Global Environmental Change 84 (2024) 102798

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Broadening resilience: An evaluation of policy and planning for drinking water resilience in 100 US cities

Mirit B. Friedman[a,*], Sara Hughes[b], Christine J. Kirchhoff[c], Eleanor Rauh[b], Chesney McOmber[d], Davis J. Manshardt[e], Jalyn M. Prout[b]

[a] Taubman College of Architecture and Urban Planning, University of Michigan, Ann Arbor, MI 48109, United States
[b] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109, United States
[c] School of Engineering Design and Innovation, Pennsylvania State University, State College, PA 16801, United States
[d] Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT 06269, United States
[e] Department of Natural Resources and the Environment, University of Connecticut, Storrs, CT 06269, United States

ARTICLE INFO

Keywords:
Drinking water
Resilience
Measurement
Policy
Infrastructure

ABSTRACT

Around the world, drinking water systems provide safe, accessible drinking water to the communities they serve. While they are faced with a growing number of short and long-term challenges, assessing the resilience of drinking water systems—or their ability to cope with disturbances and surprise and continuously adapt to stress and change—is an ongoing challenge. Many drinking water resilience assessment methodologies focus narrowly on the technical dimensions of the resilience of infrastructure systems, ignoring the human or environmental dimensions, and consider resilience to the present, ignoring resilience to future change. To fill this gap, we developed a conceptual framework and scoring methodology for evaluating municipal-scale policy and planning for drinking water system resilience. Our approach considers social, technical, and environmental elements of resilience at broad spatial and temporal scales. We then used this methodology to assess policy and planning for drinking water resilience in 100 U.S. cities. We found that municipalities are at very different stages in their policy and planning for drinking water resilience, particularly in terms of the attention they give to climate change and their consideration of the broader social dimensions of resilience. Overall, larger cities and those with more liberal populations are likely to have higher policy and planning scores. The findings highlight the variation in municipal policy and planning for drinking water system resilience, and the importance of community characteristics as drivers of resilience planning. Our approach is transferable to assessing resilience for drinking water systems within and beyond the U.S.

1. Introduction

Drinking water systems include critical infrastructure central to public health, environmental sustainability, and community well-being. The resilience of drinking water systems around the world is challenged by rapidly changing environmental, social, and technical conditions (Immerzeel et al., 2019; Garcia et al., 2019). Drinking water system resilience is the ability "to recognize and absorb variation, disturbances, and surprises" and to subsequently evolve through ongoing adaptive management (Mullin and Kirchhoff, 2019; Linkov et al., 2013). The policy, planning, and other decisions made by a range of local managers and elected officials can help to prepare and adapt drinking water systems for change and increase their resilience (Milman and Short, 2008; Garcia et al., 2019; Larsen et al., 2016; Hughes et al., 2013). While a growing body of scholarship recognizes the important role policy and planning play in drinking water system resilience (Johannessen and Wamsler, 2017; Quitana et al., 2020), most resilience assessments continue to focus narrowly on the technical dimensions of infrastructure systems and their performance (e.g., EPA CRWU; Quitana et al., 2020). A more holistic and robust understanding of drinking water system resilience requires not only technical dimensions but identification and evaluation of the necessary policy and planning decisions and actions that improve resilience.

Emerging research is beginning to include policy and planning in examinations of drinking water resilience, but these efforts typically stop short of operationalization and empirical measurement

* Corresponding author.
E-mail address: mirit@umich.edu (M.B. Friedman).

https://doi.org/10.1016/j.gloenvcha.2024.102798
Received 28 June 2023; Received in revised form 21 December 2023; Accepted 3 January 2024

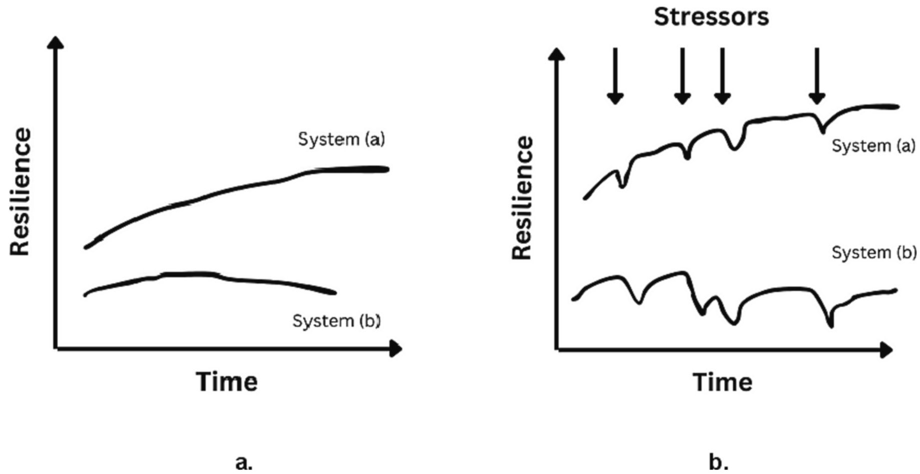

Fig. 1. The resilience of two idealized systems where system (a) considers interconnected social-ecological-technological dimensions and not just bouncing back but also bouncing forward is more resilient over time, while system (b) focuses primarily on technical dimensions of drinking water provision and bouncing back. 1b. System (b) is impacted more and resilience diminishes over time because of multiple external and internal stressors compared with system (a). Inspired by Gunderson and Holling (2002).

(Johannessen and Wamsler, 2017). This omission may be for good reason: the often complex and decentralized nature of drinking water systems can make it challenging to identify and assemble the policy and planning information needed to conduct assessments for a large number of systems. In the U.S. specifically, relevant information is difficult to access, housed in disparate databases, or simply unavailable (Hughes et al., 2023). A challenge, therefore, is developing both data and methods to capture more systematically and empirically the policy and planning activities that underpin and drive drinking water system resilience (Kim et al., 2022).

A second and related need is for greater understanding of the factors or conditions that make municipal-scale resilience policy and planning more likely to occur (Garcia et al., 2019). For example, local decision makers may be compelled to improve resilience due to environmental stress or political pressure from residents; a desire to improve resilience may be impeded by barriers to innovation often experienced in smaller communities (Rommelmann, 1995; Homsy and Warner, 2015; Swann and Deslatte, 2019). Understanding empirically the conditions and contexts associated with policy and planning for drinking water system resilience can provide important insight for those in a position to foster and support such efforts.

Taken together, there are conceptual, methodological, and empirical challenges to resolve in forwarding our understanding of municipal policy and planning for drinking water system resilience. This paper takes up these challenges by asking three key questions: (1) how can policy and planning for drinking water system resilience be effectively measured, (2) how does policy and planning for drinking water system resilience vary between cities, and (3) do community, institutional, and environmental characteristics of drinking water systems explain this variation?

We answer these questions in two steps. First, we develop a conceptual framework and methodology for evaluating municipal policy and planning for drinking water system resilience. The framework includes seven key policy and planning measures and we quantify these measures for 100 drinking water systems using publicly available information. Second, we use secondary data from the Municipal Drinking Water Database (Hughes et al., 2023) to examine quantitatively the extent to which a drinking water system's community, institutional, and environmental contexts explain variation in policy and planning for drinking water system resilience. We use the results to develop new insights into the drivers of drinking water system resilience and important areas for research going forward.

2. Conceptualizing drinking water system resilience

Drinking water systems have long been considered primarily technological systems that rely on engineered physical and chemical processes to treat, convey and store water; this technological view has likewise dominated thinking about the resilience of drinking water systems. This view of drinking water system resilience reflects in part the fact that in the US and many other countries' drinking water systems are highly regulated, and those regulations tend to focus predominantly on ensuring the continuous provision of a safe, reliable water supply through the operation and maintenance of physical infrastructure components. Less consideration is given to planning for changing social or environmental conditions. This technological focus is also reflected in regulators' definitions of resilience. For example, the US Environmental Protection Agency (the primary regulator of drinking water systems), defines resilience to include the "design, maintenance, and operations of [the water system]" that "works together to limit the effects of disasters and enable rapid return to normal delivery of safe water to customers" (Klise et al., 2020, p. 44). While this definition of resilience includes people, their involvement is still conceived narrowly–e.g., operation and maintenance to help recover quickly from disruption (Chu-Ketterer et al., 2023; Quitana et al., 2020, p. 8; Bruneau et al., 2003). The focus is also narrow temporally, e.g., rapid recovery from disasters such as through having redundant treatment trains or backups.

In contrast to regulatory approaches to resilience, over recent decades scholars have begun to recognize drinking water systems as much more than simply technological systems, also considering the social and environmental context within which water systems operate (e.g., Linkov et al., 2013; Lawson et al., 2020). More recently, scholars have begun to think about water and other infrastructure systems as complex, interdependent socio-ecological-technical systems. This broadened perspective is in part driven by the fact that failures often stem from the undesigned, non-linear relationships that emerge when one part of the system (often the technological) is optimized without consideration of the interactions between technical, social, and ecological dimensions which impact system performance (Walker, 2015). By extension then, scholars have begun to conceive of the resilience of these complex systems as the ability to manage complexity, emergence and change (Lawson et al., 2020; Rodina, 2019) and so depending not just on the technological components, but also on social and ecological factors and their interconnections (Marques et al., 2015; Milman and Short, 2008; Quitana et al., 2020). Likewise, emerging engineering and regulatory considerations are beginning to embrace this broader view of resilience

Table 1
Examples of previous research examining drinking water resilience and their attention to the empirical assessment of policy and planning.

