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Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience

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Key Points:
- Infrastructure systems should be considered social-ecological-technological systems (SETSs), not simply technical or socio-technical systems
- Underappreciated complexity and reliance on techno-centric/robustness-oriented solutions contribute to lock-in and reduced adaptive capacity
- A SETS lens aids in the identification and prevention of system vulnerabilities and illumination of multidimensional adaptation strategies

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Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience

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Abstract Traditional infrastructure adaptation to extreme weather events (and now climate change) has typically been techno-centric and heavily grounded in robustness—the capacity to prevent or minimize disruptions via a risk-based approach that emphasizes control, armoring, and strengthening (e.g., raising the height of levees). However, climate and nonclimate challenges facing infrastructure are not purely technological. Ecological and social systems also warrant consideration to manage issues of overconfidence, inflexibility, interdependence, and resource utilization—among others. As a result, techno-centric adaptation strategies can result in unwanted tradeoffs, unintended consequences, and underaddressed vulnerabilities. Techno-centric strategies that *lock-in* today's infrastructure systems to vulnerable future design, management, and regulatory practices may be particularly problematic by exacerbating these ecological and social issues rather than ameliorating them. Given these challenges, we develop a conceptual model and infrastructure adaptation case studies to argue the following: (1) infrastructure systems are not simply technological and should be understood as complex and interconnected social, ecological, and technological systems (SETSs); (2) infrastructure challenges, like lock-in, stem from SETS interactions that are often overlooked and underappreciated; (3) framing infrastructure with a *SETS lens* can help identify and prevent maladaptive issues like lock-in; and (4) a SETS lens can also highlight effective infrastructure adaptation strategies that may not traditionally be considered. Ultimately, we find that treating infrastructure as SETS shows promise for increasing the adaptive capacity of infrastructure systems by highlighting how lock-in and vulnerabilities evolve and how multidisciplinary strategies can be deployed to address these challenges by broadening the options for adaptation.

Plain Language Summary Instead of thinking of infrastructure as purely technological artifacts, we instead propose considering infrastructure as linked social, ecological, and technological systems (SETS). Adopting a SETS lens can help identify vulnerabilities that develop within infrastructure systems over time. Ultimately, adopting this SETS perspective will not only help us better understand our infrastructure systems, but also aid in the development strategies for adapting to the many challenges that our infrastructure will continue to face (climate change, interdependencies, technological evolution, growing complexity, etc.)

1. Introduction and Background

Infrastructure systems have traditionally been designed to manage (and in some cases control) environmental systems and ensure that critical services and resources are available where and when they are needed (McPhee, 1989). For example, dams, canals, aqueducts, and pipelines have been constructed throughout the United States to provide water to population centers like Phoenix, Los Angeles, New York City, and others. Similarly, in the context of weather events, levees, dams, drainage culverts, retention basins, and pumps have been designed and sized to mitigate unwanted effects from extreme rainfall, storm surge, or riverine conditions. These *control* efforts are highly techno-centric in that they rely on the installation or upgrading of physical infrastructure components (e.g., pumps and culverts) as opposed to more ecologically based efforts like bioswales, constructed wetlands, or *living shorelines* that use vegetation or a mix of *green* and *gray* infrastructure to provide necessary services (Casal-Campos et al., 2015; National Oceanic and Atmospheric Administration, 2017; U.S. Environmental Protection Agency [U.S. EPA], 2017a; U.S. EPA, 2017b; Wang et al., 2013). They also tend to emphasize strengthening and armoring infrastructure—an approach that fits best under the robustness regime of resilience, where traditional risk analysis is used to determine the acceptable likelihood and magnitude of an event to which infrastructure are expected to withstand (Kim et al., 2017; Park et al., 2013; Seager et al., 2017; Woods, 2015). For example, levees and stormwater management systems are often designed to withstand the impacts from a storm that has a magnitude equivalent to a 1% chance of occurring in any given year—also known as a 100-year storm event. The link between robustness and techno-centric solutions is also used in forward looking analyses by establishing certain storm thresholds as design objectives projected into the future, and then developing models to test how various engineering adaptation strategies might perform with respect to the established threshold (e.g., Iowa Department of Transportation, 2015).

In well-constrained and understood circumstances, techno-centric, robustness-based strategies can be effective at preventing major disruptions. However, there are limits to the applicability of solely robustness/techno-centric practices, and our infrastructure systems appear to be increasingly running up against these limits (McPhail et al., 2018). Markolf et al. (2018) point out that the effectiveness of robustness strategies can be diminished by many challenges such as climate variability and unpredictability, changes in demographics and preferences, complexity and interconnectedness within infrastructure systems, and unpredictable human behavior—each of which are further discussed later in the manuscript. Thus, the true concern with our infrastructure appears to be our ability to recognize and respond to these limits in a timely manner, because when robust and techno-centric adaptations do fail, it is often to catastrophic effect.

While robustness appears to have been a relatively effective strategy for mitigating extreme events in the past, and will certainly play a crucial role moving forward, there is a growing notion that the challenges facing our infrastructure systems require more than techno-centric, robustness-only strategies. Robustness cannot simply become synonymous with resilience. Instead, emphasis should be placed on increasing the ability of our infrastructure systems to move across the following different resilience regimes as dictated by varying internal and external conditions (Chester & Allenby, 2018; Seager et al., 2017; Woods, 2015):

1. Rebound—the ability of damaged/degraded systems to return to predisruption conditions
2. Robustness—the capacity to prevent or minimize disruptions via a risk-based approach and emphasis on control and strengthening
3. Graceful extensibility—the ability to improvise solutions and extend system performance to mitigate the consequences of surprising or sudden events
4. Sustained adaptability—the long-term ability to transform and balance system conditions in response to constantly evolving external circumstances

Events like Hurricanes Harvey and Maria; the Southern California wildfires in December 2017; the ongoing drought and water supply issues in Cape Town, South Africa; and the long history of extreme events in the United States (National Oceanic and Atmospheric Administration National Centers for Environmental Information, 2017) not only illustrate the challenges that extreme events continue to pose to our infrastructure systems but also bring attention to the fact that these challenges may not simply be a matter of having the right technology in place or increasing robustness to correspond to a given hazard or threat level. For example, after Hurricane Katrina, nearly $14.5 billion was spent to reinforce levees, install additional pumping capacity, and construct the 1.8-mile-long Lake Borgne Surge Barrier (Burnett, 2015; U.S. Army Corps of Engineers [USACE], 2013a, 2013b, 2015). Nonetheless, pumping and drainage capacity was still not sufficient to prevent widespread flooding in several neighborhoods (and ultimately a declaration of a state of emergency) during an August 2017 rain storm (Craig, 2017; G.R., 2017). Essentially, vulnerability to flooding in New Orleans is not necessarily contingent on the height of the levees or the capacity of the pumping stations (i.e., robustness). Similarly, unprecedented meteorological conditions notwithstanding, at least some portion of the flooding that occurred during Hurricane Harvey is attributable to nontechnological issues such as rapid population growth and urban development, the lack of consistent and strong zoning regulations, and widespread replacement of ecological systems with impervious surfaces (Fleming, 2017; U.S. EPA, 2008; Wallace et al., 2018). The impact of this complex interaction between seemingly disparate factors is highlighted in multiple analyses related to flooding in the Houston area. For example, it was estimated that Federal Emergency Management Agency (FEMA) 100-year floodplain maps failed to capture 75% of the insured losses that occurred in Houston suburbs from five serious storm events between 1999 and 2009 (Blessing et al., 2017). Similarly, it was estimated that over 50% of the inundation in Harris County, Texas, during Hurricane Harvey was located in areas designated as *minimal flood hazard* by FEMA (Fessenden et al., 2017; Pinter et al., 2017). Essentially, the failure to fully account for social and ecological dynamics within the Houston region greatly reduced the effectiveness of flood mapping and assessment, which in turn resulted in misinformed flood prevention measures, zoning laws, and insurance mechanisms.

The New Orleans and Houston examples highlight that perhaps resilience should be thought of as more than just a technological and/or robustness challenge—necessitating a deeper consideration of the social and ecological context of a given infrastructure system. In the case of New Orleans, resilience is not simply a matter of increasing robustness by adding more pumps or raising levees. While these types of interventions play an important role and may prove to be effective against the next major hurricane, they were ineffective during (and possibly even exacerbated) the August 2017 flooding (Carr, 2017; Craig, 2017; Domonoske, 2017; Reckdahl, 2017). In this case, one cannot help but wonder if the *sunk costs* (in terms of money, time, knowledge, and other resources) associated with the levee and pump systems encouraged renewed investment in these interventions after Katrina at the expense of making other parts of the city more susceptible to flooding from rainfall. Systems can usually be designed to handle higher levels of stress or be inspected daily to ensure all components are functioning properly, but achieving these tasks will eventually be financially exhausting. Eventually, the right hazard or system degradation characteristics will emerge and lead to some level of failure. Thus, social response and the public safety system appear to be at least as important as the physical infrastructure systems. As illustrated to devastating effect during Katrina, people's location relative to hazards and the services and protections available to them prove to be vitally important (Bullard & Wright, 2009; Colten, 2007; Layzer, 2012).

