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Perspectives and Propositions on Resilience as Interdisciplinary, Multi-Level and Interdependent

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Abstract

The concept of resilience is surging in popularity, but relevant discussions are often disconnected from one field to another. To prompt integration of disparate conversations on resilience, we examine the concept's origins etymologically, genealogically, and by analyzing

the interdependencies of drinking water and public health systems in six academic disciplines and practice-oriented fields. These disciplines are engineering, social work, urban studies, political science, communication, and public health. While the disciplinary resilience literatures are relatively stove-piped from one another's contexts, they all theorize resilience at multiple levels of analysis. They also engage a range of understandings of how to build resilience in complex systems. This paper brings several conversations together, addressing gaps and resonances in disciplinary conceptualizations of resilience with nine propositions to cultivate interdisciplinary and transdisciplinary discussions and debates. We ground this creative inquiry in real-world examples of water system crises to highlight subthemes among the propositions and stimulate more diverse discussions moving forward. We examine dynamics of interfaces and interactions within and between systems through the Elk River Water chemical contamination in Charleston, West Virginia in 2014. We investigate tensions that arise in knowledge and practice through lead poisoning of public water systems in Washington, D.C. and Flint, MI. Finally, we consider how change and persistence shape learning through water infrastructure in Southern California. All together, these propositions offer a starting point and a provocation to strengthen theorizing around resilience for critical infrastructure systems.

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Introduction

To study the resilience of critical infrastructures as socio-technical systems, scholars have had to reach across traditional disciplinary boundaries and form new multi-disciplinary teams (NRC, 2015). This paper examines six disciplines applied to the resilience of drinking water and public health systems. We included: *engineers* to understand the construction, operations, and maintenance as well as physical design and materials of the water system; *social work* scholars to focus on the welfare of vulnerable residents; *urbanists* to examine the city's physical terrain and social relations; *communication* specialists to analyze interactions between people and institutions; *political scientists* to interpret the policy environment; and *public health* experts to identify systemic medical threats. "Resilience" had different meanings, both complementary and contradictory, for these disciplines. This paper examines how distinct disciplinary lineages can inform interdisciplinary, interconnected, and multi-level theoretical propositions about systems resilience in the face of disaster.

The multiplicity of the construct may explain why resilience has generated broad interest and a "collective surge" among researchers from physical, social science, and engineering disciplines, as well as among policy makers and disaster managers (Tierney, 2015). This surge, however, complicates various and sometimes incongruous uses of the concept. For instance, some community-based and organizational approaches to risk management emphasize decentralized response capacities (Somers, 2009; Spialek & Houston, 2018), while a range of policy initiatives aim to build resilience in local, national, and international institutions (e.g. IPCC, 2012; NIST 2015). At different scales, contemporary organizations, communities,

and institutions have embraced resilience to address social problems, manipulate physical environments, and prepare for system stressors such as urbanization, population migration, globalization, climate change, natural disasters, technological disruptions and the interaction of these factors (Rodin, 2014). Different disciplines can trace their own origins and development of resilience, and that lens focuses them on different levels of analysis and objects of study. One commonality across disciplinary traditions of resilience is that they each focus on complex systems dynamics. We draw out these disciplinary approaches to complex systems theoretically, showing that they are somewhat stove-piped, even as they are interrelated. To push this disciplinary theorizing toward interdisciplinary integration, this paper makes propositions to theorize resilience across disciplines, grounding in real world examples of water system crises.

This paper suggests one way to systematize an interdisciplinary investigation of the big idea of resilience. The authors illustrate how various disciplinary approaches to resilience can be applied to one type of socio-technical, ecologically embedded system: drinking water. Because of the brevity of the journal format, we offer a brief treatment of these concepts to stimulate broader thinking and more integrated discussions. We examine the origins of resilience, the evolution of water systems, and six disciplinary approaches to resilience in fields concerned with drinking water systems -- engineering, social work, urban studies, communication, political science, and public health. Brief disciplinary reviews and examples of water system crises provide groundwork for nine propositions that suggest an expanded, multi-scalar, and interconnected framework for resilience of interdependent systems. Before unpacking the disciplinary entanglements of systems resilience, we first examine the origins of the resilience construct, and identify disciplines concerned with water systems.

Origins of the Resilience Construct

Following its emergence as a research construct, resilience quickly branched into distinct disciplinary lineages. We identify areas of consistency and variability of the concept over time, punctuated by the recent surge in use of resilience across diverse fields.

From its earliest days, “resilience” referred both to physical systems and to people (Bourbeau, 2018; Bené et al., 2018). The etymology of the word traces to the 1620s, from the Latin re- “back” (see re-) + *salire* “to jump, leap.” Over the next few centuries, resilience referred to an echo bouncing back, rebounding from mental and emotional difficulty, elasticity, and measuring a material’s endurance to stress for weapons development. These multiple originations of resilience expanded into varied scholarly applications by the mid-20th Century. For instance, in the 1940s-1950s, resilience in the psychology literature described individuals’ abilities to withstand adverse conditions. By the 1960s-1970s, resilience became an engineering measure of materials under stress. In the 1970s, distinguishing the stability inherent in engineering resilience from constant adaptation in ecology, Holling (1973; 1996) defined resilience as the measure of the persistence of systems, namely an ability to absorb change and disturbance within critical thresholds while maintaining key relationships between populations and their environments, and between system centers and boundaries (Walker & Cooper, 2011; Folke et al 2010).

When applied to social systems, resilience took at least two paths, highlighting its relevance to both policy and research implications. Governmental bodies began to adopt the term, with the Intergovernmental Panel on Climate Change [IPCC] (2012) employing the concept by the 1980s. Meanwhile, by the 1990s, social scientists joined with ecologists to examine the close coupling of social and ecological systems, understanding humans and their

environments as imbricated components of resilience in adaptive and transformative social-ecological systems (Bené et al, 2018; Folke, 2006).

In many cases, the concept was used to further the neoliberal rationality of governance by emphasizing personal reliance to contend with collective risks (Bourbeau, 2015, Joseph, 2013). Noting this trend in the 2005 response to Hurricane Katrina, Tierney (2015) explains that disaster resilience often mediates state-society relationships, constructs at-risk subjects, and employs technocratic solutions. Responding to the rise of resilience policies and narratives in the wake of Hurricane Katrina, Noyes argues, “The public idiom of resilience evinces a loss of societal confidence in the modern progress narrative. Its rise indexes the decline of institutional willingness to assume responsibility for the collective wellbeing. We might call it abdication” (2016, p.420).

These various conceptual strands have shaped an accelerating number of studies through distinct disciplinary interpretations of resilience, especially over the past two decades. The psychological, social-ecological, and engineering strands of resilience meet in the study of socio-technical complex systems, including those that make up critical infrastructures, such as drinking water (Boin & McConnell, 2007; L'Heureux & Therrien, 2013). We next examine how municipal drinking water emerged as a widespread interdependent complex system that can demonstrate key aspects of resilience.

Municipal Drinking Water: An Emerging Complex System

Water systems involve sophisticated environmental engineering that requires advanced social and political organization to ensure public health and the welfare of population centers during both normal times and emergencies. Complex systems are not simply reducible to their

parts, entailing dynamic interactions in evolving environments between physical and nonphysical components, with nonlinear effects and feedback loops (Cillers, et al, 2013; Carvalhaes, et al, 2022). For instance, there are critical dependencies and interdependencies between a water system and other critical infrastructure systems, as operating a water system relies on electric power, telecommunication, and transportation systems. To demonstrate interdisciplinary investments in water systems' origins and evolution, we examine how water systems evolved and how these complex, dynamic systems have bounced back from threats.

Current municipal water systems in the U.S. provide clean drinking water to communities by gathering, treating, and moving water through physical infrastructure with managerial components to businesses and residences. Water systems were initially developed in response to a series of public health crises and continue to be informed by existing political and urban systems (Melosi, 2000). As the U.S. urbanized and population density outgrew local cisterns and wells, advances in public health revealed that contaminated water was a vector for disease (Blake, 1956). Water infrastructure, distribution and later treatment and disinfection, evolved in direct response to a series of reoccurring cholera and then typhoid fever and yellow fever outbreaks throughout the 1850s to early 1900s (Ravenel, 1970; Melosi, 2000). With urban economic prospects threatened by populations too ill to work, water infrastructure that could carry and treat water from distant sources to cities became a matter of civic need and social welfare (Blake, 1956; Tarr, 1996). Expanding urban populations and social changes, such as the development of sewer systems and water-using appliances (e.g., extensive indoor plumbing) were critical to improving living conditions through the early 20th century and resulted in an ever growing need for greater quantities of clean water and continual expansion of water infrastructure (Melosi, 2000). These systems were owned by municipalities and largely financed

through municipal bonds and tax revenues from 1880-1920, with pipe routing and other infrastructure decisions influenced by politics as much as by engineering principles (Blake, 1956; Melosi 1980). By 1923, municipal water systems served 97% of the residents in the 100 largest U.S. cities. With rising pollution and the economic squeeze of the Great Depression, the federal government made funding of water systems a national issue and supported public works projects to expand supply and service. This era led to a sharp decline in waterborne disease outbreaks, confirming that good health, political stability, and social wellbeing relied on clean water (Melosi, 2000).

While waterborne disease rates were largely under control, post-World War II industrial processes created a new set of source water contaminants, opening a new phase for water infrastructure (Melosi, 2000). These contaminants brought more ambiguous and delayed public health effects, such as cancer due to extended exposures. These chemicals also had visible environmental consequences, such as the 1959 burning of the Cuyahoga river (Melosi, 2000; US EPA, 2015) . The environmental movement of the 1960s and 1970s shifted the public's understanding of water pollution and resulted in regulatory changes, centralizing water quality regulations under the new U.S. Environmental Protection Agency through the 1972 Clean Water Act and 1974 Safe Drinking Water Act (Melosi, 2000; Tiemann, 2017). This period was also marked by extensive expansion of cities, as residents moved out of dense urban cores to the suburbs, increasing the size and expense of municipal water systems (Tarr, 1996). Despite the growing cost of all infrastructure systems, including drinking water, wastewater, transportation and garbage collection, the federal government decreased funding for water systems by 60% between 1960 and the late 1980s. This left local governments to fund 83% of water system expenses via user rates or taxes (Melosi, 2000). In response, many smaller systems have been

consolidated or privatized. To compound matters, federal water regulations are continually increasing the number of regulated contaminants, from 22 in 1974 to 91 in 2020, further raising the cost of water treatment (Tiemann, 2017). Underfunded and in need of modernization to address failing infrastructure and an ever-increasing list of contaminants, water quality degradation in many systems has contributed to inequality among urban and racialized communities at risk of exposure to waterborne contaminants.