Source	Purpose of Analysis	Specific Measures Included	Empirical Assessment of Resilience Measures
Richter et al., 2018	Self evaluation indicator system for urban water sustainability.	Water governance; Emergency preparedness; Water monitoring; Water affordability; Efficiency and conservation; Quality; Watershed Protection	No
Marques et al., 2015	Add 'assets' and 'governance' to environmental, economic, and social sustainability in measurements of urban water sustainability.	Social; Environmental; Economic; Governance; Infrastructure	Yes, Portugal
Gonzales and Ajami, 2017	Consider the local social and institutional factors in urban water system resilience.	Social; Institutional; Supply; Demand; Adaptive capacity	Yes, local case study of the San Francisco Bay Area
Milman and Short, 2008	Develop metrics to determine the ability to continue water service amidst disruptive events.	Supply; Infrastructure; Service provision; Finances; Water Quality; Governance	Yes, three cities (Ceské Budejovice, Czech Republic; San Juan Opico, El Salvador; Nogales, Mexico)
Quitana et al., 2020	Propose a definition of critical infrastructure resilience for drinking water systems.	Social; Technical; Environmental; Organizational; Economic	No
Linkov et al., 2013	Develop a framework that assesses the intersection of systems across the stages of resilience.	Social; Physical; Information; Cognitive;	No
Lawson et al., 2020	Examine impediments to improving the resilience of the water sector, particularly as a socio-technical system.	Technical; Social	Yes, England and Wales
Howard et al., 2021	Develop a system to score rural and small town water systems according to resilience criteria.	Infrastructure; Environmental Setting; Water and Sanitation Management; Supply Chains; Community Governance and Engagement; Institutional Support	Yes, four systems in Nepal and Ethiopia

as encompassing not just technological dimensions, but also human dimensions (Kirchhoff and Watson, 2019). This is because there is increasing recognition that resilience is not achieved by controlling the internal or external stressors that can affect a system, but rather through improving the ability of the system as a whole to respond to stress and change and manage performance (Butler et al., 2017; Mullin and Kirchhoff, 2019; Wilson, 2012).

Resilience thinking is also expanding temporally by going beyond just bouncing back to include also bouncing forward. This kind of resilience involves a range of capacities that go beyond technological robustness and redundancy to include organizational and institutional capacities, e.g., absorptive, adaptive, and transformative capacity (Fallon et al., 2022) that enable systems to manage change and transform over time. It follows then that assessing the resilience of drinking water systems must similarly evolve to broaden the analytic scope to include technical, socio-economic, organizational, and environmental dimensions of resilience (Balaei et al., 2021; Pamidimukkala et al., 2021; Quitana et al., 2020) and their interdependence (Grabowski et al., 2017; McPhearson et al., 2022) and to go beyond bouncing back to also bounce forward and potentially transform. We see this difference manifest in the resilience to internal and external stressors of two idealized systems shown in Fig. 1, where (b) is a system focused primarily on technical dimensions and bouncing back which has lower overall resilience than system (a), a system that considers interconnected social-ecological-technological dimensions of resilience and is not only bouncing back but also bouncing forward. System (b) is impacted more severely by internal and external stressors, takes longer to recover, and gradually becomes less resilient than system (a).

3. Evaluating municipal policy and planning for drinking water system resilience

Realizing the broadened conceptualization of drinking water system resilience discussed above requires a broad suite of policy and planning interventions, such as ensuring equitable access and affordable water to customers (Lawson et al., 2020) and investing in community engagement (Howard et al., 2021). Table 1 provides an overview of a subset of relevant studies of drinking water resilience. While several previous studies recognize the importance of policy and planning (also referred to as "governance") for realizing drinking water system resilience, there has been less progress on specifying and evaluating the specific activities in this category. Past empirical assessments of water policy or governance practices have typically been limited to one or a few case studies and have not provided transferable frameworks for more systematic evaluations.

In the US, while drinking water systems are regulated by the federal government, policy and planning in support of the social, environmental, and technical components of drinking water systems is often the responsibility of local governments. In many communities, the local government manages the drinking water system and is responsible for land use and population growth planning, investing in community health and well-being, ensuring healthy watersheds, and adapting to climate change. We refer to this collection of management capacities and community-centered policy and planning responsibilities across broad spatial and temporal scales (present and future, local and watershed) as *municipal policy and planning for drinking water system resilience.* It plays an important, yet understudied role, in ensuring drinking water system resilience.

More specifically, municipal policy and planning for drinking water system resilience targets the social, environmental, and technical dimensions of drinking water systems and improves resilience through the accumulation and coordination of a range of local policies and planning (Fig. 2). For example, municipalities that center the needs and broader well-being of the community by ensuring the affordability of drinking water and robust communication with consumers about their drinking water are more resilient. Affordability in drinking water systems accounts not only for the ability of the drinking water system to cover their operating costs, but also for the ability of customers to pay those costs (Beecher and Shanaghan, 1998). Unaffordable drinking water bills place undue financial stress on communities (Mack and Wrase, 2017), diminishing the ability of communities to respond to disturbances. Drinking water system affordability programs, such as rate design, water efficiency programs, bill assistance, and crisis relief focus on end user cost reductions and offer relief for rising water costs when applied with community needs in mind (Pierce et al., 2021; Teodoro, 2019). Robust,

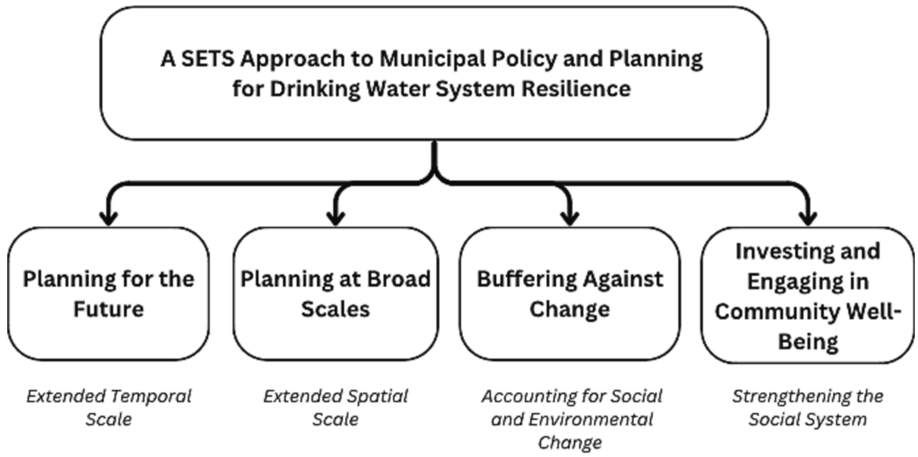

Fig. 2. Conceptual framework delineating the categories of municipal policy and planning that comprise a SETS approach to drinking water system resilience. The four categories of policy and planning incorporate consideration of the social, environmental, and technological components of drinking water system resilience and incorporate attention to expanded temporal and spatial scales.

accessible and transparent communications with communities builds trust (Nicholas and Vedachalam, 2021), which has been shown to make water consumers more likely to support voluntary efforts that increase sustainable water use (Golladay et al., 2021), and enable improved water system resilience (Dilling et al., 2023).

Adaptability and reliability of infrastructure (Marques et al., 2015) indicates physical preparedness for changing conditions. Resilience is improved through inspections and maintenance that keep systems up and running and by long-range investments that help systems prepare for the future (Milman and Short, 2008) and protect against damage (Howard et al., 2021). Similarly, resilience is improved by moving beyond the hyper-local water system itself to include watershed protection and restoration (Richter et al., 2018), pollution prevention (Marques et al., 2015), and flood protection measures (Howard et al., 2021) that protect water quality and quantity. In addition to protecting physical water supplies, engaging in supply and demand management plans allows municipalities to account for variations in environmental conditions and population growth (Milman and Short, 2008; Gonzales and Ajami, 2017; Lawson et al., 2020; Howard et al., 2021) while future-oriented planning broadens resilience beyond a focus on today and recovering quickly from disruption to encompass uncertain future disruptions and broad spatial scales. Future-oriented planning facilitates a long-term view and helps municipalities anticipate and plan for future water system needs (Milman and Short, 2008; Marques et al., 2015). Moving away from traditional planning (Pamidimukkala et al., 2021) to ensure planning is integrated across municipal departments improves resilience. Integrated planning ensures plans made by different departments work together (Berke and Kaiser, 2006; Woodruff, 2022) and align with long-term community development (DeAngelis et al., 2021) across spatial and temporal scales.

We synthesize these policy and planning activities into four key categories of actions that can be taken by local governments to support and build drinking water system resilience, broadly conceived: planning for the future, planning at broad scales, buffering against change, and investing and engaging in community well-being (Fig. 2). This framework elucidates the categories of municipal policy and planning that attend to the multiple social, environmental, and technical dimensions of drinking water systems across broad spatial and temporal scales. Policy and planning within each category independently responds to some facet of drinking water system management, and when integrated are well-positioned to support drinking water system resilience. This framework extends beyond a check box approach common in regulatory requirements, and considers a broader definition of resilient drinking water systems. The framework suggests that if these categories of policy and planning were effectively undertaken by local governments our communities would be better served by more resilient drinking water systems. In Section 4, we describe in greater detail our methodology for measuring these policy and planning elements in US municipalities to develop new insight into the extent to which US local governments are engaged in these various components of policy and planning for drinking water system resilience.

4. Drivers of municipal policy and planning for drinking water system resilience

As discussed above, municipal policy and planning for drinking water system resilience involves a collection of actions that take place throughout local governments. In this study we examine not only the extent to which municipalities are engaging in these practices, but also the conditions and characteristics that are associated with higher levels of policy and planning for drinking water system resilience. Despite growing awareness of interconnections and broader system boundaries, drinking water systems are still largely managed in a silo with decision makers mostly responding to regulatory pressures. Actions that would support resilience might subsequently be ticked off but not fully embraced as an integrated aspect of managing the drinking water system. In many ways drinking water managers and local decision makers are overlaying new ideas onto an old system.