Similarly, for Houston, resilience is not simply a techno-centric matter of widening bayous and reinforcing dams in preparation for the next Harvey. The fact that flood maps captured no more than 50% of the actual damages associated with flooding events in the Houston area since 1999 points to a major gap in how we currently think about and try to mitigate risk in our cities. There are many likely causes for this gap, but at least in the case of Houston, a primary factor appears to be the failure to fully account for the changing social, ecological, and technological dynamics associated with years of population growth and land development (Boburg & Reinhard, 2017; Bogost, 2017; McGuire, 2016). These conflating factors, and the poor modeling results in Houston, highlight the fault in the common assumption that design storm standards and floodplain mapping information are highly accurate and reliable. In fact, this may even be a case of disinformation being worse than no information, in the sense that the existing flood mapping data may have provided a false sense of security for many residents and businesses. Given the exacerbating factors of climate change and constantly transforming urban land use patterns, it is reasonable to expect continued difficulties with flood mapping information. Nonetheless, even the existence of prescient information does not guarantee effective protective strategies and management of flood risk. Prior to Hurricane Harvey, Houston had experienced several large flooding events (including 500-year storm events in 2015 and 2016) that provided key insights into existing flood prone areas and system vulnerabilities. Yet little action was taken to address these vulnerabilities or implement strategies for mitigating the impacts of future storms (Ingraham, 2017; Lind, 2017; Resnick, 2017; Shaw et al., 2016).

Recognizing that a very large literature exists related to defining and assessing vulnerability (e.g., Adger, 2006), this manuscript considers that vulnerability consist of the exposure and sensitivity of a system/component/individual/group to a hazard or stressor (i.e., increased exposure and/or sensitivity to a stressor translate to increased vulnerability to that stressor). All of this is to say, technically oriented strategies are dependent on the social, institutional, and ecological context in which they are implemented. Thus, a transition toward resilience that considers more regimes than robustness should combine new design practices that do not require predicting future extreme events as tightly, are based on new design criteria distinct from hazard and risk thresholds, and incorporate social and ecological elements. The challenge facing infrastructure resilience efforts is finding complementary approaches to current design practices, rather than deepening our commitment to them.

We posit that expanded perspectives on the complex, multidisciplinary, and interconnected nature of infrastructure systems that reveal lock-in and path dependency offer a crucial first step toward resilient infrastructure services. We define lock-in as constraints on infrastructure today as an outcome of past decisions and actions, even in the context of changing operating conditions or the emergence of more effective alternatives (Corvellec et al., 2013). Lock-in is perpetuated and often exacerbated by the related concept of path dependency, which refers to constraints on a system's ability to change (e.g., adapt or transform), in that it is often very costly and difficult to alter an existing infrastructure system from its current trajectory (Arthur, 1989; Payo et al., 2016). For the purpose of simplicity, these concepts will collectively be referred to as lock-in for the duration of this manuscript. Additionally, we refer to infrastructure complexity as the unpredictable, yet unchaotic nature of infrastructure systems and dynamics. For example, infrastructure complexity is revealed when systems fail due to tractable and seemingly predictable reasons, yet the causality behind these failures remains a mystery prior to their onset. We argue that overconfidence in infrastructure robustness is the consequence of ignoring infrastructure complexity by narrowly understanding infrastructure systems as technological systems.

In contrast to this constrained perspective, infrastructure systems appear to warrant treatment as complex social, ecological, and technological systems (SETSs) where feedback between humans, infrastructure, and the environment dictate failures and their consequences (or the lack thereof; Miller et al., 2018). For example, the impacts and failures associated with Hurricane Katrina may not have been as profound if more substantial social considerations and protections had been in place (Bullard & Wright, 2009; Colten, 2007; Layzer, 2012). The SETS perspective, in particular, helps reveal the complex causality of infrastructure failures due to lock-in and demonstrates how a reliance on historical information for environmental and social drivers *locks* infrastructure into *fragile* designs (i.e., shocks bring higher harm as their intensity increases; Aven, 2015; Taleb, 2012). Subsequently, complex SETS interactions, initiated by the construction of new infrastructure or the rebuilding of old infrastructure, create escalating risks (due to increasing consequences of disruption) that are difficult to avoid. Together, a SETS perspective highlights how infrastructure systems become locked-in, and how this increases fragility and erodes the adaptive capacity needed to address new hazards and risks. Although previous work has been done on incorporating various S, E, and T elements, for example, in indices to ascertain overall vulnerabilities (Borden et al., 2007) and case studies of infrastructure related failures (Layzer, 2012), the full integration of these elements and recognition of the role of lock-in in providing a perspective for such integration has not been the focus of these earlier works.

In this manuscript, we explore SETS as a perspective on infrastructure complexity, show how SETS interactions reveal lock-in, and then demonstrate this approach through multiple case studies. Ultimately, we argue that by not accounting for the emergent and interconnected nature of SETS within our infrastructure, we are limiting our ability to (1) fully comprehend the fragility and inflexibility (i.e., the inability to effectively respond to changing system dynamics) within our infrastructure systems, in terms of both the built materials and the social and institutional rules and norms—particularly related to lock-in, and (2) fully explore and develop the solution space related to resilience to changing environments and extreme events.

2. SETS Characteristics and Challenges for Infrastructure Systems

2.1. SETS Characteristics of Infrastructure Systems

Several authors have considered social-technical and social-ecological perspectives on resilience and infrastructure systems. Examples of social-technical perspectives include Swilling et al. (2013), Bolton and Foxon (2015), Walker (2015), Eisenberg et al. (2017), and Amir and Kant (2018). Examples of social-ecological perspectives include Berkes and Folke (1998), Walker et al. (2002), Edwards (2003), Anderies et al. (2004), Walker et al. (2004), Folke et al. (2005), Folke (2006), Walker et al. (2006), Ostrom (2009), Fischer et al. (2015), Muneepeerakul and Anderies (2017), Bene and Doyen (2018), Garrick et al. (2018), and Walker et al. (2018). Despite this wealth of literature, studies of infrastructure from the perspective of integrated SETS are a relatively nascent concept. The citations above offer a variety of perspectives on social-ecological systems (SES) that form a strong foundation for our perspective. For example, the Stockholm Resilience Center's perspective on SES introduces important concepts such as an emphasis on nonlinear dynamics,

Figure 1. Overview of social, ecological, and technological components and interactions of infrastructure systems. Adapted from Depietri & McPhearson (2017), Grabowski et al. (2017), Labi (2014), and Rubin (2001).

thresholds, uncertainty, and surprise with respect to resilience (Berkes & Folke, 1998; Folke, 2006; Walker et al., 2006). Frankfurt Social Ecology emphasizes societal relations to nature with the beliefs that nature and society are distinct but cannot be treated as independent from one another and that observable patterns characterize the relations between society and nature (Becker & Jahn, 2005; Hummel et al., 2017). Similarly, the Institute of Social Ecology in Vienna describes SES as consisting of a natural sphere and a cultural sphere that are mutually dependent and influential on each other (Haberl et al., 2016; Kramm et al., 2017; Singh et al., 2013). Although there is an acknowledgement that the relationship between nature and society is often facilitated by technology (Kramm et al., 2017), most SES perspectives view technological systems as a subset of social systems. For example, the Vienna perspective on social interactions with nature emphasizes natural systems as the primary source of inputs and sinks for outputs of *social metabolism*–implicitly facilitated by social-economic systems and their technological subsets (Haberl et al., 2016; Singh et al., 2013). However, as discussed throughout this manuscript, technological systems appear to have meaningful influence and *agency* relative to social and ecological systems. Thus, we view resilience and infrastructure systems from the collective perspective of SETS.

In general, a SETS perspective integrates socio-technical and socio-ecological perspectives and expands upon them to also consider ecological-technological interactions (see Figure 1). Stokols (2018) expands on traditional SES perspectives by describing human environments as consisting of natural, built, sociocultural, and virtual systems that occur at varying temporal, geographic, and social scales. Stokols (2018) also emphasizes the importance of interconnections, as in this paper, though the bounding of those elements may differ. Other existing literature on SETS primarily focus on definitions and conceptual framing (Grabowski et al., 2017; Grimm et al., 2017; Hale et al., 2015; Krumme, 2016; McPhearson et al., 2016; Ramaswami et al., 2012) or discuss the three components independently. Similar to analysis by Tellman et al. (2018), we expand on existing SETS literature by directly applying the SETS lens to infrastructure development and management, particularly in relation to identifying maladaptive lock-in processes and establishing approaches to help infrastructure adapt to the effects of extreme events. Our manuscript supports many of the findings of Tellman et al. (2018): human decision-making dynamics and environmental context shape the evolution of coupled infrastructure systems, each adaptation decision exists in the context of (and is shaped by) previous decisions, and attempts to increase robustness to specific threats in the present often result in increased vulnerability to unforeseen risks and unintended consequences. However, we also differentiate and expand upon their analysis in several ways. First, our manuscript more explicitly emphasizes and explores the interactions and shifting influence among SETS in the development of vulnerability and lock-in over time (see sections 2.2 and 3). In contrast, Tellman et al. (2018) place their emphasis much more on the implications of governance decisions (i.e., social systems) over time—albeit with acknowledgement of the broader ecological and infrastructural context in which these decisions are made. Second, due to our more explicit examination of the shifting influence and interactions among SETS, our analysis not only allows for the identification of lock-in but also highlights specific intervention points for possibly breaking said lock-in. Third, Tellman et al. (2018) emphasize that one of the primary contributors to lock-in and unintended consequences of resilience decision-making is the fact that previously externalized risks often eventually become endogenous to the system. However, the lock-in and unintended consequences apparent in the case studies in our manuscript appear to be relatively endogenous to the system from the beginning. Finally, in addition to using a SETS lens to better identify and address lock-in, our manuscript also discusses how a SETS lens might help facilitate more comprehensive and holistic resilience strategies (see section 4). Ultimately, our work appears to be a nice complement to Tellman et al., and both papers seem well positioned to contribute to a better understanding of and response to the broader social, environmental, and historical context in which adaptation and infrastructure decisions occur.

Similar to the SETS literature, lock-in literature for infrastructure systems is also limited and tends to focus on defining concepts and identifying core characteristics, rather than relating to the realization of system failures or extreme events (Hommels, 2005; Payo et al., 2016). We expand on the literature by more deeply exploring how lock-in appears to evolve and how it contributes to increased *fragility* (lowered adaptive capacity) in infrastructure systems. Furthermore, we outline possible strategies for *interdicting* maladaptive lock-in and developing alternative anticipatory SETS pathways.

