliance, funding, and planning coordinate their activities.

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Bell, Emily V., Katy Hansen, and Megan Mullin. n.d. Multicriteria assessment of capacity for state oversight of U.S. drinking water systems. Revise and resubmit at *Journal of Water Resources Planning and Management*.

Gonsenhauser, Rachel, Katy Hansen, Walker Grimshaw, Jannette Morris, Klaus Albertin, and Megan Mullin. 2020. Digitizing a statewide map of community water system service areas. *Journal of the American Water Works Association* 112 (10): 56-61.

Hansen, Katy, Shadi Eskaf, and Megan Mullin. 2021. Avoiding punishment? Electoral accountability for local fee increases. *Urban Affairs Review*. doi: 10.1177/1078087421992116.

Mullin, Megan. 2020. The effects of drinking water service fragmentation on drought-related water security. *Science* 368: 274-277.

Mullin, Megan. 2021. Learning from local government research partnerships in a fragmented political setting. *Public Administration Review* 81: 978-982.

Otero, Catherine, Emily V. Bell, Sarwari Das, and Megan Mullin. n.d. North Carolina newspaper coverage of disruptions to drinking water delivery and quality. In preparation for submission to *Journal of the American Water Works Association.*

Appendix 1: Abbreviations and symbols

DWR: Division of Water Resources
EFC: Environmental Finance Center, University of North Carolina-Chapel Hill
LWSP: Local Water Supply Plans
SDWA: Safe Drinking Water Act
SDWIS: Safe Drinking Water Information System

Appendix 2: Products

Journal articles

Bell, Emily V., Katy Hansen, and Megan Mullin. n.d. Multicriteria assessment of capacity for state oversight of U.S. drinking water systems. Revise and resubmit at *Journal of Water Resources Planning and Management*.

Gonsenhauser, Rachel, Katy Hansen, Walker Grimshaw, Jannette Morris, Klaus Albertin, and Megan Mullin. 2020. Digitizing a statewide map of community water system service areas. *Journal of the American Water Works Association* 112 (10): 56-61.

Mullin, Megan. 2021. Learning from local government research partnerships in a fragmented political setting. *Public Administration Review* 81: 978-982.

Otero, Catherine, Emily V. Bell, Sarwari Das, and Megan Mullin. n.d. North Carolina newspaper coverage of disruptions to drinking water delivery and quality. In preparation for submission to *Journal of the American Water Works Association.*

Outreach documents

Estimating and mapping North Carolina's Drinking Water Service Areas. November 2021.

Vulnerability comparison for North Carolina Community Water Systems. December 2021.

Presentations

Presentation on the panel "Natural disasters and the politics of infrastructure," American Political Science Association annual meeting, Seattle, September 2021.

Presentation on the panel "Political-ecological systems: Innovations in connecting environmental data, scales, and impacts to political processes," Western Political Science Association annual meeting, virtual, April 2021.

Lightning student presentation titled "North Carolina newspaper coverage of drinking water disruptions," WRRI Annual Conference, virtual, March 2021.

Communication of results

Consultation with state and local officials and water industry stakeholders:

Participation at Confluence Conference, Asheville, December 2021.

Participation at NC AWWA-WEA Annual Conference, Winston-Salem, November 2021.

Participation at Aspen-Nicholas Water Forum, virtual, October 2021.

Ongoing consultation with officials in the Division of Water Resources and the Division of Water Infrastructure at NC DWR.

Consultation with federal officials:

Katy Hansen presented and met with members of the Justice40 team (from the US Digital Service in partnership with the Council on Environmental Quality (CEQ)) three times about water and wastewater-related data issues, in particular about using the data and methods from our vulnerability assessment for tracking the benefits of investments in water systems.

Megan Mullin met with program leaders of the Clean Water and Drinking Water State Revolving Fund (SRF) programs at the U.S. Environmental Protection Agency about a related topic: using data already collected by state agencies to track the benefits of SRF-funded investments.