Prior research suggests that social, institutional, and environmental conditions influence local governments' attention to issues of resilience and sustainability (Fallon et al., 2022; Kloosterman et al., 2021; Hughes et al., 2018). Municipalities whose residents are of higher socioeconomic status are often more likely to adopt and implement environmental and social policies of various kinds, presumably reflecting demand for environmental quality and amenities from these residents (Lubell et al., 2009; Svara et al., 2013). Larger and wealthier communities may have greater capacity to prioritize longer-term planning and make additional investments in both infrastructure and governance (Scott et al., 2018). A large body of research has shown that municipalities with more politically liberal residents are also more likely to prioritize infrastructure spending and investment (Einstein and Kogan, 2016; Tausanovitch and Warshaw, 2013; Hajnal and Trounstine, 2010; Vedachalam et al., 2014; Leiserowitz et al., 2011; Hansen and Mullin, 2022) and climate action more broadly (Krause, 2012; Gerber, 2013). A community's racial composition may also play a role in explaining differences in municipal policy and planning for drinking water resilience given historical racial disparities in infrastructure investment, drinking water costs, and climate risk (Butts and Gasteyer, 2011).

The environmental conditions and context of a municipal drinking water system may also drive decisions about resilience policy and

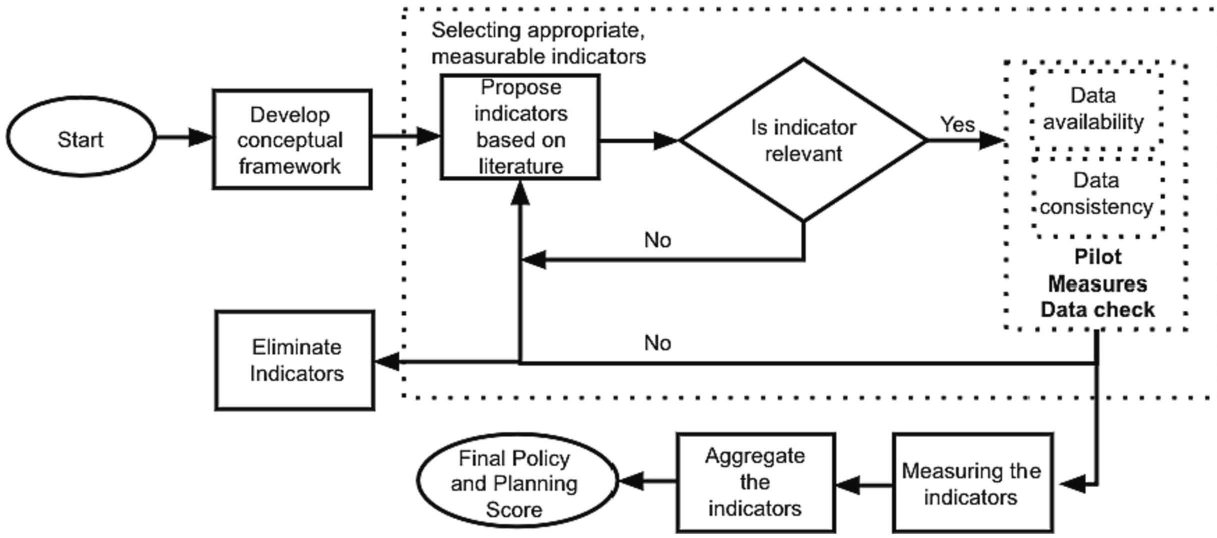

Fig. 3. Process for identifying and operationalizing specific municipal policy and planning actions for drinking water system resilience (process). adapted from Balaei et al., 2021

Table 2
Definitions of the municipal policy and planning actions for resilient drinking water systems.

Resilience Policy and Planning Category	Action	Definition
Planning for the Future	Capital Improvement Planning	The municipality strategically plans for capital investments in drinking water infrastructure. There is evidence of prioritizing where capital investment is needed, over a medium to long-term time frame. This could come in a dedicated plan/document or embedded elsewhere.
	Climate Change Planning	The municipality is planning for the implications of climate change for the municipality's drinking water system. This could come in the form of an actual or dedicated climate change plan; a climate change component to a comprehensive plan; or be embedded in a larger or broader plan of some kind.
Buffering Against Change	Supply Management	The municipality diversifies where it gets their water supply. The municipality has access to more than a single aquifer (groundwater) or surface water source, purchases additional water, or has backup access to supplies.
	Demand Management	The municipality manages and/or reduces future demand for water from population growth and industry water use.
Planning at Broad Scales	Watershed Protection	The municipality employs policies to protect and conserve the watershed that supplies their drinking water.
Engagement and Community Well-Being	Affordability	The municipality has policies and programs in place to support affordability goals for drinking water users.
	Communication	The municipality communicates effectively with the public via a Consumer Confidence Report using detailed tables, graphics, and explanations of their drinking water quality.

planning. Infrastructure failures and subsequent drinking water quality challenges can raise the salience of drinking water planning for communities and decision makers (Milman and Short, 2008; Marques et al., 2015; Richter et al., 2018). If drinking water systems struggle with regulatory compliance or have health-related drinking water quality violations, they must remediate these issues (Kirchhoff et al., 2019) which may also elevate the importance of resilience policy and planning for decision makers. Similarly, resilience policy and planning may be more salient for communities already facing high drinking water service costs. Drinking water systems in areas already water stressed or facing increased water stress may be more likely to engage in proactive and forward-looking planning (Hughes et al., 2013; Kirchhoff et al., 2016; Hughes et al., 2018), though research has shown this is not always the case (Garcia et al., 2019).

Finally, the institutional and organizational context of municipal drinking water systems can also influence policy and decision making. Organizational capacity is a strong and consistent predictor of whether municipalities engage in sustainability planning efforts (Swann and Deslatte, 2019). Investing in planning and preparedness can be easier for larger communities and correspondingly larger drinking water water systems that have more technical, human, and financial resources in the form of staff or revenue (Kirchhoff, 2013; Marcillo and Krometis, 2019; Rommelmann, 1995). For example, Michigan cities with in-house planning staff and higher income residents are more proactive in coastal planning (Norton et al., 2018) and in the Pacific Northwest and Southwestern U.S., well-resourced water systems have been shown to be more likely to engage in long-term planning (Kirchhoff, 2013). At the same time, larger systems often face greater organizational and financial challenges in managing their drinking water infrastructure, compared to smaller systems (McFarlane and Harris, 2018). In the US, local governments have either an elected mayor or an appointed city manager as the chief executive, and these differences in institutional structures influence the extent to which local officials are accessible and responsive to public opinion (Lubell et al., 2009; Gerber, 2013), and therefore responsive to sustainability policy priorities (Bae and Feiock, 2013).

These known drivers of municipal policy and planning, together with our conceptual model (Fig. 2), inform our empirical analysis of municipal policy and planning for drinking water resilience. In the following section we describe our methods for collecting data on both the measures and drivers of policy and planning for resilience for 100 municipal drinking water systems in the U.S.

5. Methods

5.1. Measuring municipal policy and planning for drinking water system resilience

It is important not only to further conceptualize a broader version of drinking water system resilience but to also begin to measure how well local governments are doing in developing the policy and planning necessary to achieve this resilience. To operationalize the categories of policy and planning municipalities can undertake for drinking water system resilience depicted in Fig. 2, we evaluated a set of possible actions using an iterative and deliberative process adopted from Balaei et al. (2021) (Fig. 3). We first examined 33 papers that discuss resilience in water and infrastructure. From these papers we identified 14 relevant actions spanning four categories of planning and policy for drinking water resilience.

We then performed a pilot application of these 14 actions for a subset of 20 cities to check for data availability and consistency. Based on the findings from this first phase of data collection, the seven of 14 actions were eliminated: number of water main breaks, time of last major investment or plant upgrade, presence on social media, posted board meeting minutes, number of mouse clicks to get to CCR, drinking water testing and monitoring protocols, and staffing. These actions were eliminated due to limited data availability, inconsistencies in the availability of information across municipalities, or concerns raised during the pilot regarding suitability of the actions as a reliable indicator of drinking water system resilience. For example, the research team was only able to find information about water main breaks for 6 of the 100 municipalities. Similarly, information about the last major investment or plant upgrade was often only available through external news sources, which raised questions about the consistency of the availability of the information across diverse communities (Mullin and Hansen 2022). The final scoring guide can be found in Table A1.

Following the pilot application, seven actions remained for which consistent and reliable data could be collected using publicly available information: capital improvement planning, climate change planning, supply management, demand management, watershed protection planning, affordability programs, and communication. These seven actions represent distinct, non-overlapping areas of planning and policy that collectively support the broader conception of drinking water system resilience described in section 2. Each action is defined in Table 2.

5.2. Applying and assessing policy and planning actions

We selected 100 drinking water systems for data collection and analysis from the Municipal Drinking Water Database (MDWD) (Hughes et al., 2023), a sample size that balances the feasibility of data collection with sufficient power for statistical analysis. Our focus on local governments with municipally owned and operated drinking water systems allows us to maintain consistency in management contexts; this need to control the management context means the sample does not reflect the diversity of institutional arrangements across all drinking water systems (Dobbin and Fencl, 2021). Given the importance of capacity, including financial resources on the capability of water systems to invest in planning and preparedness (Kirchhoff, 2013; Marcillo and Krometis, 2019; Rommelmann, 1995), we first stratified the 2,219 community water systems in the MDWD based on financial condition. Specifically, we stratified the municipalities in the MDWD into quantiles (1) low revenue and high debt (HH high stress), 2) low revenue and low debt (HL high revenue stress), 3) high revenue and high debt (LH high debt stress), and 4) high revenue and low debt (LL low stress) and then randomly sampled twenty-five municipalities from each quantile.