Water systems, as we describe here, developed in the U.S. despite unanticipated stressors and engaged a variety of disciplines. *Engineering* built, operated, and maintained physical infrastructure, while planning to ensure welfare of urbanizing populations involved *social work* and *urban studies*. Structuring and facilitating public and institutional interactions required *communication* and *political science*, and preventing and treating disease and toxicity is the realm of *public health*. Each of these disciplines developed its own approach to the study of water systems and their response to crisis. This focus on water systems grounds a local scale infrastructure that ratchets up to global significance and helps in the formulation of generalized propositions.

Disciplinary Frames for Resilience

Engineering, social work, urban studies, communication, political science, and public health have different understandings of resilience and how to build resilience in complex systems. Each discipline takes a distinct approach, even with regard to common concepts such as community and community resilience, while also encompassing some degree of internal deviation and disagreement. Here we provide an overview of each discipline's tradition of

resilience. Despite their differences, these fields share responsibility for the design, construction, operation, and maintenance of physical infrastructure to meet the needs of residents and businesses, while functioning within the bounds of regulatory regimes. Their theoretical dissonance may cause tension when systems interface with each other, creating misunderstanding and barriers to functionally supporting a broad understanding of resilient systems that become especially apparent during disasters. To build an interdisciplinary conversation addressing this gap, we review how each of these disciplines approaches resilience, particularly in relation to complex system dynamics. These approaches, summarized in Table 1, provide a foundation for the interdisciplinary propositions presented subsequently.

Engineering and Water Engineering

The concept of “engineering resilience” refers to a capacity to reach equilibrium after disruption in human-engineered systems, and their ability to respond to change, tolerate collapse, and recover to normal functioning, possibly in a better state than before (Yodo & Wang, 2016). Water system engineers also focus on robustness as a component of resilience, defined by a minimal deviation from acceptable or ideal conditions when subjected to an atypical scenario (Huck & Coffey, 2004). The engineering community often discusses resilience as reliability, framed as a measure of a system’s ability to maintain water service under failure scenarios (Gheisi et al., 2016) to ensure system functionality (Bruneau et al, 2003; Ayyub, 2015) and services (Davis, 2021; Davis, Mostafavi & Wang 2018). However, a consistent definition of resilience does not exist for waters systems, reflecting the complexity of the concept (Ostfeld, 2004).

Table 1: Resilience across six disciplines

Discipline	Summary of Resilience	Illustrative Definition	Levels of Analysis	Key Citations
Water Engineering	<i>Place in the field</i> - Computer modeling and measurement of physical infrastructure and systems to achieve water delivery within budget under a range of conditions, able to withstand attack and age, and to recover quickly <i>System connections</i> - Ability to bounce back to some equilibrium state after disruption - Conceptually intertwined with robustness, reliability, redundancy and rapidity - Includes multiple dimensions, including technical, organizational, social, and economic	Resilience is the degree to which the system minimizes the level of service failure magnitude and duration over its design life when subject to exceptional conditions (Mugume et al, 2015), with five elements to provide safe drinking water: 1. Source, 2. Treatment, 3. Distribution, 4. Monitoring, 5. Response to adverse monitoring results (Huck and Coffee 2004).	Water system	AWWA, 2010; Gheisi et al., 2016; Lempert, 2019; Morley, 2012; Pagano et al., 2018
Social Work	<i>Place in the field</i> - Emphasis on individual and social emotional wellbeing during times of significant distress - Social justice challenge: baseline conditions and burdens are unequal, so marginalized communities face chronic problems <i>System connections</i> - Interaction of various actors and characteristics within a formal group's response to an external stressor. - Understanding and intervening to measure quality of life and use as capacity building tool clinically - Resilience as a path towards things as they should be rather than as they were	Interdependent members, contexts, and influences interact in adaptive processes to “maintain the well-being and functioning of the system and to recover efficiently from disruption.” (Van Breda, 2016, p. 63)	individuals, families/house holds, communities, organizations, societal forces	Newell, 2020; Allmark et al., 2014; Rose & Palattiyil, 2020; Park, et. Al., 2020; van Breda, 2016

Urban Studies	<i>Place in the field</i> • Early usage drew from engineering and ecology, and expanded to social ecology & evolutionary approach • Intertwined with industrial ecology, urban ecology, and political ecology <i>System connections</i> • Returning to equilibrium states from disaster and climate change • The social coupled with the ecological; embracing systems change, instability, adaptation, transformation, and instability • Address social justice	“Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity” (Meerow, et al 2016)	Cities, neighborhoods, communities, regions, transnational circuits	Beilin & Wilkinson, 2015; Béné et al., 2018; Davoudi et al., 2012; Meerow & Newell, 2019; Meerow et al., 2019
Political Science	<i>Place in the field</i> • Communities bouncing back from disaster, terror attack, flooding etc. <i>System connections</i> • Administrative capacity to adapt and self-organize in times of significant adversity • Political blame and credit taking or collaborative governance	Capacity to withstand and ‘bounce back’, founded upon the classical liberal subject’s capacity for rational behavior	Community, national, public-private partnerships, international/global	Aldrich, 2012; Birkland & Waterman 2008; Platt, 2012; Roberts, 2009; Ross, 2013; Humbert & Joseph, 2019; Joseph 2013)
Communication	<i>Place in the field</i> • Resilience is a function of communication systems and resources, community relationships, strategic communication processes, and community attributes • Resilience process involves multiple layers that interact and overlap with each other	Communication processes that enact resilience: (a) crafting normalcy, (b) affirming identity anchors, (c) maintaining and using communication networks, (d)	Individual, organizational, community	Buzzanell, 2010, 2018, 2020; Seeger, 2006;

	<i>System connections</i> • Unifying processes, resources and capacities developed, sustained, and grown through discourse, interaction, and material considerations • Communication primarily serves as an instrument to constitute adaptive capacities that help a system bounce-forward	constructing alternative logics, and (e) foregrounding productive action while backgrounding negative emotion. (Buzzanell, 2020)		Houston et al., 2015
Public Health	<i>Place in the field</i> • Long-term focus on disaster preparedness, but language of “resilience” is new, due to federal mandate • No common overarching concept of resilience <i>System connections</i> • System’s ability to transform to improve functions despite significant adversity • What communities can do for themselves to strengthen their capacities, rather than concentrating on their vulnerability to disaster or their needs in an emergency	Health system resilience is “the capacity of health-care actors, institutions, and populations to prepare for and respond to crises, maintain core functions in time of crisis; and, informed by lessons learned during a crisis.” (Kruk et al., 2015)	Individual, family/household, natural and physical built environments, organizational/ community/ national/international	Morton & Lurie, 2013; Kruk et al., 2015; Fridell et al., 2020; Turenne et al., 2019

Water system engineers have always considered resilience in their work, since the reliability of clean water is critical to human health and habitation. However, quantitatively defining ways to measure resilience did not evolve until the late 1980s with the expansion of water system infrastructure modeling and analysis capabilities. While metrics typically focus on physical infrastructure performance, in some cases ignoring the interconnectedness of water systems with other societal systems, (Gheisi et al., 2016; Su et al., 1987; Wagner et al., 1988), engineers have begun to incorporate social, economic, and organizational aspects in measuring water system resilience (Balaei, et al, 2018).

In general, the degree to which a water system minimizes the magnitude and duration of a service failure over its design life when subject to exceptional conditions constitutes water system resilience (Mugume et al., 2015). Specifically, mechanical features (of the pipes, pumps, etc.); hydraulic components (managing water pressure and meeting consumer demand), and water quality (ability to meet policy requirements and quality benchmarks) can serve as metrics for resilience. Water systems must meet water demands under defined conditions and within budget constraints. If a population is exposed to a contaminant, early detection is key. Moreover, water quality may change dramatically due to pipe breaks (American Water Works Association, 2010; Gheisi et al., 2016; Morley, 2012; Su et al., 1987; Wagner et al., 1988). Systemic events are typically classified as either catastrophic (i.e., low probability, high consequence events, such as a hurricane or terrorist attack) or chronic (i.e., high probability, low consequence events, such as increased leakage from aging pipes). Designing and planning for events known and unknown is critical, as is recognizing interfaces and interdependencies with other systems (Bruneau et al 2003, NIST 2015). Typically, however, water engineering narrowly focuses on measuring

resilience within infrastructure components, rather than analyzing municipal water systems within their larger socio-technical context.

Social Work

Social work practice, pedagogy, and scholarship has centered resilience as a useful concept for understanding and intervening with individuals, families, communities, and organizations who face adversity. Social work's definitions of resilience influence practice and policy interventions. Resilience research in social work grew from Garmezy in the 1970s, who found that some children who would be considered "at risk" for psychopathology were able to function well despite adversity (Kolar, 2011). This research helped inspire a shift in the field away from deficit or risk- centered approaches towards an emphasis on positive adaptation and client empowerment, despite challenging circumstances (Bottrell, 2009). Four waves of resilience research within the behavioral sciences have occurred in the decades since, with the following sequential objectives: identifying key assets or markers for positive adaptation; discovering how people develop these features; promoting policies and interventions to increase both internal and external factors of resilience; and expanding understandings of the concept to different levels of analysis and cultural contexts (Kolar, 2011). While resilience has become a dominant term within social work, its meaning, characteristics, applications, and value as a construct are not universally agreed upon and have been contested as reifying individualism and normative value judgements (Bottrell, 2009; Garrett, 2016; Park et al., 2020).

Resilience within social work is predominantly framed as an individual construct, both as a method for enhancing quality of life for students and professionals within the field and as a clinical tool for capacity-building and empowerment with clients (Newell, 2020; Park et al.,

2020; Rose, 2020). Moreover, resilience is an applicable concept to the various analytic and practice domains that concern social work, including interpersonal relationships, family systems, organizations, and communities. For instance, ecological systems theory and social capital frameworks have helped the field broaden their analysis of resilience to include social factors and examine its presence within complex systems (Folke, 2006; Pinkerton & Dolan, 2007). Social workers conceptualize resilience at the organizational and community levels as part of this dynamic and complex web of relationships between power-laden people and systems. For marginalized and under-resourced communities, the burden to demonstrate resilience under adverse conditions may be both frequent and untenable. Following Almark et al.'s (2014: 2) important distinction that the “as-you-were endpoint” common in resilience literature is not sufficient for chronic problems within marginalized communities, social workers often examine and promote resilience as a path towards things as they should be rather than as they were.