Figure 1 provides a broad, nonexhaustive overview of what constitutes SETS. Here we define social systems as a broad domain that includes both human actors and their roles and activities, such as cultural and institutional values, tacit knowledge, public discourse, policy, economics, governance, public health, financing, citizens, regulators, managers, and the institutions in which these reside (Grabowski et al., 2017). Similar to its discussion in the context of sustainable development (Speth, 2009; Sachs, 2015; UNDP, 2018), strong and just governance is a key element within the social domain of SETS. Additionally, on a smaller scale, education, communication, beliefs, values, attitudes, lifestyle choices, and decision making have been found to influence people's understanding, engagement, perception, and interaction with broader ecological and technological systems (Goleman, 2010; Graham & Abrahamse, 2017; Meerow et al., 2016; Myers et al., 2012; Revkin, 2007; Schultz & Kaiser, 2012; Swim et al., 2009). Therefore, these individual elements and characteristics are also included with the social domain of SETS. The ecological domain encompasses natural resources, pollution and environmental degradation, ecological structures, ecological functions, ecological behaviors, and weather/climate effects (Grabowski et al., 2017). The technological domain includes physical and cyber infrastructure, as well as any supporting knowledge systems, software, and other forms of decision-support (Grabowski et al., 2017). In agreement with Stokols (2018), we view virtual and cyber-based features to be of increasing influence and importance within the technological domain and beyond. Whether discussing teleconferencing systems and social media, or emerging concepts like virtual and augmented reality, the Internet of Things, the sharing economy, and artificial intelligence, cyber-based technologies are increasingly shaping how we perceive and engage with each other and our surrounding ecological systems (Stokols, 2018). Although largely outside the scope of this manuscript, the emergence and growing influence of virtual and cyber-based technologies on broader SETS appear to warrant considerable multidisciplinary exploration moving forward.

The components described in Figure 1 are divided into separate S, E, and T domains to provide clarity about what is meant by SETS. When analyzing and discussing SETS, we acknowledge that social, ecological, and technological components do not always fit neatly into distinct, decoupled classifications. In particular, ecological and social systems are continually interacting with and influencing each other via technological systems. Technological systems are often the mechanisms by which social systems affect ecological systems via pollution, resource consumption, land use change, etc. Similarly, technological systems also tend to be the mechanisms that enhance the services (or disservices) provided by ecological systems to social systems. For example, water infrastructure systems are used to purify and deliver drinking water; electric power systems are used to gather and convert natural resources (coal, natural gas, wind, sunlight, etc.) to electrical energy. Finally, technological systems are often used as the primary mechanism for *protecting* social systems from unfavorable ecological conditions. For example, buildings and space heating/cooling protect people from extreme heat or cold, and dams and levees protect people and property from flooding.

In addition to technological systems commonly serving as the intermediary between social and ecological systems, it is important to recognize that each of the SETS domains have varying degrees of *agency* and influence on the other systems. Ecological systems can exist in the absence of social and technological systems—although this is rarely the case anymore. Perhaps more appropriately, ecological systems rely on the proper functioning of technological systems and stewardship from social systems to function unperturbed. Social systems rely on both ecological systems (for basic resources like food, water, and materials) and technological systems (to access and utilize ecological goods and services at any meaningful scale and to increase standards of living). Finally, technological systems could not exist independently of social systems nor ecological systems—they are developed from natural resources to meet certain needs and functions deemed necessary by society. Overall, the strength and directionality of these relationships point to a certain level of interconnectedness that can be instructive when thinking about the evolution of lock-in in the context of system resilience. Ultimately, social and technological systems appear to be interdependent—in modern times, one cannot function or be decoupled from the other. For example, energy and water systems are interconnected with food systems, which in turn are linked to social concerns and the technological systems that enable food production (Zimmerman et al., 2016). The relationships between ecological and social systems and ecological and technological systems appear to be best characterized as interconnected. Both of these instances are described as interconnections rather than interdependencies because ecological systems can function in the absence of both technological and social systems, but the inverse does not necessarily hold true. Nonetheless, these relationships are increasingly moving toward interdependencies as the social and technological systems of humankind have reached such a scale and scope that it is hard to find any ecological systems that are not at least influenced by human activity in some way (Allenby, 2007; Allenby, 2012; Syvitski, 2012; Thomas, 1956; Turner, 1993).

In conjunction with Ostrom et al. (1999) and Stokols (2018), SETS dynamics and interactions occur at a variety of social, temporal, and geographic scales. Ecological systems consist of individual organisms all the way up to entire ecosystems and planetary dynamics (e.g., the carbon cycle and the water cycle). Social systems can range from individuals and personal behavior/decision-making up to wide-ranging institutions and policy decisions (e.g., local, state, national, or international governance). Technological systems can range from individual infrastructure components to large-scale national/international networks (especially in the case of cyber features), and there may be additional value to be gained by more effectively coupling decentralized infrastructure (e.g., small-to-medium–scale systems like rooftop solar panels) with centralized infrastructure (e.g., large-scale power plants and transmission/distribution lines) (Tomlinson et al., 2015). Each of these SETS-specific scale dynamics will exhibit their own characteristics and behaviors that are important to acknowledge for future directions, but are beyond the scope of the current paper's theme. Nonetheless, as detailed in the case studies presented in section 3, applying a SETS lens to identify and address the evolution of vulnerability and lock-in within infrastructure systems appears particularly well suited for the *meso* level of social relations to nature as described by Hummel et al. (2017). In this context, organizations and institutions epitomize the social systems, and ecological-technological interactions primarily relate to addressing the collective needs of society (e.g., provisioning food, energy, and water; protecting against extreme events; and enabling mobility and communication). From a temporal perspective, a SETS lens on lock-in and resilience appears particularly well suited for scales on the order of multiple years (sections 3.2 and 3.3) to multiple decades (section 3.1). However, as applied in this manuscript, SETS also implicitly captures social (e.g., the initial decision to settle in a river delta; section 3.1) and ecological (e.g., natural variation and meandering of river flow; section 3.1 ; and climate change dynamics; Sections 3.1 and 3.2) dynamics that span hundreds of years.

2.2. SETS Challenges for Infrastructure

Aside from expanding our thinking to consider infrastructure systems as SETS (rather than simply technological systems), some of the primary challenges facing infrastructure are SETS-based, rather than single-system issues. For example, difficulties associated with infrastructure utilization, inflexibility, complexity, interdependence, nonstationarity, perceived protection, and social equity are all multidimensional SETS issues that can contribute to vulnerabilities of our infrastructure systems.

One of the primary challenges facing our infrastructure systems is the relatively inflexible, rigid, and long-lasting (i.e., *obdurate*) nature of most infrastructure components, the institutions that manage and maintain them, and the uncertain and changing levels of utilization that occur during the lifetime of an infrastructure system (Chester & Allenby, 2018). Typically, infrastructure systems are designed to meet demands decades into the future, but accurately anticipating, projecting, and capturing the complexity of future demands and system characteristics are often very challenging—especially when disruptive technologies, climate uncertainty, and changing behaviors are considered. Moreover, infrastructure are typically playing catch-up with an ever-changing and usually expanding user base, while the ability to meet those needs in a reasonable time period is constrained by the fact that current infrastructure systems are in need of trillions of dollars of investment in the United States (ASCE, 2017). As a result, infrastructure systems can end up being overutilized (in cases where demand exceeds capacity) or underutilized (in cases where capacity exceeds demand). These challenges will likely be exacerbated in the context of climate nonstationarity—the poor correlation between past data/trends and future conditions. The natural environment in which infrastructure exists is changing in unprecedented and uncertain ways (Butchart et al., 2010). However, from a socio-technical perspective, we traditionally design infrastructure for climate conditions that may no longer apply (Emanuel, 2017; Forsee & Ahmad, 2011; Milly et al., 2008; Slater & Villarini, 2016). From the perspective of social systems, our constantly evolving and changing preferences and demands, as well as our ability (or inability) to recognize and predict these changes, contribute to this infrastructural challenge. Thus, in response to emerging ecological changes (i.e., changes in the weather and climate conditions under which infrastructure systems operate) and social changes (i.e., changes in preferences and demands), technological systems will likely need to evolve to be able to perform under a wider variety of operating conditions that the social and ecological dimensions introduce. Additionally, the related institutional dimensions of social systems will need to adjust the planning, governance, and management of infrastructure to better account for the uncertainty associated with nonstationarity.

Another challenge is related to the growing complexity and interconnectedness of our infrastructure systems (Garrick et al., 2018; Miller et al., 2018; Rinaldi et al., 2001; Zimmerman et al., 2016, 2017). Although there are several different types of interdependences among infrastructure systems (Rinaldi et al., 2001), the two that appear to be most prevalent are physical—where the output of one system is a direct input to another system, and geographic—where multiple infrastructure systems share a common location or are located in close proximity to one another (Rinaldi et al., 2001). An example of physical interdependency is that electricity is required to operate the pumps and other components of water treatment and distribution, while water is often a critical input for the creation and cooling of steam in thermal-electric power systems. An example of geographic interdependency is the burying of fiber-optic cables, water pipelines, and electric transmission lines underneath roadways or along transportation right-of-ways. Failure in one of these systems is likely to disrupt the other co-located systems. These relationships pose challenges because the technological evolution of our infrastructure systems appears to be moving toward increased complexity and interconnectedness (e.g., electric vehicles, autonomous vehicles, *smart* water and electricity systems), and the social components of our infrastructure systems (e.g., governance, regulation, management, and planning) appear increasingly less adept at fully recognizing and reacting to these interconnections. Thus, in the context of resilience, recognizing and accounting for these complex relationships will be crucially important. As infrastructure systems become more intertwined and interdependent, it will likely become easier for a disruption in one system to propagate to other systems, thereby increasing the susceptibility to widespread and high impact cascading failures.