Once the sample was finalized, we performed web searches to collect publicly available information about the seven actions for each municipal drinking water system. Searches were exhaustive, inclusive of drinking water system websites, municipal and county government websites, relevant planning documents, and broader internet searches. Information about what municipalities have in place for each action was then analyzed and scored on a scale from 0 to 2 to capture variation in how well the municipalities were taking on each action. The scale was driven by our focus on policy and planning for resilience across temporal and spatial scales, and with a social-ecological-technical systems approach (Appendix A; Table A1). We ensured consistency in scoring such that a 0, 1 or 2 captured the same degree of resilience, from narrow conceptualizations of resilience (0) to broad (2). For each of the seven actions, a score of zero indicated the municipality had no identifiable strategies, a score of one indicated the municipality had some identifiable strategy, and a score of two indicated the municipality had more than a single identifiable strategy. Each municipality therefore received a score of 0, 1, or 2 for each of the seven actions.

Scores for each municipality were assigned and revised through a robust multi-step process. First, four graduate students performed web-based searches for data on each action and for each municipality. Each student was assigned to score twenty-five cities across all seven actions. To check for internal consistency, students met weekly with the research team to resolve issues and iterate to ensure consistency in scoring approaches. Despite these efforts, an inter-coder reliability check revealed the need to further improve consistency across the application of scores. As a result, a second round of scoring was implemented using a recursive process where the seven actions were divided between team members. Three research team members scored all cities for their assigned actions. As issues came up in the scoring process, they were cataloged and reviewed by the full research team and definitions and qualifying examples were updated for the actions accordingly (Appendix A; Table A2). This second round of scoring improved the internal consistency across the scoring for each action.

Once finalized, the seven individual scores for each municipality were then added together to create the cumulative resilience score. The scoring range was therefore granular enough to distinguish more than the presence or absence of a policy and planning action, while minimizing the potential for judgment errors that come with a finer scale. The greater the total score, the more a municipality considered both broader temporal and spatial scales and multiple dimensions of socio-ecological-technical resilience.

Finally, we incorporated data that would allow us to examine the extent to which social, political, and environmental conditions and contexts are associated with higher or lower total scores for policy and planning for drinking water system resilience. Building on prior research discussed in section 3, we operationalized the social context of municipalities using community socioeconomic characteristics: percent Black, percent Hispanic, median household income, and political ideology. Our expectation is that communities with larger population size, smaller Black and Hispanic populations, higher median household incomes, and more liberal political ideologies will have higher policy and planning scores. We operationalized environmental and system conditions using average monthly moisture index values (Willmott and Feddema, 1992; Teodoro 2010) and the number of Safe Drinking Water Act (SDWA) health violations received in the past 5 years. Our expectation is that municipalities with lower monthly moisture index values (more arid conditions) and more health violations will have higher policy and planning scores due to the salience of drinking water resilience.

We operationalized institutional and organizational characteristics of municipalities as population size, whether the municipality has a mayor or manager-led form of government, its debt-to-revenue ratio, its total revenue per capita, and monthly water costs (indicative of the cost of basic monthly water service at a rate of 6,000 gallons per month (Teodoro, 2018)). We use population size as a proxy for system size as population size and system size are highly correlated. We anticipate that larger systems, or systems serving larger populations have greater organizational and financial capacity, and thus are more likely to engage in drinking water resilience policy and planning. As discussed previously, mayor and manager-led local governments have been shown to

Table 3
Descriptive Analyses of Individual and Total Policy and Planning Scores.

Action	Mean	Minimum	Median	Maximum
Capital Improvement Planning	1.49	0	2	2
Climate Change Planning	0.76	0	0	2
Supply Management	1.1	0	1	2
Demand Management	1.13	0	1	2
Watershed Protection	0.52	0	0	2
Affordability	0.48	0	0	2
Communication	0.83	0	1	2
Total Score	6.31	0	7	14

Table 4
Full regression results for explaining total resilience scores using social, institutional, and environmental independent variables.

	Variable	Estimate	Standard Error
	Intercept	−6.5*	2.89
SOCIAL	Total Population (log)	1.45***	0.267
	Percent Black	−0.022	0.019
	Percent Hispanic	−0.14	0.015
	Median Income	1.07E-05	1.32E-05
	Political Ideology	−7.18***	1.85
INSTITUTIONAL/ ORGANIZATIONAL	Debt Ratio	0.021	0.055
	Revenue Per Capita	−2.60E-05	3.12E-04
	Form of Government	0.38	0.57
	Monthly Water Costs	−0.0022	0.014
ENVIRONMENTAL	Health Violations	−0.59	0.57
	Monthly Moisture	−0.27	1.17

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1.
Residual standard error: 2.147 on 79 degrees of freedom.
Multiple R-squared: 0.6811, Adjusted R-squared: 0.6003.
F-statistic: 8.436 on 20 and 79 DF, p-value: 1.622e-12.

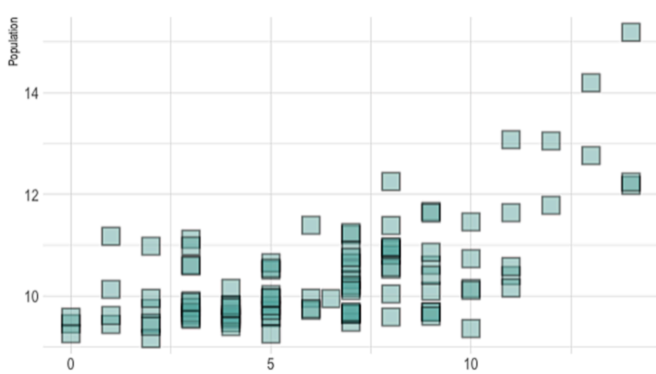

Fig. 4. Total population had a positive relationship with total score, where the larger the population, the higher the total resilience score.

have different levels of responsiveness to political preferences and long-term investment needs. Our expectation is that manager-led municipalities will have higher policy and planning scores. Debt-to-revenue ratios and total revenue per capita have been found to perform well as predictors of financial emergencies and changes in service provision, and provide information about a city's revenue stream and its broader financial position. Changes in revenue per capita is considered a good measure of the sustainability of a city's financial condition (Gordon 2018). Revenue per capita is also a clear manifestation of the broader economic conditions that lead to financial stress in city governments, such as a loss of population, declining home values, and rising poverty rates (Brookings Institution 2016). Both measures have been found to be significantly related to perceptions of financial stress by city government officials (Kim and Warner 2020). Our expectation is that municipalities with lower debt-to–revenue ratios and higher revenue per capita will have higher policy and planning scores.

Data on the social, institutional, and environmental drivers of policy and planning for drinking water resilience were drawn from the MDWD (Hughes et al., 2023). Based on these variables we found the sample of 100 municipalities to be largely representative of the full set of municipal drinking water systems in the MDWD (Appendix B; Table 1B).

6. Results

To understand variation in total scores and the drivers of scores, we used descriptive statistics and linear regression models. Descriptive analyses of the drinking water policy and planning resilience scores are shown in Table 3. The median score was 7 and the mean score was 6.34. Three municipalities received the maximum score of 14: Los Angeles, Salt Lake City, and Tacoma. All three are in the western part of the U.S. and are large, but face very different climatic and demographic conditions. We also found that three municipalities received the minimum score of 0: Grenada and Greenwood, Mississippi and Union City, Tennessee. All three of these municipalities are in the southern part of the U. S. and have relatively small populations (below 15,000). Among the individual actions, municipalities scored the lowest on affordability programs and watershed protection, and highest on capital improvement planning and demand and supply management. Correlation tests showed no significant correlations among actions (Appendix B; Table 2B).

To determine the overall impact of each action on the total scores, and whether the actions independently contribute to a composite assessment of a municipality's policy and planning for drinking water system resilience (the latent variable), we performed a Confirmatory Factor Analysis (CFA). The CFA showed that capital improvement planning has the greatest influence over the total score, while affordability programs have the lowest influence. Model fitness tests, including the Comparative Fit Index (0.889), the Tucker Lewis Index (0.833), the Root Mean Square Error of Approximation (0.097), and the Model Chi-square (0.018), indicate that the individual actions fit together well enough to comprise a composite score. That is, each action captures a different, but complementary aspect of a municipality's policy and planning efforts.

Finally, we used linear regression to understand the drivers of variation in total scores. We regressed the total scores against our eleven social, institutional and environmental context variables. Note, additional exploration of the relationship between EPA region and total score and political ideology can be found in Appendix C.

The final regression results indicate the main drivers of higher scores are total population and political ideology (Table 4). Population size has a positive and significant relationship with total score (Fig. 4), while political ideology has a negative and significant relationship with total score; specifically, the more liberal the community, the higher the total score (Fig. 5). The financial variables were not found to be significant in driving policy and planning for resilience. The adjusted R-squared value for the model was 0.6003.