Urban Studies

As “cities are complex and interdependent systems,” urban studies emphasizes interdisciplinary approaches to resilience (Godshalk, 2003). As such, urbanists employ a range of concepts, methods, issue areas, and theoretical commitments evolving from engineering, ecology, and social ecological traditions of resilience. The engineering approach focuses on recovery from disasters by returning city systems to pre-crisis states of equilibrium, while the ecological approach stresses the magnitude and features of a disruption in which systems could be expected to return to baseline functioning (Adger, 2003; Holling, 1996). Social-ecological resilience departs from a focus on returning to pre-crisis states of equilibrium by embracing instability, conceiving of the social as interconnected with the ecological, addressing the

complexity of non-linear systems interdependencies, and employing a transdisciplinary analysis with a social justice orientation (Beilin & Wilkinson, 2015; Stokols, 2018). This evolutionary approach to resilience moves beyond “bounce-back-ability” or returning to normal, toward complex adaptation and transformation (Davoudi, 2012). Resilience has spanned the wide range of issue areas and normative debates that comprise urban studies and planning since the 1970s, but use of the term has increased significantly since the early 2000s, with growing concern for how cities should be adapting to and mitigating risks associated with climate change, including sea level rise, hurricanes, and worsening urban heat, as well as other natural disasters, such as earthquakes (Béné et al., 2018).

Urban studies scholars analyze resilience through and across the levels of neighborhoods, communities, cities, regions, and global networks. With the city as unit of analysis, scholars have examined how urban planners can assess their level of resilience amidst population change, economic stress, and other pressures (Liu, 2014). Studying across levels, researchers have found that hyperlocal, communal practices contribute to the city’s overall resilience (Petrescu et al., 2016). Urbanists also consider inter-city network systems and comparative analysis across cities (Orleans et al., 2013; Rogov & Rozenblat, 2018). Urban researchers in the social ecological tradition view cities, neighborhoods, communities, and larger networks as embedded within social, political, economic, and environmental systems that influence resilience as well as other urban conditions, like inequality and poverty. Contesting resilience metrics that examine systems out of context, Meerow et al. (2019) encouraged urbanists to critically concern themselves with resilience for whom and for what, as well as where, when and why. Senier et al. (2014) argued that resilience studies must take “race as a central category of analysis; race is the node around which environmental damage, community vulnerability, and economic imperatives collide.” For

resilience studies to transform, rather than deepen, the dynamics of inequality and racism in modern cities in the neoliberal era, a rigorous approach centering equity must be central to interdisciplinary and interconnected conceptualizations of urban resilience (Meerow & Newell, 2019).

Communication

The communication field has embraced resilience as a broad set of unifying processes, resources, and capacities. These approaches have emerged from theories of discourse, communication ecology, public relations, and strategic communication. Buzzanell's (2010, 2018) Communication Theory of Resilience, for example, describes social resilience as a collective process by which individuals reintegrate from some disruption and co-construct a new normal. Following this conceptualization, resilience is developed, sustained, and grown through discourse, interaction, and material considerations (Buzannell, 2010). A second major communication-based approach to resilience has been offered by Houston et al. (2015). They suggest that community resilience is a function of communication systems and resources, community relationships and attributes, and strategic communication processes.

These conceptualizations highlight the interconnections between individual, organizational, community, and societal levels of analysis for resilience. For instance, Buzzanell (2010) describes the communication processes that function across levels, arguing, "The construction of resilience is a collaborative exchange that invites participation of family, workplace, community, and interorganizational network members" (p. 9). More recently, Buzzanell (2020) describes five interrelated communication processes that enact resilience: (a) crafting normalcy, (b) affirming identity anchors, (c) maintaining and using communication

networks, (d) constructing alternative logics, and (e) foregrounding productive action while backgrounding negative emotion. These elements emphasize the multi-dimensional, interactive, and emergent aspects of resilience that can be developed concurrently across various levels. Houston et al. (2015) also stress interconnected levels of analysis. The broader ecosystem is comprised of various features, such as media resources, sources of information, infrastructure, and the communication activities of citizens and organizations, as well as multifaceted relationships, connections, and associations between citizens, organizations, government, or media. These relationships contribute to resilience by constituting functional networks along with sources of social capital and support, entailing flexibility, creativity, efficacy, diversity, equality, social justice, and economic resources. Thus, the communication field offers a robust and diverse approach to resilience that reveals critical interconnections between individuals, community, and society, as well as an invitation to respond to adverse conditions with creativity and innovation.

Political Science

Variations of the resilience concept have been employed in European political discourse for centuries, including in the State Papers of Henry VIII in the 16th century and in Queen Christina of Sweden's education policy in the 17th century, referencing a bounce back, return to a previous position, a retraction, or a recovery (Alexander, 2013). Despite its historical presence in state discourse and its popularity in other social sciences, however, resilience has not been highly developed within political science literature. Nevertheless, the concept has gained traction within specific areas of study for the field, for instance, around the ability of certain regimes or political parties, particularly authoritarian ones, to retain power despite external pressures (Hess,

2013; Hellman, 2018; Li, 2018; White, 2017). Holling's (1973) work on adaptations of ecological systems amidst adversity led to more recent conceptualizations and applications within political science (Alexander, 2013; Walker et al., 2004). Resilience has also been used in political science to understand policies' persistence over time and how resilience can be used to design policy solutions (Capano & Woo, 2016; White & O'Hare, 2014).

Most of the scholarship on the resilience concept in political science focuses on resilience after a natural disaster or technological crisis (Birkland & Waterman, 2008; Roberts, 2009; Ross, 2013). As with other fields, political science adopts a view of resilience as,

The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UNISDR, 2009, p. 24, as cited in Alexander, 2013, p. 2710).

A tradition of political ecology allows for more reflection on how vulnerability and uncertainty are largely socially and politically produced rather than naturalized preconditions (Huang 2018; O'Brien et al. 2006; Quarantelli & Perry 2005). It highlights the neoliberal tendency in policy approaches to exploit resilience by overtly emphasizing adaptation of communities to conform to changes of all kinds and become agents of their own change without questioning the logic of a market economy (Evans and Reid 2015). For instance, Huang (2021) recently unpacks how community resilience in a post-disaster context incentivizes paradoxical practices of land politics for indigenous farmers in Taiwan.

The primary levels of analysis involve political systems at various levels, such as national, regional/state, or local/community. Disasters are seen as political events, with winners who benefit and losers who bear the costs (Platt, 2012). As such, while resilience occurs at the

systems level, its presence or absence is not experienced uniformly across the system.

Additionally, resilience can be politicized within systems as a target for credit or blame within the aftermath of a disaster or crisis, as political systems take an administrative role in promoting resilience through preparation, recovery, and learning efforts. Stark and Taylor (2014) define community resilience as, “a synthesis of local (non-state) and government resources, which enables communities to help themselves during emergencies in ways which complement larger crisis-management objective” (p. 300). Engaging citizen participation in crisis management policy and enhancing social capital are important practices in facilitating community resilience after a disaster (Aldrich, 2012; Stark & Taylor, 2014). Resilience in political science reveals the complex nature of official state interventions, while also emphasizing non-state actors in social and political systems, including water systems.

Public Health

Resilience is an integrative construct for understanding how people and their communities achieve and sustain mental and physical health in the face of adversity (Zautra et al., 2010). While public health has long engaged in the study and practice of disaster preparedness and response, the terminology of resilience is relatively new to the field (Morton & Lurie, 2013). Public health departments have been motivated in part by recent policies and mandates to incorporate resilience into programming. Specifically, the US Centers for Disease Control and Prevention issued a set of standards for public health preparedness in 2011 which include “community resilience” among the domains that public health departments must address to receive funding. A 2018 update defines community resilience as “the capacity to absorb stress or destructive forces through resistance or adaptation; manage or maintain certain basic functions

and structures during disastrous events; and recover or ‘bounce back’ after an event” (CDC, 2018, p. 156). The guidance notes, “A focus on resilience means putting more emphasis on what communities can do for themselves and how to strengthen their capacities, rather than concentrating on their vulnerability to disaster or their needs in an emergency (pp. 156-157).”

In both practice and research, public health conceptualizes the role of resilience at multiple scales of analysis, including individual, family, community, nation/society, as well as within the physical environment. Health resilience involves person’s ability to positively adapt to health adversity, and there is a growing interest in developing markers for the “epidemiology of resilience” (Cairns-Nagy & Bambra, 2013; Glonti, 2015). Furthermore, health resilience involves developing strong communities within the large, global forces impacting and burdening communities. Regarding disaster preparedness, the field emphasizes building capacity for resilient health care systems. Kruk et al. (2015) define health system resilience as “the capacity of health-care actors, institutions, and populations to prepare for and respond to crises, maintain core functions in time of crisis; and, informed by lessons learned during a crisis.” However, Fridell et al.’s scoping review (2020) found that while Kruk et al. (2015) are commonly cited, their argument that learning is central to resilience is often overlooked. Public health systems can enhance resilience to crisis by increasing preparedness beforehand, maintaining functioning throughout, and engaging in learning afterwards.

These six distinct disciplinary conceptualizations of resilience indicate the breadth of the concept within and beyond these fields. Taken together, they portray resilience as an interactive systems dynamic and highlight the diversity of approaches, perspectives and bodies of knowledge necessary to generate resilient systems. They also reveal tensions embedded in the