The obdurate, complex, and interdependent nature of many infrastructure systems also contributes to the *fallacy of control*, where there is the inclination to overestimate the level of protection provided by technological systems and underestimate the variability and instability of ecological and social systems. The channelization and damming of the Mississippi River are exemplary of this. Over time, we have implemented a series of dams, levees, and other technologies to control how, when, and where the water moves. The establishment of control structures then led to increased development along and near the river due to the assumption that many of the threats posed by the river had been neutralized. However, as exhibited by the Mississippi River floods of 1993 and 2011 and Hurricane Katrina in 2005, ecological systems do not remain indefinitely predictable and can overwhelm control structures to highly impactful results. This is often a result of misunderstanding the inherent unpredictability and variance of natural systems, of overconfidence in the robustness of infrastructure systems, or some combination of the two. To make matters worse, the technological systems put in place to protect people and property can exacerbate the impacts of an extreme event when a failure does occur. For instance, it is likely that New Orleans would not have had as large of a population or as much industrial/economic activity if not for the protection (real and perceived) provided by the levees and pumping stations around and throughout the city. Thus, more people and property are exposed if and when the levees and pumps fail. It is also important to note that the fallacy of control can occur across a variety of different levels within social systems: the water crisis in Flint, Michigan (i.e., there were prolonged water quality and health concerns associated with switching between water supply systems), is an example of infrastructure planners, funders, and politicians believing that the system was under control (in addition to other complicating social, economic, and political factors); the near catastrophic failure of the Oroville Dam is an example of infrastructure operators and regulators believing that the system was under control (California Department of Water Resources, 2018); and Hurricanes Harvey and Katrina are examples of the public believing that the system was under control.

Finally, without broader consideration of social and ecological conditions, physical infrastructure systems can be implemented and managed in an inequitable manner where much of the vulnerability is wittingly or unwittingly shifted to citizens of lower socio-economic standing. Historically, often as a result of broader social and cultural power dynamics and inequities, citizens of lower socio-economic standing have lived in locations with the poorest ecological conditions (e.g., little-to-no green space and higher exposure to noncoastal flooding; Bullard & Wright, 2009; Chakraborty et al., 2014; Collins et al., 2018; Landry & Chakraborty, 2009; Maldonado et al., 2016; Wolch et al., 2014). Similarly, physical infrastructure and resources are not typically distributed evenly across urban areas—citizens of lower socio-economic standing often do not have access to as much or as high-quality physical infrastructure or institutional protections (e.g., flood insurance and preparedness programs) as citizens of higher socio-economic standing (Chakraborty et al., 2014; Collins, 2010; Collins et al., 2018; Maldonado et al., 2016). Therefore, in the context of resilience from a socio-ecological perspective, it appears that improvements can be made by not permitting development/settlement in areas with poor ecological conditions—particularly for citizens of lower socio-economic standing. Similarly, from a socio-technological perspective, it is important to think more critically about how, when, and where physical infrastructure systems are implemented, and who is benefitting (or harmed) by that implementation.

3. Using a SETS Lens to Identify How Vulnerability Develops Over Time: Case Illustrations

The embeddedness of technological systems within larger social and ecological systems, and the resulting complexity that emerges, can ultimately result in unintended consequences and trade-offs within the technological system and across SETS that are often undesirable and difficult to manage. One of the primary unintended consequences that emerge within our infrastructure systems is lock-in. Thus, an important aspect of increasing resilience within infrastructure systems will be identifying maladaptive lock-in—particularly in the context of the aforementioned multidimensional challenges. The remainder of this section contains

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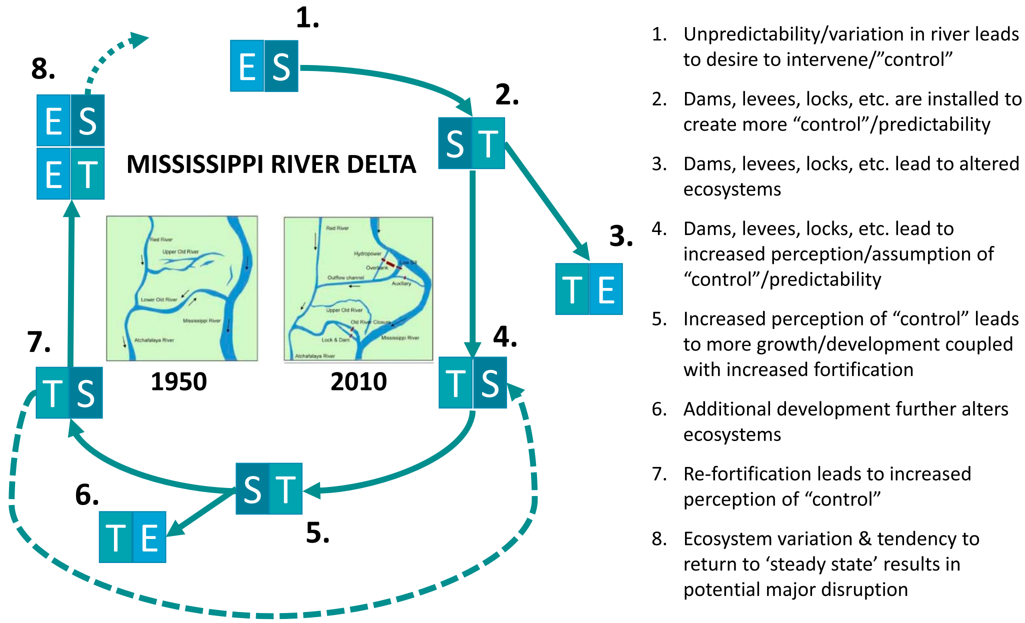


Figure 2. Summary of social, ecological, and technological system developments along the Atchafalaya and Mississippi Rivers between the 1950s and the 2010s. The dashed line indicates a feedback loop between points 7 and 4. The dotted line indicates that system dynamics and interactions continue into the future beyond point 8.

illustrative examples of how a SETS approach appears well suited for aiding decision-makers in this process by (1) recognizing that changes to technical infrastructure systems influence and are influenced by aspects of ecological and social systems and (2) analyzing the temporal dynamics of these influences to help identify (and anticipate) points along a pathway where vulnerability/fragility may reach undesirable levels.

3.1. The Atchafalaya and Mississippi River Basins: SETS in a Historical/Diagnostic Context

One of the best illustrations of the temporal dynamics of SETS and the emergence of lock-in over time is the Atchafalaya and Mississippi River Basins (Madrigal, 2011; McPhee, 1987; U.S. Army Corps of Engineers, 2009). In the early 1950s, the Army Corps of Engineers determined that if left untouched, the Mississippi River would change its course to the Atchafalaya River by 1990 (as part of the natural geologic process of avulsion)—an ecological forcing on social systems. Should such a shift in the river occur, settlements within the Atchafalaya River Basin would likely flood and Baton Rouge and New Orleans would be faced with the serious economic ramifications of the Mississippi River *drying up*. Considering the relatively large number of people that could be affected (roughly 800,000 people when considering the populations of New Orleans, Baton Rouge, and the towns along the Atchafalaya River), and the high economic and cultural significance of Southeastern Louisiana, a significant shift in flow from the Mississippi River to the Atchafalaya River, was determined to be unacceptable. As a result, the Army Corps of Engineers constructed the Old River Control Structure in 1963 to prevent the main channel of the Mississippi River flow from deviating from its historical path—technological forcing on ecological systems in response to social concerns/desires. A severe flood in 1973 almost caused catastrophic damage to the Old River Control Structure. In response to the 1973 flood, construction of an auxiliary control structure was completed in 1986 to reduce pressure on the original floodgates. Finally, in 1990, the Murray Hydroelectric Station was added to provide additional flow and flood control at the site. Figure 2 summarizes these developments over time from a SETS perspective.

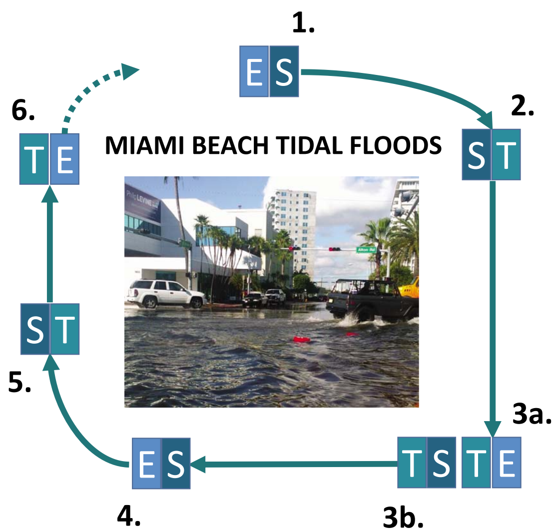
Overall, this example highlights a few key issues: (1) at various points in time, different S, E, and T elements are exerting influence on the overall system; (2) any *S* concerns are addressed almost exclusively via technological systems (i.e., the Old River Control Structure)—even in the aftermath of a near failure, the response was to strengthen commitment to *T* systems by installing the auxiliary control structure and the Murray Hydroelectric Station; (3) the increased reliance on T systems increased lock-in and fragility within the system; and (4) a feedback loop (illustrated by the dashed line in Figure 2) appears to emerge related to the installation/enhancement of T, increased perception of control, increased growth and development related to the perceived control, and increased fragility and vulnerability associated with the increased growth and development. The intersection and interaction of S, E, and T systems in the Atchafalaya River Basin have resulted in the flows of the Mississippi and Atchafalaya Rivers being *locked* into a 70/30 split since 1963 and likely for perpetuity. As a result, virtually all people and economic activity down river are reliant on the continued performance of the Old River Control Structure, and as population and economic activities continue to grow within the area, the criticality and fragility of the Old River Control Structure rises. As the criticality rises, it becomes increasingly difficult and costly to pursue any alternative approaches—thereby increasing lock-in. Therefore, the vulnerability to and impact from the possible (if not probable) failure of the Old River Control Structure are continually increased by the complex interactions of SETS and lock-in within the overarching system.