7. Discussion

This study advances conceptual, methodological, and empirical understanding of municipal policy and planning for drinking water system resilience. Whereas traditional modes of thinking about drinking water systems focus on balancing supply and demand as populations change, and focus on the near term through capital improvement planning and ensuring compliance with water quality standards, more resilient drinking water systems include more future-oriented policy and planning to respond to possible system disruptions from climate change; more resilient systems also focus on more than their physical

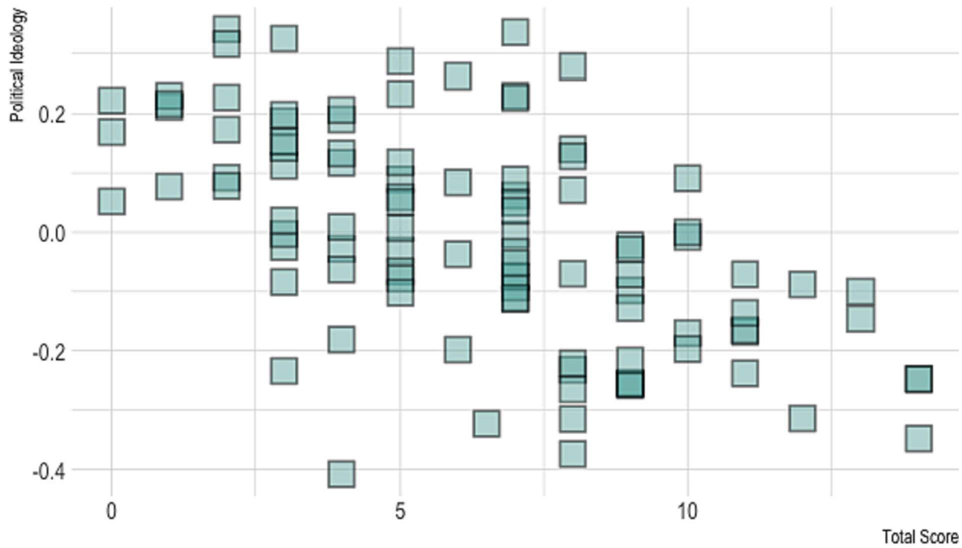

Fig. 5. Political ideology had a negative relationship with total score, where the lower the political ideology value (more liberal), the higher the total resilience policy score.

infrastructure, investing in the well-being and engagement of their community through affordability programs and improved communication. In operationalizing this expanded conceptualization of drinking water system resilience, we offer new insights into the how and why local governments in the US are taking action.

Our analyses showed that, overall, US municipalities are further along in policy and planning actions related to supply and demand management and capital improvement planning. These relatively higher scores reflect the strengths of continued attention to traditional drinking water management approaches. As a result, performance on four actions largely distinguished between the municipalities with higher and lower total scores: affordability programs, communication through the consumer confidence report, climate change planning, and watershed protection. These four measures represent some of the considerations central to our framework: acting at broader spatial (watershed) and temporal (climate change) scales, and considering the broader social dimensions of drinking water resilience such as affordability of services and establishing strong relationships between the water service provider and the community, such as through robust communication efforts. These results indicate the need for greater investment and attention to these municipal policy and planning actions to strengthen the resilience of drinking water systems.

Our analysis also offers insights into the conditions currently associated with greater investment in policy and planning for drinking water resilience in the U.S. The results suggest that population size (a proxy for system size) and political ideology are the two primary predictors of policy and planning for municipal drinking water system resilience. These findings are consistent with previous research showing larger municipalities are responding more to climate change (Hughes et al., 2018; Kirchhoff, 2013) and achieve efficiencies when operating water systems at larger scales (Shih et al., 2006) due to increased capacity and economies of scale. These findings also reinforce the continued importance of attention to, and investment in, the hundreds of smaller drinking water systems serving US communities (Allaire et al., 2018; Klasic et al., 2022; McFarlane and Harris, 2018).

Looking more closely at the actions of more liberal municipalities, we find they are more likely to have climate change plans, supply management plans, watershed protection plans, robust consumer confidence reports, and affordability programs. More conservative municipalities tended to receive lower scores in climate change planning and consumer confidence reports in particular. These findings reflect those from previous studies that have found links between local politics and climate adaptation planning in local governments (Wood et al., 2014) and between political ideology and funding and preferences for environmental protections (i.e., watershed protection plans and climate change planning) (Wolters and Steel, 2021).

While this study empirically and theoretically forwards scholarship on drinking water system resilience, our analysis was focused on a particular subset of water systems and limited by the lack of publicly available data. First, drinking water systems have diverse institutional forms (Dobbin and Fencl, 2021), but we focused on municipally owned and operated drinking water systems to maintain consistency in management contexts. Second, regarding data, we had hoped to include measures of infrastructure condition and performance such as water main breaks and time of last major investment or plant upgrade. However, collecting these data for a large number of municipal drinking water systems proved prohibitive, as the availability of these data was inconsistent. The lack of available data on physical system vulnerabilities and performance, or a broader range of technical and financial capacities, limits our understanding of policy and planning for drinking water system resilience and points to potential opportunities for both researchers and policy makers if such data were made available.

While relying on publicly available information enabled us to collect information for a large number of municipalities relatively quickly and at relatively low cost, it is difficult to confidently know how well a municipality's policy and planning efforts are accurately represented on their webpage or in other publicly available materials and documents. While we took many steps to ensure a comprehensive and robust search and scoring process, this methodological choice could potentially bias our results. For example, if materials and information may be more readily available in large cities with greater capacity to share and in liberal cities where sharing is more likely to generate favorable political returns, that availability might contribute partially to the relationship we found between population size, political ideology, and climate resilience planning. However, each municipality in our sample was ultimately subjected to the same biases, as our data collection methods were consistent across each municipality. This is an area ripe for further exploration, but given limitations of other data collection methods in terms of costs, response rates, and time intensiveness, our reliance on public data is a reasonable alternative and appears to offer an effective means to gain a broad understanding of policy and planning conditions across a broad set of municipal drinking water systems.

Table A1
Scoring Guide.

Measure	Score		
	0	1	2
Capital Improvement Planning	There are no CIPs or budgets on the website, water related or unrelated to the water system.	The available annual budget includes funding specific to the drinking water system	Water system projects are specifically in a capital improvement plan that extends beyond 1 year, despite the level of information or where information is located.
Climate Change Planning	No climate change planning on the website or mention of 'climate change' in any planning documents.	Climate change (or global warming) is mentioned in planning documents or in a climate change specific plan, but there is no mention of the drinking water system.	Climate change impacts on drinking water are considered and planned for
Supply Management	The city relies on a single source.	The city relies on a mix of local sources (groundwater and/or surface water from different sources) or they purchase water.	Interconnection (physical interconnection - pipe and valve to nearby system that is opened for emergency/issue use, alternative water supply (water reuse/purple piping); Evidence of system interconnection/ alternative water supply (e.g., recycled water), as well as diverse local sources or plans to diversify local sources.
Demand Management	No planning for demand management.	Only one strategy is employed.	More than one strategy is used.
Watershed Protection	There is no watershed protection planning at the municipal level.	One strategy for watershed protection is discussed in planning documents or on the website.	More than one strategy for watershed protection is discussed in planning documents or on the website (i.e. source monitoring beyond state, collaboration for protection).
Affordability	No strategies are employed.	Only one strategy is employed.	Multiple strategies are offered.
Communication	The CCR included one or none of the following: tables, graphics, or explanations.	The CCR included 2 of the following: tables, graphics, or explanations.	The CCR included a table that had valuable information that was easily accessible and understandable, a graphic that aided understanding of the information in the CCR, and an explanation of the information above and beyond the minimum language required by the EPA and the state.

8. Conclusion

Municipal policy and planning that incorporates broad considerations of temporal and spatial scale, and broad considerations of social, environmental, and technical dimensions of drinking water systems, is critical to preparing for current and future shocks and stressors both from climate and other changes. This study proposes a new framework for examining policy and planning for drinking water resilience and develops methods for operationalizing these concepts using publicly available information. Applying these methods to gather new data allowed us to assess policy and planning for drinking water resilience for a large number of US municipalities, and the conditions and contexts that drive these efforts.

Our framework and methodology can serve as a resource or adaptable template for scholars and analysts within and beyond the US. Research in different institutional contexts could examine whether local governments make decisions differently when their drinking water is provided by a special district or private utility (e.g., they do not own and operate the water system), or when they hold different kinds of authority and responsibility for drinking water, as might be the case in countries with more centralized management. For those in a position to fund or advocate for local policy and planning, the results also highlight where needs and gaps lie. For example, given that population size was one of the strongest predictors of more future- and community-oriented policy and planning important for resilience, this is yet more evidence of the need to support improving the resilience of smaller communities and systems. Investments in relevant data collection and storage can also support these efforts.

The results also point to important areas for future research. Given the role that climate change, affordability, and watershed planning play in distinguishing between high and low scoring municipalities, future research is needed to examine the dynamics behind these particular policy and planning elements for municipal drinking water systems in greater depth. For example, why are municipalities with more conservative residents less likely to account for climate change in their drinking water planning? Further examination of the pathways through which these ideological differences translate to policy and planning action and inaction would be highly beneficial for both theory and practice. Similarly, better understanding what distinguishes communities with and without affordability supports, or those that undertake more comprehensive watershed planning, would help illuminate opportunities and barriers to building resilience. Our approach measures the presence and quality of policy and planning actions, but additional research could explore the integration of these or the cultural shifts that underpin them. With a larger sample size, future research could also explore the effect of state level policy variation. Beyond the US, scholars could build on our framework and adapt its operationalization to local contexts and data availability, providing an opportunity to test the consistency of our predictors.

Drinking water systems are critical for public health and community development, and as we invest in the organizations and governments that manage these systems it is important to find opportunities to support the policy and planning measures that underpin resilience. Our study provides new approaches for conceptualizing and measuring the broadened approach to resilience policy and planning that accounts for the socio-ecological-technical dimensions of drinking water systems.

Table A2
Measure Refinement Example.