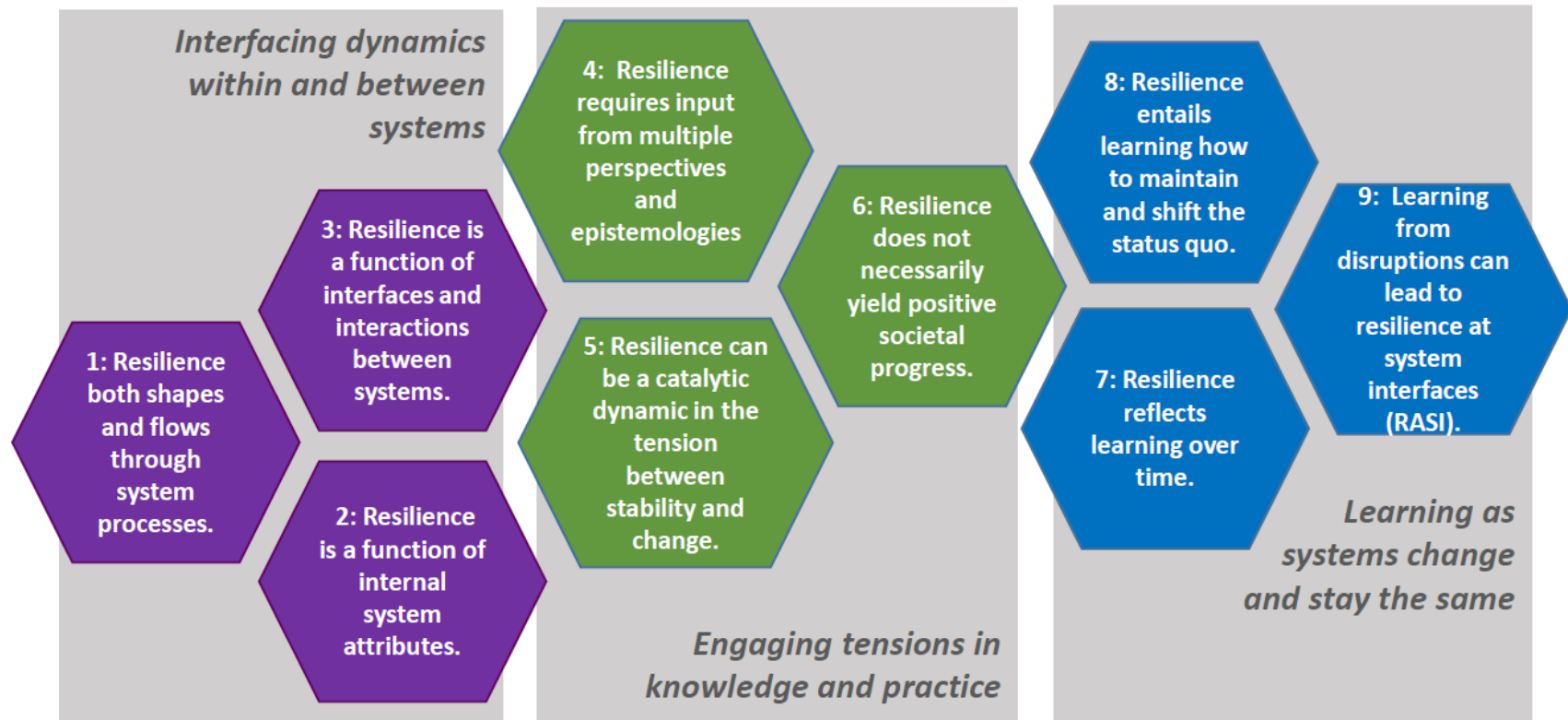
concept and its sometimes contradictory nature. The following discussion unpacks these general observations by applying them to water system crises and using these disciplinary perspectives to propose nine propositions for advancing the concept of resilience.

Propositions

Building on the disciplinary lineages above, we use water system crises as exemplars to think through how resilience works in these complex systems. While some of the concepts and relationships described in these propositions have been discussed elsewhere within the broad body of resilience literature, their application to the specific context of water and public health systems is novel and may be useful in exploring resilience in other contexts. Propositions 1-3 argue for understanding resilience as an interactive dynamic that manifests both within and between systems. Propositions 4-6 speak to key questions and tensions that resilience reveals around expertise, stability, and change. Propositions 7-9 address the key role of learning in producing resilience.

This theorizing draws on the disciplinary frames to engage the range of system connections we identified across fields as they pertain to water systems and public health crises. We see these propositions as provocations to strengthen interdisciplinary and transdisciplinary thinking and theory development for key concepts. These propositions, displayed in Figure 1, offer a starting point for interdisciplinary theorizing around specific challenges facing critical infrastructure systems.

Figure 1: Nine Propositions for Resilience within and between Complex Systems



Interfacing dynamics within and between systems

A storage and processing company for the coal industry, Freedom Industries was responsible for a 2014 chemical spill in West Virginia's Elk River that resulted in contamination of a downstream drinking water system serving 300,000 people across nine counties in the Charleston metropolitan area (Whelton et al. 2017). Prior to the crisis, economic interests in mining, fracking, and tourism had contaminated mountain springs and local streams, leading to generations of birth defects and limiting local Appalachian residents' clean water access to the Elk River via the American Water Company (Turley, 2016). During the water crisis, with limited storage reserves, Charleston's water operators made the decision not to close the source water intake for risk of losing fire protection. This decision resulted in chemical contaminants entering the distribution system, resulting in more than 2,000 reported exposures to contaminated water in the two weeks after the spill (Thomasson et al, 2017; Whelton et al, 2015). Despite a Do Not Drink order, as well as declaration of a state emergency and a federal disaster, negative health exposures occurred. Some residents consumed water directly after the spill, while others were exposed by air during recommended in-home flushing (Whelton et al, 2015).

- *Proposition 1: Resilience both shapes and flows through system processes.*

In opposition to early conceptualizations of resilience as a static characteristic, communication theorists have encouraged understanding resilience as a process (Buzzanell, 2010, 2018; Norris et al., 2008). Social work built on these processual views to conceptualize resilience as a flow, distributed among interconnected bodies (Menakem, 2017, p.51). Mapping

this view from a social network to a critical infrastructure system, we argue that resilience is not *in itself* either an attribute (i.e., a quality or possession) or a process (i.e., what happens and how it is done), but rather it is a *dynamic* of processes, orientations, and connections in systems. A dynamic has to do with the force, direction, and energy to fuel, trigger, and direct processes and define attributes. The resilience dynamic, distributed throughout a system and interconnected systems, may spark, push, carve out, define, maintain, or change ongoing systems operations, capacities, and features, ranging from physical infrastructure to institutional relationships. Rather than a concrete attribute or defined process, resilience as a dynamic emphasizes its role in directing activity and managing conditions of both stability and change. It also emphasizes that resilience may compete and interact with other dynamics of complex socio-technical systems.

During the Elk River chemical spill, also known as the West Virginia Water Crisis, water systems balanced varied static and emergent socio-technical components, along with organizational and ecological components and interactions, to continually provide drinking water in the face of contamination, inequality, and aging infrastructure. In normal operations, resilience flows and redistributes through a system and interconnected systems to insulate them against disturbances and reinforce existing processes when, for example, source water contamination is mitigated through routine treatment. In the face of a disastrous chemical spill, resilience shaped how the water system oriented and responded. This included the system's decision not to close the source intake and their approach to communication and coordination with the company at fault, the government, and the larger public. Resilience, as a dynamic vector shaping and flowing through systems, affected the community and its stakeholder's' capacities for response, recovery time, and health going forward, including how the system changed (Thomasson et al, 2017; Whelton et al, 2015).

- *Proposition 2: Resilience is a function of internal system attributes.*

Attributes and features internal to systems interact in complex ways to produce capacities for resilience (Norris et al., 2008). For example, bodies of knowledge and practice such as engineering, political science and communication hold that technical capacity, monitoring methodologies, experiences, risk monitoring and recognition systems, bodies of knowledge, slack resources, equipment, funding, and relationships may all contribute to a system's resilience. A complex system's internal resilience can be understood as a function of these intersecting and interrelated components. As the disciplinary frames demonstrated, resilience functions at multiple levels and in multiple domains. The chemical spill by Freedom Industries illustrates how resilience relies on a water system's internal system attributes, such as storage capacity, along with internal system processes, such as post-contamination monitoring of chemical concentrations (Whelton et al., 2017). A singular focus on the internal attributes of a system reflects a common myopia of resilience traditions. We include this proposition to emphasize that an analysis of internal systems dynamics is necessary, albeit not sufficient for understanding the dynamics of resilience.

- *Proposition 3: Resilience is a function of interfaces and interactions between systems.*

Resilience relies not only on internal characteristics of individual systems and their components but also on their interactions with other systems. It relies on the social, ecological, material, organizational, and technical attributes and processes discussed throughout the disciplinary frames in a web of interfacing systems. Systems interface around various elements, including communication, resource sharing, and learning. One way complex systems manifest

resilience at their systems' interfaces is by developing interoperative capacity to share information about emerging risks (O'Shay et al., 2020). As such, the resilience of a given system relies in part on the associations, agreements, relationships, and networks with stakeholders and interdependent systems. An organization, such as a municipal water system, exists within a larger context of stakeholders, agencies, communities, and other organizations with whom they interact more or less frequently. In many cases, the interdependence of these elements may not be fully appreciated until they are revealed by a disruption. The function and quality of these relationship dynamics also factor into the capacity to bounce back and forward from disruptions.

Responding to the West Virginia Water Crisis required the municipal water system to coordinate and interact with dozens of public, nonprofit, and private organizations at local, state, and federal levels (Snair, 2014). A major lesson, according to local public health official Dr. Rahul Gupta, was that "it is crucial to continuously earn and maintain the public's trust and confidence." To grow resilience at the public interface, Gupta identified several areas for staff training and education to address the gap in skillsets and interdependencies revealed by the crisis. From the public view of that interface, the widespread contamination of local source water historically had already reduced the resilience of communities around Charleston. As they faced the trauma of longstanding environmental injustice compounded by a new disaster, residents felt responsible for being resilient during and after the crisis (Turley, 2016, p. 34), while neoliberal narratives of resilience emphasizing individual responsibility and downplaying the role of system interactions may have reduced the overall resilience of critical interconnected systems (Joseph, 2013). At multiple points during the crisis, different sets of stakeholders interfaced with each other to formulate responses that affected recovery. Each interface where systems intersected

revealed different systems and features of system dynamics modulating where resilience would be most robust and where it might be lacking or redistributed.

Thus, we propose that building Resilience at System Interfaces (RASI) is crucial to navigating such complex interdependent relationships and dynamics. As propositions 1 and 2 discussed, resilience is an inter-system dynamic as much as it is a dynamic internal to systems. While it is beyond the scope of this paper to fully develop the concept of system interfaces, we view them as where two or more systems host interactions, exchanges, and resources. We believe these system interfaces are crucial to the flow and distribution of resilience through interconnected systems. Recognizing and understanding the dynamics of RASI could be an important approach to building resilience in critical infrastructures. RASI can also serve as a conceptual anchor for emerging interdisciplinary frameworks and fields of inquiry, such as sustainability science.

Engaging tensions in knowledge and practice

Water systems may introduce chronic stressors that disproportionately impact minority groups. Historical use of lead in drinking water plumbing and service lines continues to cause health problems through drinking water systems (Rabin, 2013), with Washington, D.C. (Edwards et al, 2009) and Flint, MI (Hanna-Attisha et al, 2016) serving as two important examples. In each case, the engineering systems designed for lead control, corrosion control, and water monitoring protocols failed, and the consequences reverberated throughout the interconnected subsystems. In Washington, D.C., a change in disinfectant designed to control cancer-causing byproducts led to changes in water chemistry, resulting in elevated lead release (Edwards et al, 2009). In Flint, MI, elevated lead release, due to a change in source water, also resulted in a *Legionella* outbreak (Zahran et al, 2018). In both cases, water system failures were exacerbated by regulatory and political system failures to identify the risk, address the problem, and communicate effectively with the public. The consequent disasters overwhelmingly burdened the working class and poor Black communities of Flint and D.C. with generational health disparities and stigmas (Butler et al, 2016; Nowling & Seeger, 2020).