3.2. Nuisance Flooding in Miami Beach: SETS in a Contemporary/Anticipatory Context

Recent developments in Miami Beach illustrate how a SETS perspective might also assist with anticipatory efforts. A combination of a dense, relatively impervious urban environment, old and degrading stormwater infrastructure, intense precipitation events, and rising sea levels have led to increased occurrences of street-level flooding in Miami Beach. Historically, flooding in Miami Beach has been the result of intense rain events. However, more recently, sea level rise has led to more occurrences of *sunny-day floods*. These floods are common during particularly large high tide events (or, King Tides) and are the result of overtopping seawalls and seawater entering through stormwater outlets and bubbling up into the streets via storm drains or seeping up through porous limestone bedrock (Cohen, 2017; Di Liberto, 2017; Neal, 2017). In response to these flooding events, in 2014, the City of Miami Beach announced a series of flood prevention projects that include $300–$500 million in new investments to enhance stormwater and flood mitigation infrastructure (Clark, 2016; Fagenson, 2014; Flechas, 2017, 2018; Flechas & Staletovich, 2015; Waldheim et al., 2017). These investments include the installation of pumping stations (to pump excess storm water and seawater from the land surface), the raising of roads, and the raising of seawalls—another illustration of the emphasis placed on technological solutions.

The primary concern with the current strategy for mitigating the flood events (the installation of pumping stations throughout the island) is with the quality of the water pumped into Biscayne Bay. Preliminary water sample results found that water pumped into the Bay had elevated levels of nitrogen, phosphorus, and *E. coli* (Flechas, 2018; Flechas & Staletovich, 2015; Gidley, 2016; Jones, 2018; Peterson & Weiland, 2016; Staletovich, 2016a; Staletovich, 2016b; Wendel, 2016). While efforts are being made to address these water quality concerns, continued damage to the water quality and ecosystems of Biscayne Bay could also damage tourism and development. Figure 3 summarizes the SETS elements of this system over time.

Another potential concern relates to the *fail-safe* nature of the pumping systems and road changes. While the City of Miami Beach acknowledges that these actions are only meant as short-term solutions, it is believed that the pumps can only handle up to 6 inches of sea level rise—a level that could be reached as early as 2030 (South Florida Regional Climate Change Compact, 2015; Sweet et al., 2017). Returning to the topic of lock-in, one might begin to wonder if the city has now locked itself into this pumping system indefinitely. Once 6 inches of sea level rise occurs, will more pumps continually need to be added or will the pumps need to be replaced with larger units? An interesting (and potentially troubling) feedback loop might emerge in this situation: the initial pumps were installed with tax revenue; to help offset some of these costs, additional development might be encouraged in the area to raise more revenue from property or sales tax; the combination of additional development and sea level rise can potentially increase the vulnerability to flooding and the need for more pumping capacity (or other interventions); more pumping capacity will require more public funding, which will likely need to come from additional property or sales tax; and so on. Additionally, the pumps were installed to mitigate fairly predictable events (i.e., the timing of the King Tide events is fairly well understood even if the extent of the flooding still has some uncertainty), but it is unclear how well they will function during less predictable/more extreme events (e.g., hurricanes or extreme precipitation events). In other words, was a T solution put in place at the expense of future social and economic well-being? There is also the possibility that raising the street levels may lead to increased vulnerability of shops, storefronts, and residences to flooding during extreme precipitation events (Flechas, 2016, 2017, 2018; Waldheim et al., 2017).



1. Sea level rise contributes to more frequent and troublesome tidal flooding
2. Concerns over King Tide flooding lead to elevation of certain roadways and installation of pumping stations
3. A) Untreated water from pumping stations has negative effects on water quality in Biscayne Bay

   B) Elevated roadways contribute to increased flooding at commercial properties during precipitation events
4. Importance of Biscayne Bay to tourism/local economy leads to concerns over water quality
5. Social importance of clean water in Biscayne Bay leads to retrofitting of pumping stations with water filtration systems
6. Installation of water treatment systems helps address water quality concerns

Figure 3. Summary of social, ecological, and technological system dynamics related to addressing tidal flooding in Miami Beach. The dotted line indicates that system dynamics and interactions continue into the future beyond point 6.

In the Atchafalaya and Miami Beach cases, there appears to be a *feedback loop of fragility* emerging in these examples (e.g., the dashed line in Figure 2). First, T is used to address S concerns. Second, installed/upgraded T increases the perception of control in the S domain. Then, this increased perception of control results in increased development and population growth in high exposure areas. Fourth, variation in E and S systems leads to increased fragility within the T and increasing concerns of vulnerability within S systems—which ultimately leads us back to where we began and the cycle repeats. Given the presence of these recurrent patterns, Figures 2 and 3 (as well as Figure 4) are presented in a quasi-cyclical nature. This representation expands upon the adaptation pathways perspective implemented by Tellman et al. (2018). However, in contrast the idea that adaptation pathways primarily consist of socially driven decision cycles that have distinctive start and end points, we view these systems as a continuum of SETS interactions that can have recurring patterns, but not necessarily a distinctive beginning and end point. Therefore, an open loop depiction of these case studies appeared to be appropriate given the fact that in reality, the dynamics illustrated in Figures 2–4 began long before point #1, are still playing out beyond point #8 (or point #6 in case of Figures 3 and 4), and are constantly evolving. Increasing our ability to recognize this feedback loop (and break from it when necessary) appears to be a crucial factor in ensuring the longevity and effectiveness of our infrastructure systems—a role that a SETS lens appears well suited to fill.

3.3. Flooding and Combined Sewer Overflows in Syracuse, NY: Breaking the Cycle Through Political Change

Syracuse, New York provides an illustrative example of how the voting process, public engagement, and responsive governance can stop, or at least slow, the trajectory of SETS headed in an undesirable direction. As was true in other cities, many Syracuse residents in the 1970s–1990s decided to move from the inner city out to the suburbs where taxes were lower, houses were larger, and new infrastructure systems were being installed. With this sprawl, the total area of impervious surface also grew, causing stormwater-induced flooding and combined sewer overflows (CSOs) to become increasingly problematic. In 1988, the Atlantic States Legal Foundation sued Onondaga County over CSOs, which would be likely to worsen in the future due to climate change. A contentious situation resulted, with the county deciding to build regional treatment facilities to comply with the initial consent judgment and later amended consent judgments. The locations chosen for these new treatment plants were in low-lying areas in poor neighborhoods, leading to social unrest and cries of environmental injustice. Despite widespread protests, construction of the treatment plants began. Thus, the initial social problem—perceived undesirable conditions in the inner city—was replaced by a different problem which would commit the region to inefficient treatment of diluted wastewater for the indefinite future. It would also subject impoverished residents to living near odiferous treatment plants for the indefinite future (Flynn et al., 2014; Flynn & Davidson, 2018).

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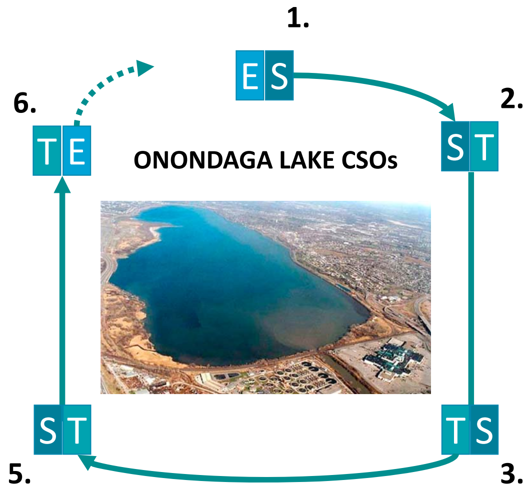

1. Increasing occurrence of combined-sewer overflows (CSOs) leads to lawsuit by Atlantic States Legal Foundation
2. First Amended Consent Judgement is entered in 1998, leading to construction of 'gray' stormwater infrastructure
3. Concern over environmental injustice and ecosystem damage leads to formation of citizen groups and multiple protests
4. New County Executive is elected and halts construction of 'gray' infrastructure
5. County-wide program of green infrastructure begins; CSO volumes decrease due to use of 'green' plus 'gray' infrastructure

Figure 4. Summary of social, ecological, and technological system developments leading to widespread adoption of green infrastructure in the Syracuse metropolitan area. The dotted line indicates that system dynamics and interactions continue into the future beyond point 6.

In the midst of this social unrest in the mid-2000s, a new candidate for County Executive emerged—with a call to stop construction of the regional treatment plants and instead promote a combination of green and gray infrastructure. The candidate won in 2008, and a new Amended Consent Judgment was entered in 2009: the final 10% CSO volume reduction (from 85 to 95%) was required to be satisfied by 6.3% green infrastructure and 3.7% gray infrastructure. This represents the first time that the use of green infrastructure was a required condition for control of CSOs in the United States. Between 2011 and 2017, more than 200 green infrastructure projects throughout the County were constructed, many funded with public-private partnerships through innovative financing (Flynn et al., 2014; Flynn & Davidson, 2018).

This sequence of events was used to develop a SES framework for green infrastructure in stormwater management by Flynn and Davidson (2016). This is similar to the SETS framework used in the current study. Data collected from Syracuse and other cities showed that the limited amounts of funding and restrictive funding schemes, as well as various regulations related to zoning, building codes, demolition practices, and stormwater management, all served as potential barriers to green infrastructure adoption. It was found that the attributes of various actors (individuals and organizations) could also promote or hinder adoption. In the case of Syracuse, the election of a new County Executive, S, caused a change that led to the adoption of green infrastructure, T-E, across the region. Figure 4 illustrates the key SETS dynamics of this example.