Measure	Municipality	Issue	Discussion	Decision Justification
Capital Improvement Planning	Centralia City	The city has a budget with water included in it, but $0 allocated to water spending between 2017 and 2023. Should they get a 1?	There's no other evidence of budgetary planning or capital improvement planning.	Without evidence of spending on their water system or a capital improvement plan, they do not get credit. Decision: 0
Climate Change Planning	Horseheads City	They mentioned climate change once on a page related to energy benchmarking. Does this get them a 1?	Energy related climate change work is mitigation. The drinking water system resilience is more about adaptation.	Energy benchmarking isn't related to the water system. Decision: 0
Supply Management	Blue Springs	The city is able to purchase more water from an alternative supply if necessary. Does purchasing more water when needed qualify as a backup supply?	Purchasing more water from a different source provides additional supply access.	Purchasing more water is considered a backup supply. Decision: 2
Demand Management	Holyoke	Found a draft ordinance for watering restriction from 2012, but can't find any evidence if it has been adopted.	City ordinances were reviewed as a team.	No watering restriction ordinance was found. The 2012 draft is out of the 10 year timeframe. Decision: 0
Watershed protection planning	Farmington	The city has a drafted Source Water Protection plan from 2017. No plan has been approved.	While the draft plan exists, no approved plan or update exists.	Since watershed protection is discussed in a plan, it receives a 1. Decision: 1
Affordability	Longwood City	Has promoted a conservation rebate program to help lower water bills, but rebates are part of the Demand Management definition.	Although their ordinance speaks about this as an affordability improvement, this seems to tackle local conservation measures more.	Rebates have been, and will continue to be, included in the Demand Management indicator definition only. Decision: 0, but apply this strategy to their Demand Management score.
Communication	Mercedes	On page 5 of the CCR, the city reported that it had failed to collect the required number of triggered source bacteriological samples following a positive total coliform test in its system.	The city is required to report such violations to its customers, but should Mercedes still get credit for being so transparent about its violation?	Mercedes received credit for its explanation of its violation because the city was so transparent about it. While some cities try to bury their violations deep in the CCR where customers are unlikely to see them, Mercedes dedicated a whole page to explaining its violation. Decision: 1

Table 1B
Representativeness of the sample of 100 municipalities relative to the 2,219 municipalities in the Municipal Drinking Water Database, using the drivers of resilience.

Variable	Mean - Full	Mean - Sample	Std. Dev. - Full	Std. Dev. - Sample	Min - Full	Min - Sample	Pctl. 50 - Full	Pctl. 50 - Sample	Max - Full	Max - Sample
Debt:Revenue Ratio	1	2.037	1.326	4.516	0	0	0.761	1.333	37.478	37.478
Revenue Per Capita	$951.0	$1,118.6	$653.1	$885.9	$19.5	$21.7	$743.2	$638.7	$5,923.2	$4,639.2
Total Population	63,022	104,011	238,089	420,611	7,952	9,535	26,526	24,527	8,560,072	3,949,776
Percent Black	11.8	13.5	16.4	17.7	0	0.11	5.03	7.04	96.6	94.26
Percent Hispanic	16.0	20.7	19.1	25.7	0	0.72	8.15	7.7	99.1	94.3
Median Household Income	$60,380	$56,804	$26,665	$22,262	$15,699	$26,583	$52,936	$51,403	$250,001	$114,354
Climate Moisture Index	0.162	0.093	0.341	0.382	−0.95	−0.91	0.29	0.2	0.85	0.58
Form of Government	0.367	0.28	0.482	0.451	0	0	0	0	1	1
Health Violation	0.167	0.27	0.373	0.446	0	0	0	0	0.373	1
Political Ideology	−0.025	−0.008	0.203	0.181	−0.693	−0.408	−0.023	−0.015	0.203	0.34
Monthly Water Cost	$38.62	$37.12	$16.34	$16.66	$4.98	$10.31	$35.64	$32.51	$16.34	$96.69

Table 2B
Correlation matrix of all seven measures.

	Affordability Program	Capital Improvement Plan	Climate Change Plan	Demand Management Plan	Supply Management	Watershed Protection	Communication
Affordability Program	1.00	0.24	0.12	0.33	0.11	0.35	0.14
Capital Improvement Plan	0.24	1.00	0.46	0.45	0.39	0.30	0.14
Climate Change Plan	0.12	0.46	1.00	0.26	0.40	0.38	0.30
Demand Management Plan	0.33	0.45	0.26	1.00	0.29	0.34	0.33
Supply Management	0.11	0.39	0.40	0.29	1.00	0.16	0.22
Watershed Protection	0.35	0.30	0.38	0.34	0.16	1.00	0.30
Communication	0.14	0.14	0.30	0.33	0.22	0.30	1.00

Funding

This work was supported by NSF Award# 2048505(S.H., C.K.).The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

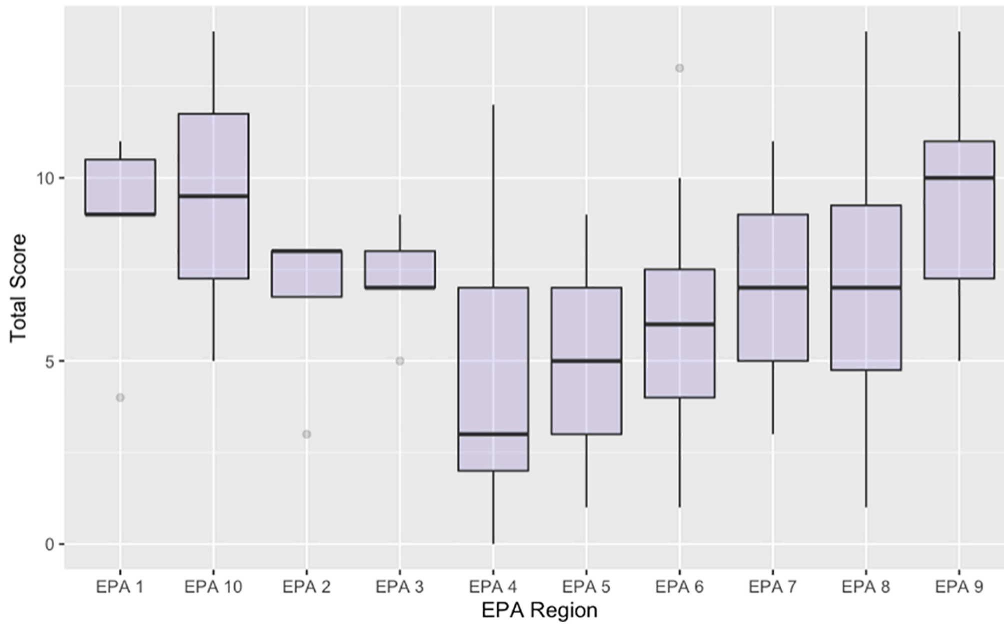

Fig. C1. The spread of the EPA region total scores.

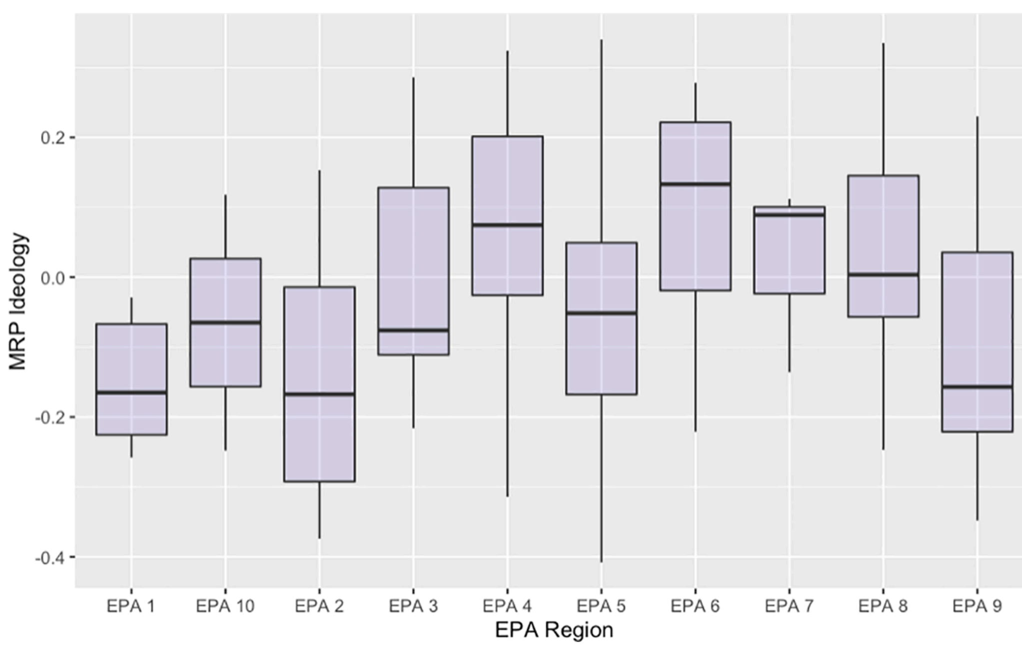

Fig. C2. EPA region compared to political ideology.

CRediT authorship contribution statement

Mirit B. Friedman: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sara Hughes:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Christine J. Kirchhoff:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Eleanor Rauh:** Conceptualization, Formal analysis, Investigation, Methodology. **Chesney McOmber:** Conceptualization, Writing – original draft. **Davis J. Manshardt:** Investigation, Writing – original draft. **Jalyn M. Prout:** Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors acknowledge the assistance of Benjamin Albee, Conner Caridad, and Kyle Dwyer.