- *Proposition 4: Resilience requires input from multiple perspectives and epistemologies.*

As discussed throughout this analysis, complex socio-technical systems are epistemic communities that coordinate and apply specialized knowledge and expertise from diverse disciplines to maintain and promote system functioning (Haas, 1992). Organizations exist within a larger environmental context, which is a source of both uncertainty and information. Requisite variety suggests that the diversity and complexity of the system must match the complexity and diversity of the external environment (Ashby & Goldstein, 2011). An organization's variety is a

measure of flexibility and capacity to recognize, process and manage external information including information about risks (Weick, 1979). Diversity of perspectives, expertise, and experience allows for richer and more complex understanding of emerging risk and risk signals. This diverse capacity to perceive and process information contributes to resilient systems, both in their ability to recognize and avoid risks and respond effectively.

Water systems and public health systems both exist within complex and dynamic organizational environments and natural ecologies, where the capacity to receive and process information is critical to success. During the Flint water crisis, for example, managers failed to recognize the emerging water crisis in a timely fashion in part because the leadership had insufficient diversity of expertise to receive, recognize, and process risk signals (Nowling & Seeger, 2020). At the time, Michigan Governor Snyder had placed the City of Flint under Emergency Management, reducing the number and diversity of decision makers from a democratically elected government accountable to the public to a single appointed Emergency Manager focused on cost reduction (Smith, 2018). Without sufficient technical expertise or environmental analysis and with implicit racial biases of a mostly white political structure disconnected from mostly African American residents, Emergency Managers abruptly made the decision to switch water sources and then ignored and discounted community complaints about the drinking water. Thus, what happened in Flint was not only a significant crisis at the intersection of water and public health systems, but also a clear example of the role of requisite variety, or lack thereof, in contributing to resilience (Nowling & Seeger, 2020).

- *Proposition 5: Resilience can be a catalytic dynamic in the tension between stability and change.*

Resilience adheres to the status quo, just as it endures change. The conceptual range between “bouncing back” and “bouncing forward better” embodied in the disciplinary frames implicitly refers to a starting point with baseline conditions in comparison to a later point, and embodies the tension between equilibrium states and boundary domains. While resilience is often presented as conceptually distinct from and in some ways opposed to renewal or transformative change, across fields the concept itself is expanding to argue that some fundamental system changes can and should occur for a system not just to bounce back to its previous state but to recover to an improved status quo.

In many ways, resilience is itself an arbiter of stability and change of equilibrium states and their boundaries. Accordingly, resilient systems must be stable enough to remain intact but flexible enough to adapt to adversity over the flux of time and space. A resilient system can fundamentally function in the same manner after a disruption, with some changed operations, processes, relationships, and technologies. Significant disruptions inevitably produce some level of change. Yet, resilience adheres with viability and fidelity to any system in question. As noted in Proposition 3, when resilient systems are interdependent, they will help each other maintain stability amidst disruption, demonstrating RASI. However, consistent with Proposition 4, if resilient systems intersect and conflict, they could require fundamental change of each other.

As a durable and flexible material that could adjust to temperature change, lead became a common material used to engineer water infrastructure across the U.S. However, the element once prized by engineering for its resilience eventually interfered with the water system’s goals to deliver safe water, because lead can poison humans, especially children. Drinking water

systems have employed various solutions, such as corrosion control, to greatly mitigate the risk. However, in D.C. and especially in the high profile case of Flint, these mitigating strategies failed, threatening the health and safety of the community, and causing a social crisis, which disrupted the stability of the political system enough to require policy changes. A number of governments, including the City of Washington, D.C. and the State of Michigan, have required the complete replacement of residential lead service lines. In these cases, dynamics of physical resilience and community resilience catalyzed change in policies governing drinking water systems to regain stability after construction of new water infrastructure.

- *Proposition 6: Resilience does not necessarily yield positive societal progress.*

Just as stability and change are not inherently good or bad, resilience is not *a priori* positive or negative. However, scholars often employ a normative view of the term (resilience as “good”) (Bourbeau, 2015). This positive connotation can position resilience as a panacea for a multitude of risks, and this view has influenced governments to require a resilience focus in funding requirements and initiatives. This approach (resilience as “solution”) may discount evidence of negative outcomes, as well as outcomes with uneven consequences for different groups of people in diverse contexts. Overall infrastructure resilience can gloss over hardships faced by minority groups and residents with lower socioeconomic status, who face disproportionate service disruptions during disasters (Coleman, et al, 2020). This discrimination is mirrored on a global scale, where residents of semi-colonial countries face chronic stressors that make them more vulnerable to disasters (Mostafavi et al, 2018). In many cases, neoliberal promotion of resilience

prioritizes market penetration for private profit over allocating public resources to shift baseline burdens faced by vulnerable populations (Bourbeau, 2015; Hall & Lamont, 2013; Klein, 2018).

Rather than embracing a normative approach to resilience, we encourage a multifaceted, transdisciplinary analysis that considers issues of power and whose interests resilience serves when adhering to the status quo. For instance, racism can be seen as an exceptionally resilient cultural system, one that overarchingly determined who got poisoned by the public water supply in D.C. and Flint, requiring exceptional resilience of those communities. Race is the strongest predictor of water and sanitation access in the U.S., with Native American households 19 times less likely than white households to have indoor plumbing, and Black and Latinx households twice less likely than white households to have indoor plumbing (Dig Deep, 2019). No matter how resilient under-resourced communities may be, they are subjected by systems of inequality and racism that are just as resilient, if not more. Thus resilience, understood as adherence to the status quo and returning to the status quo after disruptions may mean avoiding transformative change and maintaining an unequal and racist status quo.

Learning as systems change and stay the same

“Nowhere is the vital significance of water more obvious than in Los Angeles, which today imports more than 80 percent of its water supply from sources lying hundreds of miles beyond its legal boundaries. Los Angeles grew in the nineteenth century despite its lack of sewers and schools, a coastal city without a port, its growth fed by booster advertising and its development founded on prospects for the future rather than on actual demand. By the turn of the century, however, the rigid limits of the city's indigenous water supply had already begun to circumscribe the business community's prospects for continued growth and expansion. And so, with money, guns, and a unity of purpose with what they identified as the public interest, the bankers and businessmen of Los Angeles determined to seize the water resources of the Owens Valley 240 miles to the northeast. And, by correcting God's design for their community with the construction of the Los Angeles Aqueduct, they laid the foundations for the modern metropolis.” (*Kahrl, 1976*)

- *Proposition 7: Resilience reflects learning over time.*

Routine risks and disruptions to systems may not prompt the need for change. However, if routine events occur with sufficient regularity or in clusters, they may be interpreted as a substantive problem requiring change. Significant and expensive problems, however, may be so large scale and hard to understand and address that they are largely ignored by managers, consumers, and policymakers.

A significant disruption or crisis could lead to learning and promote system resilience, but this occurs beyond the immediate timeframes of immediacy and urgency. Additionally, the follow-through or impacts of actions systems take to learn after a disruption will not be

measurable at a single point in time and should be continuously assessed. Thus, the approach a system takes in addressing disruptions at various scales of severity and temporality governs the overlapping processes of resilience.

Droughts, defined as “the mismatch between the amounts of water nature provides and the amounts of water that humans and the environment demand,” have become a persistent and intensifying feature of a modern California lifestyle (NAS, 2015). Droughts in 1992 and 2002 prompted legislative action in California to require and provide minimal standards for municipal groundwater management plans. After 2009, drought created crisis-level water shortages with significant and ongoing consequences to residents, the economy, agricultural practices, and ecosystems (Service, 2009). Previous learning strategies to adapt to drought conditions involved a range of interventions, engaged diverse stakeholders, and led to “significant water conservation, development of alternative surface water supplies, and increased groundwater recharge and groundwater banking opportunities” (Harter & Dahlke, 2014). Recent research shows that California is at its driest in 1,200 years (Williams et al 2022), and drought is also plaguing the Horn of Africa, large parts of South America, and the Iberian peninsula. Resilience to known and unknown contingencies of climate change, economic imperatives, and threats to ecosystem diversity will necessitate learning new strategies for coping with droughts as a chronic concern (Morris & Bucini, 2016).

- *Proposition 8: Resilience entails learning how to maintain and shift the status quo.*

To be resilient, systems must continually learn about new and changing risks and what to do differently to maintain the integrity of the system going forward. This learning may guide intentional system change, which may improve resilience. Learning is the outcome of a process

of consideration. A variety of activities facilitate learning. These processes are markers of stability and change. Learning is also an iterative process of creating, retaining, and transferring knowledge within a system such that an organization improves over time (Antonacopoulou & Sheaffer, 2014). Organizations may learn directly from experiences and a trial and error process, and they may learn through observation. Learning does not necessarily promote positive outcomes. In some cases, learning fails. In other cases, organizations may learn the wrong lessons and in these cases, disruptions may lead to reduced resilience. As discussed in Proposition 6, resilience is neither inherently good nor bad; thus, learning in the face of disruption is a crucial mechanism for systems to employ to discern “what needs to be transformed and what needs to be conserved,” (Martusewicz et. al. 2015) rather than just what is needed to “bounce back.”

Over the past 150 years, Californians learned to live in and the U.S. learned to rely on “the most hydrologically altered landmass on the planet” as a population center and agricultural powerhouse (Water Education Foundation, n.d.). The second largest U.S. city, Los Angeles alone relies on three massive aqueducts pumping water up and over mountain ranges from Northern California and Colorado (Lehrman, 2018). Over the next 100 years, California’s water demand is expected to rise to three times larger than its supplies (Ackerman & Stanton, 2011, p. 17). Climate change will also increase flooding, wildfires, and heat waves, and decrease water supply. These realities are already shifting California lifestyles, as well as supply chains that rely on the state’s agriculture (Hagar, 2022). Under these conditions, learning how to build a new status quo for municipal drinking water systems will be necessary for the region and beyond.