For all three of the examples presented, it is important to keep in mind that each of the SETS elements and the manner in which they are interconnected are likely to vary dramatically across cases, yet the common theme of promoting the integration is highlighted.

4. Using a SETS Lens to Move Beyond Technologically Focused Resilience Strategies

In addition to helping identify the development of vulnerabilities over time (as shown in the varying cases above), a SETS lens may also help open the design and decision space to more than just technologically-based strategies for responding to extreme events—especially considering that there may be cheaper or more effective socially or ecologically focused solutions. As highlighted by many of the examples in the previous section, the historical response to undesirable natural conditions and extreme weather events has typically been to fortify and rebuild the infrastructure stronger, taller, or larger. However, we posit that a SETS approach to infrastructure, as opposed to a solely T or S-T approach, can potentially increase the adaptive capacity of a system by illuminating new strategies (and serve as a means to explore the potential implications of alternative pathways) that may not have been recognized or fully realized under a techno-centric perspective. A number of examples illustrate the intersection of the three SETS dimensions simultaneously and how they enhance the understanding of the problems, and thus point toward more anticipatory solutions.

One of the best examples of a SETS approach to resilience is the *Room for the River* strategy to riverine flood prevention in the Netherlands. In contrast to the techno-centric approach of levee building and channelization, Room for the River has the following key elements: (a) development is set back from the banks of the river to accommodate natural variation in river levels; (b) land directly along the banks of the river is dedicated to farming, which allows for additional economic development while also providing an ecologically-based *buffer* for absorbing flood waters during extreme events; and (c) in the case that crops are lost during flood events, farmers are reimbursed with public funds (Rijke et al., 2012; Roth & Warner, 2007; Warner & van Buuren, 2011; Wiering & Arts, 2006). This example highlights social and ecological elements that may not be present in strategies typically employed to prevent flooding. In particular, social systems play a key role in Room for the River in the form of the subsidies provided to farmers for lost crops, and in the initial decision to keep nonagricultural development away from the river. Similarly, ecological systems play an important role in the form of the *natural* flood water buffer that is provided by the crops adjacent to the river.

Returning to the Miami Beach example described earlier, the current solutions fit almost exclusively within the T domain and are implemented as T solutions to S concerns (i.e., technical/engineering solutions of installing pumps and raising roads were put in place to allow tourists and residents of Miami Beach to maintain certain quality of life and standards of service without being impacted by periodic flooding). The E domain was almost entirely absent from initial project planning and implementation and is just now starting to get recognition. Had a complete SETS outlook been adopted from the very beginning of the project, the additional costs of retroactively developing water quality systems within the pumps could have potentially been avoided. For example, initial pumping systems might have been designed with built-in water treatment systems to ensure that the water leaving the pumps is contaminant free. Under this scenario, stormwater that is historically a diffuse source of contaminated runoff can be concentrated into a point source that is easier to treat—potentially enhancing the health and ecosystem services of Biscayne Bay. Concurrently, more ecologically based water treatment systems could be established, such as placing wetland and estuarine habitats just off the pump evacuation points to filter some of the contaminants from the runoff. Additionally, E-based approaches could be implemented to help mitigate runoff and flood waters. Strain on the stormwater system could potentially be reduced by increasing the amount of vegetated and pervious surfaces throughout the city via increased incorporation of green infrastructure and landscape ecology (Waldheim et al., 2017). For example, bioswales (or similar solutions) could be placed at stormwater drains to help absorb excess water being pushed back through the drain and onto the street during *sunny-day* floods. Finally, given the relatively predictable nature of these events, certain S solutions could also be implemented. For example, residents may alter their commute pattern or schedule during expected King Tide events. Similarly, businesses and home owners in areas known to be affected by these tidal floods could install a mix of vegetation and physical barriers to help minimize the impact of the flooding. In the long-run, adaptive changes might be needed in building and development codes (Waldheim et al., 2017), and policies that focus on incentive-based approaches to managed retreat (i.e., "the strategic relocation of structures and abandonment of land to manage natural hazard risk; Hino et al., 2017") may warrant strong consideration—in terms of both the associated land use planning implications and the potential implications for local residents and businesses.

Another example of a SETS approach to mitigate the effects of extreme weather conditions is the ongoing efforts to protect public transit riders and infrastructure from extreme heat in Phoenix. Technologically oriented strategies include shade structures, evaporative cooling systems, stations with solar-powered cooling systems, and tracking systems for buses and trains (City of Phoenix, 2017; Valley Metro, 2018). If needed, there is also the possibility of installing enclosed, air-conditioned transit stops similar to those deployed in Dubai and Miami (Ahmed, 2008; Gulf News Staff, 2015; Miami-Dade County Transportation and Public Works, 2016). Ecologically based solutions include trees for shading (especially as a component of the city's Master Tree and Shading Plan) and increased vegetation at and around transit corridors to provide natural cooling (City of Phoenix, 2010; Iwaniec & Wiek, 2014). Some of the socially based strategies being explored include altering route schedules (e.g., increased frequency of buses and trains to decrease wait times) and service levels (e.g., pickup /dropoff anywhere along the route instead of at designated stops, supplementary first/last mile service to reduce need for walking and cycling between transit stops and trip origin/destination; City of Phoenix, 2017; Fraser & Chester, 2017). An important aspect of implementing these strategies is to ensure that they are executed in an integrated manner to avoid conflicts and promote synergies among different approaches. For example, although the City of Phoenix and Maricopa County provide heat refuge locations throughout the region, there does not appear to be an established transportation plan for citizens to get from their house to these refuge centers (Fraser et al., 2016; Fraser & Chester, 2017). Similarly, installing trees near a transit stop that already has a substantial shade structure or an evaporative cooling system may provide relatively lower benefits—having cool and comfortable transit stops may not do much good if ridership cannot get from their origin to a transit stop (or from a transit stop to their destination) in an effective and timely manner. Finally, another element of effectively integrating SETS solutions is monitoring for undesirable feedback loops. For example, the installation of evaporative cooling systems or trees may conflict with water management and conservation goals (Iwaniec & Wiek, 2014). Similarly, installation of air-conditioned transit stops may conflict with energy and environmental goals.

SETS approaches have also been recently applied (or proposed) for reducing the impacts of drought in California. Technologically oriented options being implemented or explored include desalination (such as the 50 million gallons per day Carlsbad Desal Plant near San Diego), groundwater drilling, and wastewater recycling (Cooley et al., 2014; Gorman, 2015; Howard & Millsap, 2014; Kang & Jackson, 2016; McKenzie, 2015; San Diego County Water Authority, 2018; Underwood, 2016). Ecologically based solutions include the use of more native vegetation in landscaping and the implementation of *fog harvesting* systems inspired by nature (California Water Service, 2018; FogNet, 2018; Goldstein, 2015; Knickmeyer, 2016; Weiss-penzias et al., 2016). Socially oriented solutions include mandatory water restrictions for homes and businesses, *behavioral water efficiency* techniques (e.g., indication of one's water usage compared to neighbors and tiered pricing schemes based on usage), and altered agricultural practices (e.g., shifting away from water-intensive products like citrus, almonds, and cattle). While each of these strategies are categorized as having a specific emphasis, many of them are multidimensional. For example, although wastewater recycling might primarily be considered a technical issue and increased use of native vegetation might primarily be considered an ecological issue, both of them require a cultural shift and social buy-in (Dolnicar & Scha, 2009; Fielding et al., 2018; Po et al., 2003; Rott, 2018). Similarly, although fog harvesting could be considered a more ecologically inspired approach, there are still substantial technical elements associated with designing and implementing such systems. The multidimensionality seen in these examples further emphasizes the importance of thinking across SETS rather than individual disciplines or systems.

Ultimately, the SETS-based strategies outlined in this section appear to exhibit inherent levels of flexibility and agility that are not always found in more techno-centric strategies. Flexibility and agility have been suggested as important competencies to adaptive capacity (Chester & Allenby, 2018; Markolf et al., 2018). Thus, to the extent that more SETS-based, rather than T-based resilience strategies are implemented, we expect adaptive capacity to increase. In turn, increased adaptive capacity allows systems to more effectively move between and across the rebound, robustness, graceful extensibility, and sustained adaptability regimes of resilience (Markolf et al., 2018; Seager et al., 2017; Woods, 2015).

5. Conclusions

The primary goal of this manuscript is to begin to frame the options and encourage continued research that supports the generation and application of knowledge about the complex, interconnected, and transdisciplinary nature of infrastructure systems in the context of extreme events. In turn, proposing new empirical methods for quantifying SETS interactions, lock-in, or resilience is left for follow-up studies. Thus, from the framing and case studies developed in this paper, we advance the following key concepts: (1) infrastructure systems are not simply technological (or even socio-technical or socio-ecological) artifacts—they are complex and interconnected SETS; (2) in addition to infrastructure being complex and multidimensional, the challenges facing our infrastructure are also SETS issues (e.g., inflexibility, utilization, and social equity); (3) by not thinking of infrastructure systems (and their related challenges) as SETS, the complexity inherent in our infrastructure systems can often be overlooked and underappreciated—potentially leading to catastrophic effects if left unchecked; (4) by underappreciating the complexity of our infrastructure systems, we become susceptible to incorrectly predicting future conditions and overestimating the predictability of future conditions, which in turn tends to encourage and perpetuate a strong emphasis on robustness and techno-centric practices; and (5) overconfidence in the predictability of future conditions and the reliance on techno-centric/robustness-oriented solutions can contribute to lock-in that is ultimately antithetical to the adaptive capacity (and thus resilience) of our infrastructure systems.