Appendix A:. Details on the measure development and scoring

Appendix B:. Further exploration of the sample and resilience measures

We selected the sample of 100 municipalities from the full Municipal Drinking Water Database (MDWD). To check the representativeness of the sample, we compared descriptive statistics for the drivers of resilience for the sample to the 2,219 municipalities in the MDWD (Table 1B). We find the sample is largely representative of the larger database on these measures.

To confirm the measures of policy and planning for resilience were independent of one another, we created a correlation matrix (Table 2B). No significant correlations were found between the measures.

Appendix C. Model checks and adjustments

Regional effects

State and regional policies can influence the decisions municipalities make about their drinking water systems. Due to the stratified random sampling method we used, we had very few municipalities in the same state, and EPA regions were also represented unevenly. We nonetheless attempted to discern whether the were regional effects on municipal policy and planning outcomes. Despite the under-sampling from a few regions, some regional effects were visible. The sample had fewer than five municipalities for EPA regions 2, 7, and 10. EPA regions 1 (northeast), 9 (southwest), and 10 (pacific northwest) had the highest mean scores (Fig. C1), while EPA regions 4 (southeast) and 5 (Midwest) had the lowest mean scores. In a pairwise comparison between the scores broken down by EPA region, there was a significant difference between EPA regions 1 and 5, EPA regions 4 and 9, and EPA regions 5 and 9. Since there are fewer than five municipalities in EPA regions 2, 7, and 10, we cannot assess whether the scores for those EPA differed significantly from the other regions. In the regression model, EPA regions were used as a fixed effects control for regional policy differences.

We manually examined the reasons for significantly lower scores for EPA regions 4 and 5. Municipalities in these regions often scored zero points for a lack of affordability programs and climate change plans, and in some cases, no watershed protection planning. EPA region 4 includes states with some of the highest poverty rates in the country, yet there are few established affordability programs in this region. EPA region 4 also includes many states already experiencing climate change impacts (e.g. seawater flooding, higher temperatures causing greater demand for water, increase in extreme weather events) (EPA 2016). Despite the experienced impacts of climate change, this region scored low on reporting of climate change plans. An area known for an abundance of freshwater, EPA region 5 also lacks local level climate change plans.

With the exception of EPA region 5, political ideology mirrors the inverse of the total score by EPA region (Fig. C2). EPA regions with lower political ideology scores (more liberal) had higher total scores and vice versa.

Collinearity

In the regression model of drivers of resilience, we originally included full time equivalent employees per capita (FTE per capita). In examining the variance inflation factors for all variables in the regression model we found that FTE per capita had a VIF above 5, indicating high multicollinearity. We found FTE per capita and revenue per capita were somewhat correlated (0.84) as were percent Hispanic and climate moisture index (-0.57). To reduce the multicollinearity of FTE per capita and revenue per capita, we removed FTE per capita from the model. Neither percent Hispanic nor climate moisture index had a VIF above 5.

References

Allaire, M., Wu, H., Lall, U., 2018. National trends in drinking water quality violations. Proc. Natl. Acad. Sci. 115 (9), 2078–2083. https://doi.org/10.1073/pnas.1719805115.

Bae, J., Feiock, R., 2013. Forms of government and climate change policies in US cities. Urban Stud. 50 (4), 776–788. https://doi.org/10.1177/0042098012450481.

Balaei, B., Noy, I., Wilkinson, S., Potangaroa, R., 2021. Economic factors affecting water supply resilience to disasters. Socioecon. Plann. Sci. 76 https://doi.org/10.1016/j.seps.2020.100961.

Beecher, J.A., Shanaghan, P.E., 1998. Water affordability and the DWSRF. J.—Am. Works Assoc. 90 (5), 68–75. https://doi.org/10.1002/j.1551-8833.1998.tb08435.x.

Berke, P., Kaiser, E.J., 2006. Urban Land Use Planning, 5th ed. University of Illinois Press, Urbana.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., von Winterfeldt, D., 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthq. Spectra 19 (4), 733–752. https://doi.org/10.1193/1.1623497.

Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., Fu, G., 2017. Reliable, resilient and sustainable water management: The Safe & SuRe approach. Glob. Chall. 1, 63–77.

Butts, R., Gasteyer, S., 2011. Environmental Reviews & Case Studies: More Cost per Drop: Water Rates, Structural Inequality, and Race in the United States—The Case of Michigan. Environ. Pract. 13 (4), 386–395. https://doi.org/10.1017/S1466046611000391.

Chu-Ketterer, L.J., Murray, R., Hassett, P., Kogan, J., Klise, K., Haxton, T., 2023. Performance and Resilience Analysis of a New York Drinking Water System to Localized and System-Wide Emergencies. J. Water Resour. Plan. Manag. 149 (1) https://doi.org/10.1061/jwrmd5.wreng-5631.

DeAngelis, J., Pena, J., Gomez, A., Masterson, J., Berke, P., 2021. PAS Memo: Building Resilience through Plan Integration. American Planning Association. https://www.planning.org/pas/memo/2021/jan/.

Dilling, L., Daly, M.E., Travis, W.R., Ray, A.J., Wilhelmi, O.V., 2023. The role of adaptive capacity in incremental and transformative adaptation in three large U.S. Urban water systems. Glob. Environ. Chang. 79 https://doi.org/10.1016/j.gloenvcha.2023.102649.

Dobbin, K.B., Fencl, A.L., 2021. Institutional diversity and safe drinking water provision in the United States. Util. Policy 73. https://doi.org/10.1016/j.jup.2021.101306.

Einstein, K.L., Kogan, V., 2016. Pushing the City Limits: Policy Responsiveness in Municipal Government. Urban Aff. Rev. 52 (1), 3–32. https://doi.org/10.1177/1078087414568027.

Fallon, A., Jones, R.W., Keskinen, M., 2022. Bringing resilience-thinking into water governance: Two illustrative case studies from South Africa and Cambodia. Glob. Environ. Chang. 75 https://doi.org/10.1016/j.gloenvcha.2022.102542.

Garcia, M., Koebele, E., Deslatte, A., Ernst, K., Manago, K.F., Treuer, G., 2019. Towards Urban Water Sustainability: Analyzing Management Transitions in Miami, Las Vegas, and Los Angeles. Glob. Environ. Chang. 58, 101967 https://doi.org/10.1016/j.gloenvcha.2019.101967.

Gerber, E.R., 2013. Partisanship and Local Climate Policy. Cityscape 15 (1), 107–124.

Golladay, S.W., Craig, L.S., DePalma-Dow, A.D., Emanuel, B.N., Rogers, S.G., 2021. Building resilience into water management through public engagement. Freshwater Science 40 (1), 238–243. https://doi.org/10.1086/712514open_in_new.

Gonzales, P., Ajami, N.K., 2017. An Integrative Regional Resilience Framework for the Changing Urban Water Paradigm. Sustain. Cities Soc. 30, 128–138. https://doi.org/10.1016/j.scs.2017.01.012.

Grabowski, Z.J., Matsler, A.M., Thiel, C., McPhillips, L., Hum, R., Bradshaw, A., Miller, T., Redman, C., 2017. Infrastructures as Socio-Eco-Technical Systems: Five Considerations for Interdisciplinary Dialogue. J. Infrastruct. Syst. 23 (4), 02517002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000383.

Gunderson, L.H., Holling, C.S., 2002. Panarchy: Understanding Transformations in Human and Natural Systems. Island Press.

Hajnal, Z.L., Trounstine, J., 2010. Who or What Governs?: The Effects of Economics, Politics, Institutions, and Needs on Local Spending. Am. Politics Res. 38 (6), 1130–1163. https://doi.org/10.1177/1532673X10362870.

Hansen, K., Mullin, M., 2022. Barriers to Water Infrastructure Investment: Findings from a Survey of U.S. Local Elected Officials. PLOS. Water 1 (8), e0000039.

Homsy, G.C., Warner, M.E., 2015. Cities and Sustainability: Polycentric Action and Multilevel Governance. Urban Aff. Rev. 51 (1), 46–73. https://doi.org/10.1177/1078087414530545.

Howard, G., Nijhawan, A., Flint, A., Baidya, M., Pregnolato, M., Ghimire, A., Poudel, M., Lo, E., Sharma, S., Mengustu, B., Ayele, D.M., Geremew, A., Wondim, T., 2021. The how tough is WASH framework for assessing the climate resilience of water and sanitation. NPJ Clean. Water 4 (1). https://doi.org/10.1038/s41545-021-00130-5.

Hughes, S., Pincetl, S., Boone, C., 2013. Triple exposure: Regulatory, climatic, and political drivers of water management changes in the city of Los Angeles. Cities 32, 51–59. https://doi.org/10.1016/j.cities.2013.02.007.

Hughes, S., Miller Runfola, D., Cormier, B., 2018. Issue Proximity and Policy Response in Local Governments. Rev. Policy Res. 35 (2), 192–212. https://doi.org/10.1111/ropr.12285.

Hughes, S., Kirchhoff, C.J., Conedera, K., Friedman, M., 2023. The Municipal Drinking Water Database. PLOS Water 2 (4), e0000081.

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., et al., 2019. Importance and Vulnerability of the World's Water Towers. Nature 577, 364–369. https://doi.org/10.1038/s41586-019-1822-y.

Johannessen, Å., Wamsler, C., 2017. What Does Resilience Mean for Urban Water Services? Ecol. Soc. 22 (1) https://doi.org/10.5751/ES-08870-220101.

Kim, Y., Carvalhaes, T., Helmrich, A., Markolf, S., Hoff, R., Chester, M., Li, R., Ahmad, N., 2022. Leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change. Current Opinion in Environmental Sustainability 54, 101153. https://doi.org/10.1016/j.cosust.2022.101153.