- *Proposition 9: Learning from disruptions can lead to resilience at system interfaces (RASI).*

When disruptions are dramatic, large scale, and attention grabbing, they tend to create pressure for changes. They may do so by bringing a particular policy issue or organizational deficiency to the attention of decision makers as well as the public. Political science indicates that a disruption may become a focusing event if it is sufficiently sudden, uncommon, harmful, or concentrated in a particular place and time (Birkland, 1998). Such events are often the impetus for transformative change of interdependent complex systems. Smaller disruptions, which may be perceived as background noise or part of normal operations to be managed with existing resources and skillsets, may not require change or capture public attention enough to induce change. Larger scale disruptions, in contrast, may produce an agenda for change.

A disruption can implicate elements internal to an organization, creating an agenda for internal change. These internal or system levels changes are generally limited to policies, procedures, technologies, and resources internal to organizations. Disruptions may also focus attention on the relationship between systems, which we are interested in here. This may include the development of coordinated risk sensing and response procedures that take place at system interfaces. A variety of activities can facilitate learning, and different levels of learning may produce different degrees of change, ranging from modest changes and tweaks in operations to fundamental structural and operational changes to an organization. Learning focuses the processes by which change occurs and can lead to new engagements between interdependent systems. Resilience at systems interfaces (RASI) emerges when interactions and learning lead to stronger interoperability, relationships, communications, and capacity across distinct systems.

Responding to the Governor's and State Water Board's push for more aggressive legislative interventions after the 2009 drought, the Association of California Water Agencies and the California Water Foundation released a set of proposals aimed at more effective groundwater management. They emphasized the need for more comprehensive and integrated data, clearer direction and tools from local management authorities, and state mandated and enforced actions, implemented at the local or regional level (Harter & Dahlke, 2014, p. 55). Furthermore, researchers of California's chronic water crisis have called for more collaboration at system and governmental interfaces, rather than siloed approaches to seemingly competing interests, as well as redesigning urban and agricultural systems with an emphasis on sustainability in the face of climate change (Drevno, 2018; Morris & Bucini, 2016). These recommendations indicate that to build resilience for the coming generation, California will have to focus attention at its systems interfaces.

Conclusion

Interest in the concept of resilience is accelerating across disciplines, scientific fields, and system levels. Expanding understanding of the concept provides a bridge for rigorous discussion between disparate domains and disciplinary traditions. Considering the interdependencies of water systems as indicative of the dynamics of complex systems, this analysis proposes an interdependent framework on systems and system interfaces, diversity of expertise, stability and change, and learning as they relate to resilience. Water systems as socio-technical systems that host organizational ecologies and are embedded in natural ecologies have internal attributes that intersect and cross boundaries to affect resilience across systems. Furthermore, water system interdependencies fall within the working domain of a number of academic disciplines, each of

which have distinct disciplinary origins and approaches to resilience. The propositions suggested here connect contexts and levels of analysis across fields to further the interconnected, multi-level, and interdisciplinary development of the resilience concept.

We argue that resilience is an interactive system dynamic; a vector shaped by internal attributes, capacities, and cross-system interdependencies, especially influenced by learning. Resilience flows through and shapes systems and system interfaces, promoting stability and/or change, with a tendency toward maintaining the status quo. This bias holds even for an adverse status quo, such as structural racism. Resilience depends on and affects contextual features, such as the natural environment, infrastructure, political will, and socio-economic structures. To optimize resilience, epistemic communities, who circulate knowledge within systems, must be in tune with the diverse epistemologies in the external environment. This tuning helps systems to manage and learn from disruptions, especially major disruptions, within and across system interfaces. Resilience entails balancing stability and change to manage disruptions and learn how to persist.

These propositions provide nuance and contour to deepen understanding of what has become a popular concept. Supported through concrete, multi-level examples at the interface of drinking water systems and public health systems, the propositions may also be generalized widely across diverse fields. As such, scholars may investigate, what evidence can other domains, with different arrays of disciplinary and epistemological commitments, offer to support or disprove these propositions?

Finally, showing that systems intersect and depend on each other, this essay offers a new sub concept, Resilience at System Interfaces (RASI). Interfaces are where two or more systems may interact with each other, and future research can examine the nature of interfaces and how

interactions at interfaces take place. Future research can also examine types, frequencies, and strength of interactions and relationships facilitated at interfaces between systems. This can further understandings of how systems interface with each other, through what mechanisms, and to what ends. Beyond water systems, this line of inquiry can examine interactions from the vantage of different systems to understand how context and perspective affect RASI.

Data Availability

No data, models, or code were generated or used during the study.

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References

Adger, W.N. (2003, Feb). Building resilience to promote sustainability. *IHDP Update*, 2, pp. 1–

3.

Aldrich, D. P. (2012). *Building resilience: Social capital in post-disaster recovery*. University of Chicago Press.

Alexander, D. E. (2013). Resilience and disaster risk reduction: an etymological journey. *Natural Hazards and Earth System Sciences*, 13(11), 2707-2716. <https://doi.org/10.5194/nhess-13-2707-2013>

Allmark, P., Bhanbhro, S., & Chrisp, T. (2014). An argument against the focus on community resilience in public health. *BMC Public Health*, 14(62).
<http://www.biomedcentral.com/1471-2458/14/62>

American Water Works Association (2010). "Risk and resilience management of water and wastewater systems." ANSI/AWWA J100-10(R13). Denver, CO: AWWA.

Antonacopoulou, E. P., & Sheaffer, Z. (2014). Learning in crisis: Rethinking the relationship between organizational learning and crisis management. *Journal of Management Inquiry*, 23(1), 5-21.

Ashby, W. R., & Goldstein, J. (2011). Variety, constraint, and the law of requisite variety. *Emergence: Complexity and Organization*, 13(1/2), 190.

Ayyub, B. M. 2015. "Practical resilience metrics for planning, design, and decision making." ASCE-ASME J. Risk Uncertainty Eng. Syst., Part A: Civ. Eng. 1 (3): 04015008.
<https://doi.org/10.1061/AJRUA6.0000826>.

Balaei, B., Wilkinson, S., Potangaroa, R., Hassani, N., & Alavi-Shoshtari, M. (2018). Developing a framework for measuring water supply resilience. *Natural Hazards Review*, 19(4), 04018013.

Beilin R, Wilkinson, C. (2015). Introduction: Governing for urban resilience. *Urban Studies*.

52(7):1205-1217. doi:10.1177/0042098015574955

Béné, C., Mehta, L., McGranahan, G., Cannon, T., Gupte, J., & Tanner, T. (2018). Resilience as a policy narrative: potentials and limits in the context of urban planning. *Climate and Development, 10*(2), 116-133. <https://doi.org/10.1080/17565529.2017.1301868>

Birkland, T., & Waterman, S. (2008). Is federalism the reason for policy failure in Hurricane Katrina?. *Publius: The Journal of Federalism, 38*(4), 692-714.
<https://doi.org/10.1093/publius/pjn020>

Blake, N. M. (1956). *Water for the cities: A history of the urban water supply problem in the United States* (Vol. 3). Syracuse University Press.

Boin, A., & McConnell, A. (2007). Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience. *Journal of Contingencies and Crisis Management, 15*(1), 50-59. <https://doi.org/10.1111/j.1468-5973.2007.00504.x>

Bottrell, D. (2009). Understanding 'marginal' perspectives: Towards a social theory of resilience. *Qualitative Social Work, 8*(3), 321-339.
<https://doi.org/10.1177/1473325009337840>

Bourbeau, P. (2015). Resilience and international politics: Premises, debates, agenda. *International Studies Review, 17*(3), 374-395. <https://doi.org/10.1111/misr.12226>

Bourbeau, P. (2018). A genealogy of resilience. *International Political Sociology, 12*(1), 19-35.
<https://doi.org/10.1093/ips/olx026>

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

- Butler, L. J., Scammell, M. K., & Benson, E. B. (2016). The Flint, Michigan, water crisis: A case study in regulatory failure and environmental injustice. *Environmental Justice*, 9(4), 93-97. <https://doi.org/10.1089/env.2016.0014>
- Buzzanell, P. M. (2010). Resilience: Talking, resisting, and imagining new normalcies into being. *Journal of Communication*, 60(1), 1-14. <https://doi.org/10.1111/j.1460-2466.2009.01469.x>
- Buzzanell, P. M. (2018). Organizing resilience as adaptive-transformational tensions. *Journal of Applied Communication Research*, 46(1), 14-18. <https://doi.org/10.1080/00909882.2018.1426711>
- Buzzanell, P. M. (2020). Reflections on Feminist Organizational Communication. *Management Communication Quarterly*, 0893318920975211.
- Cairns-Nagy, J. & Bamba, C. (2013). Defying the odds: A mixed-methods study on resilience in deprived areas of England. *Social Science and Medicine*, 91(2013): 229-237. <https://doi.org/10.1016/j.socscimed.2013.03.014>
- Capano, G., & Woo, J. J. (2017). Resilience and robustness in policy design: A critical appraisal. *Policy Sciences*, 50(3), 399-426. <https://doi.org/10.1007/s11077-016-9273-x>
- Carpenter, S. R., Westley, F., & Turner, M. G. (2005). Surrogates for resilience of social–ecological systems. *Ecosystems*, 8(8), 941-944. <https://doi.org/10.1007/s10021-005-0170-y>
- Carvalhaes, T., Rinaldi, V., Goh, Z., Azad, S., Uribe, J., & Ghandehari, M. (2022). Integrating Spatial and Ethnographic Methods for Resilience Research: A Thick Mapping Approach for Hurricane Maria in Puerto Rico. *Annals of the American Association of Geographers*, 1-23.

CDC (2018). Public health emergency preparedness and response capabilities. Retrieved from [https://docs.google.com/viewer?url=https%3A%2F%2Fwww.cdc.gov%2Fcpr%2Freadiness%2F](https://docs.google.com/viewer?url=https%3A%2F%2Fwww.cdc.gov%2Fcpr%2Freadiness%2F00_docs%2FCDC_PreparednesResponseCapabilities_October2018_Final_508.pdf)

[00_docs%2FCDC_PreparednesResponseCapabilities_October2018_Final_508.pdf](https://docs.google.com/viewer?url=https%3A%2F%2Fwww.cdc.gov%2Fcpr%2Freadiness%2F00_docs%2FCDC_PreparednesResponseCapabilities_October2018_Final_508.pdf)

Cilliers, P., H. C. Biggs, S. Blignaut, A. G. Choles, J. S. Hofmeyr, G. P. W. Jewitt, and D. J. Roux. 2013. Complexity, modeling, and natural resource management. *Ecology and Society* 18(3): 1.

Coleman, N., Esmalian, A., & Mostafavi, A. (2020). Equitable resilience in infrastructure systems: Empirical assessment of disparities in hardship experiences of vulnerable populations during service disruptions. *Natural Hazards Review*, 21(4), 04020034.