Overall, a SETS lens to infrastructure resilience appears well suited to help researchers, practitioners, and managers better identify (and prevent) lock-in and vulnerabilities that evolve within our infrastructure systems over time. This is particularly true for cases like the Old River Control Structure on the Atchafalaya River and the pumping stations in Miami Beach that have simultaneously become increasingly critical and fragile. Ideally, the SETS approach can help detect and address this criticality and fragility before a major disruption or failure occurs. At the opposite end of the spectrum, extreme events and surprises have been identified as primary mechanisms for breaking lock-in (Cowan & Hultén, 1996; Graham & Thrift, 2007; Unruh & Carrillo-Hermosilla, 2006), but with deleterious outcomes for human well-being, ecological integrity, and physical infrastructure. While proactive and preventive strategies should receive absolute precedent, the unfortunate reality is that major system disruption and failures can (and likely will) still occur. In these instances, the SETS lens can at least help mitigate the element of surprise, while also aiding the development of transformative strategies that help prevent the system from returning to a state of maladaptive lock-in.

Additionally, a SETS lens can also shed light on options that may not traditionally be considered—thereby increasing the adaptive capacity of the system to respond to surprising and unprecedented events and conditions. Moving forward, another potential resilience benefit from a SETS perspective worthy of further exploration is an examination of how different S, E, and T systems process and respond to stressors in different manners and at different rates. For example, vegetation in the Caribbean has been observed to exhibit widespread recovery from hurricanes within a few months (Bellingham et al., 1994; Tanner et al., 1991; Voiland, 2017)—rates that may not be mirrored by social and technological systems. Gaining a better understanding of these differences and catering to them may help further enhance the adaptive capacity of our infrastructure systems and their ability to move across different resilience regimes as needed. Additionally, with the growing influence of cyber systems on social elements like the spread of information (and misinformation) and environmental elements such as the growing energy and resource demands of digital systems (Belkhir & Elmeligi, 2018; Coroama et al., 2013; Stokols, 2018; Zanella et al., 2014), further examination of SETS interactions and dynamics in an increasingly cyber-influenced world will be an important avenue of future study. As cyber-technical systems continue to evolve, grow in complexity, and become increasingly automated, will the technological domain start to have an outsized influence on the social and ecological domains? Will lock-in related to cyber-based SETS interactions develop and evolve in similar matters to physical infrastructure systems or will new dynamics of lock-in emerge?

As we advance toward the use of SETS frameworks in the planning, design, and implementation of infrastructure, it is important to keep sight of the constant need to integrate the SETS dimensions in order to avoid conflict, prevent maladaptive dynamics, and promote resilient, mutually reinforcing systems. Finally, it seems evident that the challenges and issues outlined in this manuscript cannot be fully addressed or solved from the perspective of a single discipline or sectoral expertise. In order to advance the science and effective management of SETS, a new generation of scholars and practitioners will need to develop a wide variety of skills and competencies such as an emphasis on real-world problems, integration of knowledge from all sources (i.e., academia, practitioners, and citizens), acknowledgement of science as an actor in the systems it sets out to analyze, embracing complexity and interdependency, and acceptance of theoretical and practical pluralism rather than dualism (Hummel et al., 2017; Kramm et al., 2017; Miller et al., 2014; Munoz-Erickson et al., 2017; Stokols, 2018; Wiek et al., 2011). Thus, to effectively develop a SETS perspective on infrastructure, we must begin to address the lack of transdisciplinarity in our training and education, our institutions, and our governance practices.

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References

Adger, W. N. (2006). Vulnerability. *Global Environmental Change*, *16*(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Ahmed, A. (2008). 47 air-conditioned bus shelters in Dubai open to public. Gulf News2. Retrieved from https://gulfnews.com/news/uae/transport/47-air-conditioned-bus-shelters-in-dubai-open-to-public-1.97833

Allenby, B. (2007). Earth systems engineering and management: A manifesto. *Environmental Science & Technology*, *41*(23), 7960–7965. https://doi.org/10.1021/es072657r

Allenby, B. (2012). *The theory and practice of sustainable engineering*. Upper Saddle River, NJ: Pearson Prentice Hall.

American Society of Civil Engineers (ASCE). (2017). 2017 infrastructure report card. Retrieved from https://www.infrastructurereportcard.org/wp-content/uploads/2017/10/Full-2017-Report-Card-FINAL.pdf

Amir, S., & Kant, V. (2018). Sociotechnical resilience: A preliminary concept. *Risk Analysis*, *38*(1), 8–16. https://doi.org/10.1111/risa.12816
Anderies, J. M., Janssen, M. A., & Ostrom, E. (2004). A framework to analyze the robustness of.social-ecological system from an institutional perspective. Retrieved from http://www.ecologyandsociety.org/vol9/iss1/art18/
Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal*, *99*(394), 116–131. Retrieved from http://www.jstor.org/stable/2234208%0D
Aven, T. (2015). The concept of antifragility and its implications for the practice of risk analysis. *Risk Analysis*, *35*(3), 476–483. https://doi.org/10.1111/risa.12279
Becker, E., & Jahn, T. (2005). Societal relations to nature: Outline of a critical theory in the ecological crisis. Retrieved from https://www.isoe.de/ftp/darmstadttext_engl.pdf
Belkhir, L., & Elmeligi, A. (2018). Assessing ICT global emissions footprint: Trends to 2040 & recommendations. *Journal of Cleaner Production*, *177*, 448–463. https://doi.org/10.1016/j.jclepro.2017.12.239
Bellingham, P. J., Tanner, E. V. J., & Healey, J. R. (1994). Sprouting of trees in Jamaican montane forests, after a hurricane. *Journal of Ecology*, *82*(4), 747–758. https://doi.org/10.2307/2261440
Bene, C., & Doyen, L. (2018). From resistance to transformation: a generic metric of resilience through viability. *Earth's Future*, *6*, 979–996. https://doi.org/10.1002/2017EF000660
Berkes, F., & Folke, C. (Eds.) (1998). *Linking social and ecological systems: Management practices and social mechanisms for building resilience*. Cambridge, UK: Cambridge University Press.
Blessing, R., Sebastian, A., & Brody, S. D. (2017). Flood risk delineation in the United States: How much loss are we capturing? *Natural Hazards Review*, *18*(3), 1–10. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000242
Boburg, S., & Reinhard, B. (2017). Houston's "Wild West" growth. The Washington Post. Retrieved from https://www.washingtonpost.com/graphics/2017/investigations/harvey-urban-planning/?utm_term=.dc3cd4644163
Bogost, I. (2017). Houston's flood is a design problem. The Atlantic. Retrieved from https://www.theatlantic.com/technology/archive/2017/08/why-cities-flood/538251/
Bolton, R., & Foxon, T. J. (2015). Infrastructure transformation as a socio-technical process - Implications for the governance of energy distribution networks in the UK. *Technological Forecasting and Social Change*, *90*(PB), 538–550. https://doi.org/10.1016/j.techfore.2014.02.017
Borden, K. A., Schmidtlein, M. C., Emrich, C. T., Piegorsch, W. W., & Cutter, S. L. (2007). Vulnerability of U.S. cities to environmental hazards. *Journal of Homeland Security and Emergency Management*, *4*(2). https://doi.org/10.2202/1547-7355.1279
Bullard, R. D., & Wright, B. (Eds.) (2009). *Race, place, and environmental justice after Hurricane Katrina—Struggles to reclaim, rebuild, and revitalize New Orleans and the Gulf Coast*. New York: Taylor & Francis.
Burnett, J. (2015). Billions Spent on flood barriers, but New Orleans still a 'fishbowl'. National Public Radio. Retrieved from https://www.npr.org/2015/08/28/432059261/billions-spent-on-flood-barriers-but-new-orleans-still-a-fishbowl
Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., et al. (2010). Global biodiversity: Indicators of recent declines. *Science*, *1164*(May), 1164–1169. https://doi.org/10.1126/science.1187512
California Department of Water Resources (DWR). (2018). Independent forensic team report Oroville Dam spillway incident. Retrieved from https://damsafety.org/sites/default/files/files/Independent Forensic Team Report Final 01–05-18.pdf
California Water Service. (2018). Low-water and drought-resistant plants. Retrieved April 19, 2018, from https://www.calwater.com/conservation/low-water-drought-resistant-plants/
Carr, A. (2017). Louisiana Governor declares state of emergency over New Orleans flooding issues. Weather.com. Retrieved from https://weather.com/news/news/new-orleans-flooding-late-august-2017-impacts
Casal-Campos, A., Fu, G., Butler, D., & Moore, A. (2015). An integrated environmental assessment of green and gray infrastructure strategies for robust decision making. *Environmental Science & Technology*, *49*(14), 8307–8314. https://doi.org/10.1021/es506144f
Chakraborty, J., Collins, T. W., Montgomery, M. C., & Grineski, S. E. (2014). Social and spatial inequities in exposure to flood risk in Miami, Florida. *Natural Hazards Review*, *15*(3), 1–10. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000140
Chester, M. V., & Allenby, B. (2018). Toward adaptive infrastructure: flexibility and agility in a non-stationarity age. *Sustainable and Resilient Infrastructure*, *3*(1), 1–19. https://doi.org/10.1080/23789689.2017.1416846
City of Phoenix. (2010). Tree and shade master plan. Retrieved from https://www.phoenix.gov/parkssite/Documents/T and A 2010.pdf.
City of Phoenix. (2017). Phoenix Transportation 2050—Progress report #1. Retrieved from https://www.phoenix.gov/streetssite/MediaAssets/T2050English12.21.17.pdf
Clark, B. J. (2016). The battle for Miami Beach. Public Works Magazine. Retrieved from http://www.pwmag.com/water-sewer/stormwater/the-battle-for-miami-beach_o
Cohen, H. (2017). King tide is back. So how high will the water rise this time? Miami Herald. Retrieved from http://www.miamiherald.com/news/weather/article182286066.html
Collins, T. W. (2010). Production of unequal risk: The 2006 Paso del Norte Floods. *Antipode*, *42*(2), 258–288. https://doi.org/10.1111/j.1467-8330.2009.00755.x
Collins, T. W., Grineski, S. E., & Chakraborty, J. (2018). Environmental injustice and flood risk: a conceptual model and case comparison of metropolitan Miami and Houston, USA. *Regional Environmental Change*, *18*(2), 311–323. https://doi.org/10.1007/s10113-017-1121-9
Colten, C. E. (2007). Environmental justice in a landscape of tragedy. *Technology in Society*, *29*, 173–179. https://doi.org/10.1016/j.techsoc.2007.01.006
Cooley, H., Gleick, P., & Wilkinson, R. (2014). Water reuse potential in California. Retrieved from http://pacinst.org/wp-content/uploads/2014/06/ca-water-reuse.pdf
Coroama, V. C., Hilty, L. M., Heiri, E., & Horn, F. M. (2013). The Direct Energy Demand of Internet Data Flows. *Journal of Industrial Ecology*, *17*(5), 680–688. https://doi.org/10.1111/jiec.12048
Corvellec, H., Campos, M. J. Z., & Zapata, P. (2013). Infrastructures, lock-in, and sustainable urban development: The case of waste incineration in the Göteborg Metropolitan Area. *Journal of Cleaner Production*, *50*, 32–39. https://doi.org/10.1016/j.jclepro.2012.12.009
Cowan, R., & Hultén, S. (1996). Escaping lock-in: The case of the electric vehicle. *Technological Forecasting and Social Change*, *53*(1), 61–79. https://doi.org/10.1016/0040-1625(96)00059-5
Craig, T. (2017). It wasn't even a hurricane, but heavy rains flooded New Orleans as pumps faltered. The Washington Post. Retrieved from https://www.washingtonpost.com/national/it-wasnt-even-a-hurricane-but-heavy-rains-flooded-new-orleans-as-pumps-faltered/2017/08/09/b3b7506a-7d37-11e7-9d08-b79f191668ed_story.html?utm_term=.7265148855c2
Depietri, Y., & McPhearson, T. (2017). Integrating the grey, green, and blue in cities: Nature-based solutions for climate change adaptation and risk reduction. In *Nature-based solutions to climate change Adaptation in urban areas* (pp. 91–109). Cham: Springer. https://doi.org/10.1007/978-3-319-56091-5_6