Kirchhoff, C.J., 2013. Understanding and enhancing climate information use in water management. Clim. Change 119, 495–509. https://doi.org/10.1007/s10584-013-0703-x.

Kirchhoff, C.J., Lara-Valencia, F., Brugger, J., Mussetta, P., Pineda-Pablos, N., 2016. Towards joint consideration of adaptive capacity and water security: Lessons from the arid Americas. Curr. Opin. Environ. Sustain. 21, 22–28. https://doi.org/10.1016/j.cosust.2016.10.003.

Kirchhoff, C.J., Flagg, J., Zhuang, Y., Utemuratov, B., 2019. Understanding and Improving Enforcement and Compliance with Drinking Water Standards. Water Resour. Manag. 33 (5), 1647–1663. https://doi.org/10.1007/s11269-019-2189-4.

Kirchhoff, C.J., Watson, P., 2019. Are wastewater systems adapting to climate change? J. Am. Water Resour. Assoc. 55 (4), 869–880. https://doi.org/10.1111/1752-1688.12748.

Klasic, M., Fencl, A., Ekstrom, J.A., et al., 2022. Adapting to extreme events: small drinking water system manager perspectives on the 2012–2016 California Drought. Clim. Change 170, 26. https://doi.org/10.1007/s10584-021-03305-8.

Klise, K., Hart, D., Bynum, M., Hogge, J., Haxton, T., Murray, R., Burkhardt, J., 2020. Water Network Tool for Resilience (WNTR) User Manual: Version 0.2.3 (No. SAND-2020-9301R; EPA/600/R-20/185). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

Kloosterman, R.A., van der Hoek, J.P., Herder, P., 2021. Resilient Drinking Water Resources. Water Resour. Manag. 35 (1), 337–351. https://doi.org/10.1007/s11269-020-02736-9.

Krause, R.M., 2012. Political Decision-making and the Local Provision of Public Goods: The Case of Municipal Climate Protection in the US. Urban Stud. 49 (11), 2399–2417. https://doi.org/10.1177/0042098011427183.

Larsen, T.A., Hoffmann, S., Lüthi, C., Truffer, B., Maurer, M., 2016. Emerging Solutions to the Water Challenges of an Urbanizing World. Science 352 (6288), 928–933. https://doi.org/10.1126/science.aad8641.

Lawson, E., Farmani, R., Woodley, E., Butler, D., 2020. A resilient and sustainable water sector: barriers to the operationalisation of resilience. Sustainability 12 (5), 1797. https://doi.org/10.3390/su12051797.

Leiserowitz, A., Maibach, E., Roser-Renouf, C., Smith, N., 2011. Global Warming's Six Americas, May 2011. Yale University and George Mason University.

Linkov, I., Eisenberg, D.A., Bates, M.E., Chang, D., Convertino, M., Allen, J.H., Flynn, S. E., Seager, T.P., 2013. Measurable resilience for actionable policy. Environ. Sci. Tech. 47 (18), 10108–10110. https://doi.org/10.1021/es403443n.

Lubell, M., Feiock, R., Handy, S., 2009. City Adoption of Environmentally Sustainable Policies in California's Central Valley. J. Am. Plann. Assoc. 75 (3), 293–308. https://doi.org/10.1080/01944360902952295.

Mack, E.A., Wrase, S., 2017. A burgeoning crisis? A nationwide assessment of the geography of water affordability in the United States. PLoS One 12 (1), e0169488.

Marcillo, C.E., Krometis, L.A.H., 2019. Small towns, big challenges: Does rurality influence Safe Drinking Water Act compliance? AWWA Water Science 1 (1), e1120.

Marques, R.C., da Cruz, N.F., Pires, J., 2015. Measuring the Sustainability of Urban Water Services. Environ Sci Policy 54, 142–151. https://doi.org/10.1016/j.envsci.2015.07.003.

McFarlane, K., Harris, L.M., 2018. Small systems, big challenges: Review of small drinking water system governance. Environ. Rev. 26 (4), 378–395. https://doi.org/10.1139/er-2018-0033.

McPhearson, T., Cook, E.M., Berbés-Blázquez, M., Cheng, C., Grimm, N.B., Andersson, E., Barbosa, O., Chandler, D.G., Chang, H., Chester, M.V., Childers, D.L., Elser, S.R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R.L., Iwaniec, D.M., Kabisch, N., Kennedy, C., Troxler, T.G., 2022. A social-ecological-technological systems framework for urban ecosystem services. One Earth 5 (5), 505–518. https://doi.org/10.1016/j.oneear.2022.04.007.

Milman, A., Short, A., 2008. Incorporating resilience into sustainability indicators: An example for the urban water sector. Glob. Environ. Chang. 18 (4), 758–767. https://doi.org/10.1016/j.gloenvcha.2008.08.002.

Mullin, C., Kirchhoff, C.J., 2019. Marshaling Adaptive Capacities within an Adaptive Management Framework to Enhance the Resiliency of Wastewater Systems. J. Am. Water Resour. Assoc. 55 (4), 906–919. https://doi.org/10.1111/1752-1688.12709.

Nicholas, W., Vedachalam, S., 2021. Poor accessibility of water utilities' consumer confidence reports. Util. Policy 72, 101272. https://doi.org/10.1016/j.jup.2021.101272.

Norton, R.K., David, N.P., Buckman, S., Koman, P.D., 2018. Overlooking the coast: Limited local planning for coastal area management along Michigan's Great Lakes. Land Use Policy 71, 183–203. https://doi.org/10.1016/j.landusepol.2017.11.049.

Pamidimukkala, A., Kermanshachi, S., Adepu, N., Safapour, E., 2021. Resilience in water infrastructures: A review of challenges and adoption strategies. Sustainability 13 (23), 12986. https://doi.org/10.3390/su132312986.

Pierce, G., El-Khattabi, A.R., Gmoser-Daskalakis, K., Chow, N., 2021. Solutions to the problem of drinking water service affordability: A review of the evidence. Wiley Interdiscip. Rev. Water 8 (4), e1522.

Quitana, G., Molinos-Senante, M., Chamorro, A., 2020. Resilience of Critical Infrastructure to Natural Hazards: A Review Focused on Drinking Water Systems. Int. J. Disaster Risk Reduct. 48, 101575 https://doi.org/10.1016/j.ijdrr.2020.101575.

Richter, B.D., Blount, M.E., Bottorff, C., Brooks, H.E., Demmerle, A., Gardner, B.L., Herrmann, H., et al., 2018. Assessing the Sustainability of Urban Water Supply Systems. J. Am. Water Works Ass. 110 (2), 40–47. https://doi.org/10.1002/awwa.1002.

Rodina, L., 2019. Defining "water resilience": Debates, concepts, approaches, and gaps. Wiley Interdiscip. Rev, Water, p. 6.

Rommelmann, D.W., 1995. Economics of Small Systems. J. Am. Water Works Ass. 87 (11), 20–28. https://doi.org/10.1002/j.1551-8833.1995.tb06446.x.

Scott, T.A., Moldogaziev, T., Greer, R.A., 2018. Drink what you can pay for: Financing infrastructure in a fragmented water system. Urban Stud. 55 (13), 2821–2837. https://doi.org/10.1177/0042098017729092.

Shih, J.S., Harrington, W., Pizer, W.A., Gillingham, K., 2006. Economies of scale in community water systems. J. Am. Water Works Ass. 98 (9), 100–108. https://doi.org/10.1002/j.1551-8833.2006.tb07757.x.

Svara, J.H., Watt, T.C., Jang, H.S., 2013. How Are U.S. Cities Doing Sustainability? Who Is Getting on the Sustainability Train, and Why? Cityscape 15 (1), 9–44.

Swann, W.L., Deslatte, A., 2019. What do we know about urban sustainability? A research synthesis and nonparametric assessment. Urban Stud. 56 (9), 1729–1747. https://doi.org/10.1177/0042098018779713.

Tausanovitch, C., Warshaw, C., 2013. Measuring constituent policy preferences in congress, state legislatures, and cities. J. Polit. 75 (2), 330–342. https://doi.org/10.1017/S0022381613000042.

Teodoro, M.P., 2018. Measuring Household Affordability for Water and Sewer Utilities. J. Am. Water Works Ass. 110 (1), 13–24.

Teodoro, M.P., 2019. Water and sewer affordability in the United States. AWWA Water Science 1 (2), e1129.

Vedachalam, S., John, M.E., Riha, S.J., 2014. Spatial analysis of boil water advisories issued during an extreme weather event in the Hudson River Watershed, USA. Appl. Geogr. 48, 112–121. https://doi.org/10.1016/j.apgeog.2014.02.001.

Walker, G., 2015. Come back sociotechnical systems theory, all is forgiven. Civ. Eng. Environ. Syst. 32, 170–179.

Willmott, C.J., Feddema, J.J., 1992. A More Rational Climatic Moisture Index*. Prof. Geogr. 44 (1), 84–88.

Wilson, G.A., 2012. Geoforum Community resilience, globalization, and transitional pathways of decision-making. Geoforum 43, 1218–1231.

Wolters, E.A., Steel, B.S., 2021. Environmental efficacy, climate change beliefs, ideology, and public water policy preferences. Int. J. Environ. Res. Public Health 18 (13), 7000. https://doi.org/10.3390/ijerph18137000.

Wood, R.S., Hultquist, A., Romsdahl, R.J., 2014. An examination of local climate change policies in the Great Plains. Rev. Policy Res. 31 (6), 529–554. https://doi.org/10.1111/ropr.12103.

Woodruff, S.C., 2022. Coordinating Plans for Climate Adaptation. Journal of planning education and research. SAGE Publications, Los Angeles, CA.