Davis, C. A. (2021). Understanding Functionality and Operability for Infrastructure System Resilience. *Natural Hazards Review*, 22(1), 06020005.

Davis, C.A., A. Mostafavi, H. Wang, 2018, "Establishing Characteristics to Operationalize Resilience for Lifeline Systems," ASCE, *Natural Hazards Review*, 19(4)

Davoudi, S., Shaw, K., Haider, L. J., Quinlan, A. E., Peterson, G. D., Wilkinson, C., ... & Davoudi, S. (2012). Resilience: a bridging concept or a dead end? "Reframing" resilience: challenges for planning theory and practice interacting traps: resilience assessment of a pasture management system in Northern Afghanistan urban resilience: what does it mean in planning practice? Resilience as a useful concept for climate change adaptation? The politics of resilience for planning: a cautionary note: edited by Simin Davoudi and Libby Porter. *Planning Theory & Practice*, 13(2), 299-333.

<https://doi.org/10.1080/14649357.2012.677124>

Dig Deep Right to Water Project, US Water Alliance (2019). "Closing the Water Access Gap in the United States: A National Action Plan." Available at:

http://uswateralliance.org/sites/uswateralliance.org/files/publications/Closing%20the%20Water%20Access%20Gap%20in%20the%20United%20States_DIGITAL.pdf

Drevno, A. (2018). Central Coast growers' trust in water quality regulatory process needs rebuilding. *California Agriculture*, 72(2), 127-134. <https://doi.org/10.3733/ca.2018a0015>

Edwards, M., Triantafyllidou, S., & Best, D. (2009). Elevated blood lead in young children due to lead-contaminated drinking water: Washington, DC, 2001– 2004. *Environmental Science & Technology*, 43(5), 1618-1623. <https://doi.org/10.1021/es802789w>

Evans, B., Reid, J., 2015. *Resilient Life: the Art of Living Dangerously*. Polity, Cambridge.

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, 16(3): 253-267. DOI: <https://doi.org/10.1016/j.gloenvcha.2006.04.002>.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society* 15(4): 20. [online] URL: <http://www.ecologyandsociety.org/vol15/iss4/art20/>

Fridell, M., Edwin, S., von Schreeb, J., Dell D. Saulnier, D.D., (2020). Health system resilience: What are we talking about? A scoping review mapping characteristics and keywords. *International Journal of Health Policy and Management*. 9(1): 6–16. doi: 10.15171/IJHPM.2019.71

Garrett, P. (2016). "questioning tales of ‘ordinary magic’: ‘Resilience’ and neo-liberal reasoning". *The British Journal of Social Work*, 46 (7), 1909. <https://doi.org/10.1093/bjsw/bcv017>

Getchell, M. C., & Sellnow, T. L. (2016). A network analysis of official Twitter accounts during

- the West Virginia water crisis. *Computers in Human Behavior*, 54, 597-606.
- <https://doi.org/10.1016/j.chb.2015.06.044>
- Gheisi, A., Forsyth, M. & Naser, G. (2016). “Water distribution systems reliability: A review of research literature.” *Journal of Water Resources Planning and Management* 142 (11): 04016047. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000690](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000690).
- Glonti, Ketevan, et al. (2015). A systematic review on health resilience to economic crises. *PLoS One*, 10(4):1-22. | DOI:10.1371/journal.pone.0123117
- Godschalk, D. R. (2003). Urban hazard mitigation: creating resilient cities. *Natural Hazards Review*, 4(3), 136-143. [https://doi.org/10.1061/\(ASCE\)1527-6988\(2003\)4:3\(136\)](https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136))
- Haas, P. M. (1992). Introduction: epistemic communities and international policy coordination. *International organization*, 1-35.
- Hagar, Alex. “California water agencies strike an agreement to conserve some Colorado River supply.” October 5, 2022. National Public Radio KUNC.
- Hall, P. A., & Lamont, M. (Eds.). (2013). Social resilience in the neoliberal era. Cambridge University Press.
- Hanna-Attisha, M., LaChance, J., Sadler, R. C., & Champney Schnepf, A. (2016). Elevated blood lead levels in children associated with the Flint drinking water crisis: a spatial analysis of risk and public health response. *American Journal of Public Health*, 106(2), 283-290. <https://doi.org/10.2105/AJPH.2015.303003>
- Harter, T., & Dahlke, H. (2014). Out of sight but not out of mind: California refocuses on groundwater. *California Agriculture*, 68(3), 54-55.
- <https://doi.org/10.3733/ca.v068n03p54>
- Hellmann, O. (2018). High capacity, low resilience: The ‘developmental ‘state and military–

- bureaucratic authoritarianism in South Korea. *International Political Science Review*, 39(1), 67-82. <https://doi.org/10.1177/0192512117692643>
- Hess, S. (2013). From the Arab Spring to the Chinese Winter: The institutional sources of authoritarian vulnerability and resilience in Egypt, Tunisia, and China. *International Political Science Review*, 34(3), 254-272. <https://doi.org/10.1177/0192512112460258>
- Hickford, A. J., Blainey, S. P., Hortelano, A. O., & Pant, R. (2018). Resilience engineering: theory and practice in interdependent infrastructure systems. *Environment Systems and Decisions*, 38(3), 278-291. <https://doi.org/10.1007/s10669-018-9707-4>
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4(1), 1-23. <https://doi.org/10.1146/annurev.es.04.110173.000245>
- Holling, C. S. (1996). Engineering resilience versus ecological resilience. *Engineering within Ecological Constraints*, 31(1996), 32.
- Houston, J. B., Spialek, M. L., Cox, J., Greenwood, M. M., & First, J. (2015). The centrality of communication and media in fostering community resilience: A framework for assessment and intervention. *American Behavioral Scientist*, 59(2), 270-283. <https://doi.org/10.1177/0002764214548563>
- Huang, S. M. (2018). Heritage and postdisaster recovery: Indigenous community resilience. *Natural Hazards Review*, 19(4), 05018008.
- Huang, S. M., Che-Hao, H., & Chang, Y. H. (2021). The paradox of cultivating community resiliency: Re-agrarianisation and De-peasantisation of indigenous farmers in Taiwan. *Journal of Rural Studies*, 83, 96-105.
- Huck, P. M., & Coffey, B. M. (2004). The importance of robustness in drinking-water systems. *Journal of Toxicology and Environmental Health, Part A*, 67(20-22), 1581-1590.

Humbert, C., & Joseph, J. (2019). Introduction: the politics of resilience: Problematising current approaches. *Resilience*, 7(3), 215-223. <https://doi.org/10.1080/21693293.2019.1613738>

IPCC, 2012: Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

Joseph, J. (2013). Resilience as embedded neoliberalism: a governmentality approach. *Resilience*, 1(1), 38-52.

Kahrl, W. L. (1976). The Politics of California Water: Owens Valley and the Los Angeles Aqueduct, 1900-1927. *California Historical Quarterly*, 55(1), 2-25.
<https://doi.org/10.2307/25157605>

Klein, N. (2018). *The battle for paradise: Puerto Rico takes on the disaster capitalists*. Haymarket Books.

Kolar, K. (2011). Resilience: Revisiting the concept and its utility for social research. *International Journal of Mental Health and Addiction*, 9(4), 421. <https://doi-org.proxy.lib.wayne.edu/10.1007/s11469-011-9329-2>

Kruk, M.E, Myers M, Varpilah S.T, Dahn B.T. (2015.) What is a resilient health system? lessons from Ebola. *Lancet*. 385(9980):1910-1912. doi:10.1016/S0140-6736(15)60755-3

Lehrman, B. (2018). Visualizing water infrastructure with Sankey maps: a case study of mapping the Los Angeles Aqueduct, California. *Journal of Maps*, 14(1), 52-64.

L'Heureux, A. V., & Therrien, M. C. (2013). Interorganizational dynamics and characteristics of critical infrastructure networks: The study of three critical infrastructures in the greater Montreal area. *Journal of Contingencies and Crisis Management*, 4(21), 211-224.
10.1111/1468-5973.12030

- Li, Y. (2018). *Playing by the informal rules: Why the Chinese regime remains stable despite rising protests*. Cambridge University Press.
- Liu, W. T. (2014). The application of resilience assessment—resilience of what, to what, with what? A case study based on Caledon, Ontario, Canada. *Ecology and Society*, 19(4).
- Mann, M. E., & Gleick, P. H. (2015). Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences*, 112(13), 3858-3859.
<https://doi.org/10.1073/pnas.1503667112>
- Martusewicz, R., Edmundson, J., & Lupinacci, J. (2015). *EcoJustice Education: Toward diverse, democratic, and sustainable communities* (2nd Ed.). New York: Routledge.
- Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and urban planning*, 147, 38-49.
- Meerow, S., & Newell, J. P. (2019). Urban resilience for whom, what, when, where, and why? *Urban Geography*, 40(3), 309-329. <https://doi.org/10.1080/02723638.2016.1206395>
- Melosi, M. V. (1980). The urban physical environment and the historian: prospects for research, teaching and public policy. *Journal of American Culture*, 3(3), 526-540.
https://doi.org/10.1111/j.1542-734X.1980.0303_526.x
- Melosi, M. V. (2000). *The sanitary city: Urban infrastructure in America from colonial times to the present*. Baltimore : Johns Hopkins University Press. Menakem, R. (2017). *My grandmother's hands: Racialized trauma and the pathway to mending our hearts and bodies*. Central Recovery Press.
- Morley, K. M. (2012). *Evaluating resilience in the water sector: Application of the utility resilience index (URI)* (Doctoral dissertation): George Mason University.
- Morton, M. J., & Lurie, N. (2013). Community resilience and public health practice. *American*

- Journal of Public Health* 103, 1158_1160, <https://doi.org/10.2105/AJPH.2013.301354>
- Morris, K. S., Bucini, G., Kapuscinski, A. R., Locke, K. A., & Méndez, E. (2016). California's drought as opportunity: Redesigning US agriculture for a changing climate Redesigning US agriculture for a changing climate. *Elementa: Science of the Anthropocene*, 4. <https://doi.org/10.12952/journal.elementa.000142>
- Mostafavi, A., Ganapati, N. E., Nazarnia, H., Pradhananga, N., & Khanal, R. (2018). Adaptive capacity under chronic stressors: Assessment of water infrastructure resilience in 2015 Nepalese earthquake using a system approach. *Natural Hazards Review*, 19(1), 05017006.
- Mugume, S. N., Gomez, D. E., Fu, G., Farmani, R., & Butler, D. (2015). A global analysis approach for investigating structural resilience in urban drainage systems. *Water Research*, 81, 15-26. <https://doi.org/10.1016/j.watres.2015.05.030>
- Newell, J. (2020). An ecological systems framework for professional resilience in social work practice. *Social Work*, 65(1):65–73, <https://doi-org.proxy.lib.wayne.edu/10.1093/sw/swz044>.
- NIST (National Institute of Standards and Technology). 2015. Community resilience planning guide for buildings and infrastructure systems. NIST Special Publication 1190. Gaithersburg, MD: NIST.
- NIST, 2016, "Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery," NIST GCR 16- 917-39, Prepared by Applied Technology Council for the National Institute of Standards and Technology, Gaithersburg, MD. <https://www.nist.gov/sites/default/files/documents/el/resilience/NIST -GCR-16-917-39.pdf>

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008).

Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology*, 41(1), 127-150.

<https://doi.org/10.1007/s10464-007-9156-6>

Nowling, W. D., & Seeger, M. W. (2020). Sensemaking and crisis revisited: the failure of

sensemaking during the Flint water crisis. *Journal of Applied Communication Research*, 48(2), 270-289. <https://doi.org/10.1080/00909882.2020.1734224>

Noyes, D. (2016). *Humble Theory: Folklore's Grasp on Social Life*. Indiana University Press.

Orleans Reed, S., Friend, R., Toan, V. C., Thinphanga, P., Sutarto, R., & Singh, D. (2013).

“Shared learning” for building urban climate resilience—experiences from Asian cities.

Environment and Urbanization, 25(2), 393-412. doi:10.1177/0956247813501136

O'Brien, G., O'Keefe, P.R., Rose, J., Wisner, B., 2006. Climate change and disaster management.

Disasters 30, 64-80.

O'Shay, S., Day, A. M., Islam, K., McElmurry, S. P., & Seeger, M. W. (2020). Boil water

advisories as risk communication: Consistency between CDC guidelines and local news media articles. *Health Communication*, 1-11.

<https://doi.org/10.1080/10410236.2020.1827540>

Ostfeld, A., & Salomons, E. (2004). Optimal layout of early warning detection stations for water

distribution systems security. *Journal of Water Resources Planning and Management*, 130(5), 377-385.

Pagano, A., Pluchinotta, I., Giordano, R., & Fratino, U. (2018). Integrating “Hard” and “Soft”

infrastructural resilience assessment for water distribution systems. *Complexity*, 2018.

<https://doi.org/10.1155/2018/3074791>

Park, Y., Crath, R., & Jeffrey, D. (2020). Disciplining the risky subject: A discourse analysis of the concept of resilience in social work literature. *Journal of Social Work*, 20 (2): 152-172, <https://doi-org.proxy.lib.wayne.edu/10.1177/1468017318792953>.

Petrescu, D., Petcou, C., & Baibarac, C. (2016). Co-producing commons-based resilience: lessons from R-Urban. *Building Research & Information*, 44(7), 717-736.
<https://doi.org/10.1080/09613218.2016.1214891>

Pinkerton, J. & Dolan, P. (2007). Family support, social capital, resilience and adolescent coping. *Child & Family Social Work*, 12(3): 219-228. <https://doi-org.proxy.lib.wayne.edu/10.1111/j.1365-2206.2007.00497.x>

Platt, R. H. (2012). *Disasters and democracy: The politics of extreme natural events*. Island Press.

Quarantelli, E. L., & Perry, R. W. (2005). A social science research agenda for the disasters of the 21st century: Theoretical, methodological and empirical issues and their professional implementation. What is a disaster, 325, 396.

Rabin, R. (2008). The lead industry and lead water pipes “A Modest Campaign”. *American Journal of Public Health*, 98(9), 1584-1592. <https://doi.org/10.2105/AJPH.2007.113555>

Ravenel, M. (1970). *A half century of public health*. New York: American Public Health Association (reprint of 1921).

Roberts, P. (2009). An unnatural disaster. *Administration & Society*, 41(6), 763-769.
10.1177/0095399709345628

Rodin, J. (2014). *The resilience dividend: being strong in a world where things go wrong*. Public Affairs.

Rogov, M., & Rozenblat, C. (2018). Urban resilience discourse analysis: towards a multi-level

- approach to cities. *Sustainability*, 10(12), 4431. <https://doi.org/10.3390/su10124431>
- Rose, S. & Palattiyil, G. (2020). Surviving or thriving? Enhancing the emotional resilience of social workers in their organizational settings. *Journal of Social Work*, 20 (1):23-42, <https://doi-org.proxy.lib.wayne.edu/10.1177/1468017318793614>.
- Ross, A. D. (2013). *Local disaster resilience: Administrative and political perspectives*. Routledge.
- Seeger, M. W. (2006). Best practices in crisis communication: An expert panel process. *Journal of Applied Communication Research*, 34, 232–244. doi: 10.1080/00909880600769944
- Senier, S., Lioi, A., Ryan, M. K., Vasudevan, P., Nieves, A., Ranco, D., & Marshall, C. (2014). The resilience of race: A cultural sustainability manifesto. *Resilience: A Journal of the Environmental Humanities*, 1(2).
- Service, R. (March 27, 2009). California's water crisis: Worse to come? *Science*, 323(5922): 1665. DOI: 10.1126/science.323.5922.1665.
- Smith, O.G. (2018, Jan 16). Flint's history of emergency management and how it got to financial freedom. Retrieved from https://www.mlive.com/news/flint/2018/01/city_of_the_state_flints_histo.html
- Somers, S. (2009). Measuring resilience potential: An adaptive strategy for organizational crisis planning. *Journal of Contingencies and Crisis Management*, 17(1), 12-23. <https://doi.org/10.1111/j.1468-5973.2009.00558.x>
- Spialek, M. L., & Houston, J. B. (2018). The development and initial validation of the citizen disaster communication assessment. *Communication Research*, 45(6), 934-955.
- Stark, A., & Taylor, M. (2014). Citizen participation, community resilience and crisis-

- management policy. *Australian Journal of Political Science*, 49(2), 300-315.
- <https://doi.org/10.1080/10361146.2014.899966>
- Stokols, D. (2018). *Social ecology in the digital age: Solving complex problems in a globalized world*. Academic Press.
- Su, Y. C., Mays, L. W., Duan, N., & Lansey, K. E. (1987). Reliability-based optimization model for water distribution systems. *Journal of Hydraulic Engineering*, 113(12), 1539-1556.
- Tarr, J. A. (1996). *The search for the ultimate sink: Urban pollution in historical perspective*. The University of Akron Press.
- Tierney, K. (2015). Resilience and the neoliberal project: Discourses, critiques, practices—and Katrina. *American Behavioral Scientist*, 59(10), 1327-1342.
- <https://doi.org/10.1177/0002764215591187>
- Thomasson, E. D., Scharman, E., Fechter-Leggett, E., Bixler, D., Ibrahim, S. F., Duncan, M. A., ... & Lewis, L. (2017). Acute health effects after the Elk River chemical spill, West Virginia, January 2014. *Public Health Reports*, 132(2), 196-202.
- <https://doi.org/10.1177/0033354917691257>
- Turenne, C. P., Gautier, L., Degroote, S., Guillard, E., Chabrol, F., & Ridde, V. (2019). Conceptual analysis of health systems resilience: a scoping review. *Social Science & Medicine*, 232, 168-180. <https://doi.org/10.1016/j.socscimed.2019.04.020>
- Turley, B. (2016). After the spill: Environmental justice and disaster relief in West Virginia (Doctoral dissertation, The Ohio State University).
- United States Environmental Protection Agency (2015). Drinking water contaminants. In

- America's children and the environment* (3rd Ed.). Retrieved from:
https://docs.google.com/viewer?url=https%3A%2F%2Fwww.epa.gov%2Fsites%2Fproduction%2Ffiles%2F2015-10%2Fdocuments%2Face3_drinking_water.pdf.
- van Breda, A. D. (2016). Building resilient human service organizations. *Human Service Organizations: Management, Leadership & Governance*, 40(1), 62-73. Doi: 10.1080/23303131.2015.1093571
- Wagner, J. M., Shamir, U., & Marks, D. H. (1988). Water distribution reliability: Analytical methods. *Journal of Water Resources Planning and Management*, 114(3), 253-275.
[https://doi.org/10.1061/\(ASCE\)0733-9496\(1988\)114:3\(253\)](https://doi.org/10.1061/(ASCE)0733-9496(1988)114:3(253)).
- Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9(2).
<https://www.jstor.org/stable/26267673>
- Walker, J., & Cooper, M. (2011). Genealogies of resilience: From systems ecology to the political economy of crisis adaptation. *Security Dialogue*, 42(2), 143-160.
<https://doi.org/10.1177/0967010611399616>
- Water Education Foundation (n.d.). California water 101. Retrieved from
<https://www.watereducation.org/photo-gallery/california-water-101>
- Weick, K.E. (1979). *The social psychology of organizing*, 2nd ed.. Addison-Wesley.
- Whelton, A. J., McMillan, L., Connell, M., Kelley, K. M., Gill, J. P., White, K. D., ... & Novy, C. (2015). Residential tap water contamination following the freedom industries chemical spill: perceptions, water quality, and health impacts. *Environmental science & technology*, 49(2), 813-823.
- White, D. (2018). State capacity and regime resilience in Putin's Russia. *International Political*

- Science Review*, 39(1), 130-143. <https://doi.org/10.1177/0192512117694481>
- White, G.F. (1999). Changing perceptions of water management. *Environment*, 41(6), 2.
- Williams, A. P., Cook, B. I., & Smerdon, J. E. (2022). Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, 1-3.
- Yodo, N., and Wang, P. (September 12, 2016). Engineering resilience quantification and system design implications: A literature survey. *Journal of Mechanical Design*, 138(11), 111408. <https://doi-org.proxy.lib.wayne.edu/10.1115/1.4034223>
- Zahran, S., McElmurry, S. P., Kilgore, P. E., Mushinski, D., Press, J., Love, N. G., ... & Swanson, M. S. (2018). Assessment of the Legionnaires' disease outbreak in Flint, Michigan. *Proceedings of the National Academy of Sciences*, 115(8), E1730-E1739.
- Zautra, A.J., Hall, J.S., & Murray, K.E. (2010). Resilience: A new definition of health for people and communities. In J.W. Reich, A.J. Zautra & J.S. Hall (Eds.), *Handbook of adult resilience* (pp. 3–34). New York.
- Zebrowski, C., & Sage, D. (2017). Resilience and critical infrastructure: Origins, theories, and critiques. In *The Palgrave handbook of security, risk and intelligence* (pp. 117-135). Palgrave Macmillan.