Di Liberto, T. (2017). King tides cause flooding in Florida in fall 2017. Retrieved April 19, 2018, from https://www.climate.gov/news-features/event-tracker/king-tides-cause-flooding-florida-fall-2017

Dolnicar, S., & Scha, A. I. (2009). Desalinated versus recycled water: Public perceptions and profiles of the accepters. *Journal of Environmental Management*, *90*, 888–900. https://doi.org/10.1016/j.jenvman.2008.02.003

Domonoske, C. (2017). Hit by flooding and pumping system crisis, New Orleans braces for more rain. National Public Radio. Retrieved from https://www.npr.org/sections/thetwo-way/2017/08/10/542606964/hit-by-flooding-and-pumping-system-crisis-new-orleans-braces-for-more-rain

Edwards, P. (2003). Infrastructure and modernity: Force, time, and social organization in the history of sociotechnical systems. In T. Misa, P. Brey, & A. Feenberg (Eds.), *Modernity and technology* (pp. 185–225). Cambridge, MA: MIT Press.

Eisenberg, D. A., Park, J., & Seager, T. P. (2017). Sociotechnical network analysis for power grid resilience in South Korea. *Complexity*, *2017*. https://doi.org/10.1155/2017/3597010

Emanuel, K. (2017). Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1716222114

Fagenson, Z. (2014). *Miami Beach cheers succuess of flood pumps against "King Tide"*. London, UK: Reuters. Retrieved from https://www.reuters.com/article/us-usa-miami-beach-flooding/miami-beach-cheers-success-of-flood-pumps-against-king-tide-idUSKCN0HY2AP20141009

Fessenden, F., Gebeloff, R., Walsh, M. W., & Griggs, T. (2017). *Water damage from Hurricane Harvey extended far beyond flood zones*. New York: The New York Times. Retrieved from https://www.nytimes.com/interactive/2017/09/01/us/houston-damaged-buildings-in-fema-flood-zones.html

Fielding, K. S., Dolnicar, S., Schultz, T., Fielding, K. S., Dolnicar, S., & Public, T. S. (2018). Public acceptance of recycled water. *International Journal of Water Resources Development*, *627*, 1–36. https://doi.org/10.1080/07900627.2017.1419125

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., et al. (2015). ScienceDirect Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environmental Sustainability*, 144–149. https://doi.org/10.1016/j.cosust.2015.06.002

Flechas, J. (2016). Flood claim denied for restaurant turned "basement" after Miami Beach raised street. Miami Herald2. Retrieved from http://www.miamiherald.com/news/local/community/miami-dade/miami-beach/article115264938.html

Flechas, J. (2017). This restaurant waited 14 months for flood claim to be approved after city raised street. Miami Herald. Retrieved from http://www.miamiherald.com/news/local/community/miami-dade/miami-beach/article190166649.html

Flechas, J. (2018). Will Miami Beach's anti-flooding measures work? The city's getting an outside opinion. Miami Herald. Retrieved from http://www.miamiherald.com/news/local/community/miami-dade/miami-beach/article204038184.html

Flechas, J., & Staletovich, J. (2015). Miami Beach's battle to stem rising tides. Miami Herald. Retrieved from http://www.miamiherald.com/news/local/community/miami-dade/miami-beach/article41141856.html

Fleming, B. (2017). The real villains in Harvey flood: urban sprawl and the politicians who allowed it. The Guardian. Retrieved from https://www.theguardian.com/commentisfree/2017/aug/31/real-villains-harvey-flood-urban-sprawl

Flynn, C., & Davidson, C. (2016). Saving the rain in Onondaga County, New York. In *Engineering for sustainable communities* (pp. 367–372). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784414811.ch25

Flynn, C., Davidson, C. I., & Mahoney, J. (2014). Transformational changes associated with sustainable stormwater management practices in Onondaga County, New York. In *International conference on sustainable infrastructure* (pp. 89–100). Long Beach, CA: American Society of Civil Engineers. https://doi.org/10.1061/9780784478745.009

Flynn, C. D., & Davidson, C. I. (2018). Adapting the social-ecological system framework for urban stormwater management: the case of green infrastructure adoption. *Ecology and Society*, *21*(4). https://doi.org/10.5751/ES-08756-210419

FogNet. (2018). About FogNet. Retrieved April 19, 2018, from http://fognet.ucsc.edu/?page_id=27

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

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, *30*, 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511

Forsee, W. J., & Ahmad, S. (2011). Evaluating urban storm-water infrastructure design in response to projected climate change. *Journal of Hydrologic Engineering*, *16*, 865–873. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000383

Fraser, A., & Chester, M. (2017). Transit system design and vulnerability of riders to heat. *Journal of Transport & Health*, *4*, 216–225. https://doi.org/10.1016/j.jth.2016.07.005

Fraser, A. M., Chester, M. V., Eisenman, D., Hondula, D. M., Pincetl, S. S., English, P., et al. (2016). Household accessibility to heat refuges: Residential air conditioning, public cooled space, and walkability. *Environment and Planning B Urban Analytics and City Science*, *44*(6), 1036–1055. https://doi.org/10.1177/0265813516657342

G.R. (2017). Left out in the rain—Floods and political crisis are back in New Orleans. The Economist. Retrieved from https://www.economist.com/blogs/democracyinamerica/2017/08/left-out-rain

Garrick, D. E., Schlager, E., De Stefano, L., & Villamayor-Tomas, S. (2018). Managing the cascading risks of droughts: Institutional adaptation in transboundary rivers. *Earth's Future*, *6*, 809–827. https://doi.org/10.1002/2018EF000823

Gidley, M. L. (2016). Characterizing microbial water quality of extreme tide floodwaters discharged from an urbanized subtropical beach: Case study of Miami Beach with implications for sea level rise and public health. In 2016 Ocean Science Meeting. New Orleans, LA.

Goldstein, T. (2015). A guide to rebates on drought-tolerant landscaping. Los Angeles Times. Retrieved from http://www.latimes.com/local/california/la-me-lawn-rebate-explainer-20150416-story.html

Goleman, D. (2010). *Ecological intelligence: The hidden impacts of what we buy*. New York: Broadway Books.

Gorman, S. (2015). California drought gives new impetus to wastewater recycling. Reuters. Retrieved from https://www.reuters.com/article/us-usa-wastewater-california/california-drought-gives-new-impetus-to-wastewater-recycling-idUSKCN0PQ12N20150716

Grabowski, Z. J., Matsler, A. M., Thiel, C., McPhillips, L., Hum, R., Bradshaw, A., et al. (2017). Infrastructures as socio-eco-technical systems: Five considerations for interdisciplinary dialogue. *Journal of Infrastructure Systems*, *23*(4), 02517002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000383

Graham, S., & Thrift, N. (2007). Out of order: Understanding repair and maintenance. *Theory, Culture and Society*, *24*(3), 1–25. https://doi.org/10.1177/0263276407075954

Graham, T., & Abrahamse, W. (2017). Communicating the climate impacts of meat consumption: The effect of values and message framing. *Global Environmental Change*, *44*, 98–108. https://doi.org/10.1016/j.gloenvcha.2017.03.004

Grimm, N. B., Pickett, S. T. A., Hale, R. L., & Cadenasso, M. L. (2017). Does the ecological concept of disturbance have utility in urban social – ecological – technological systems? *Ecosystem Health and Sustainability*, *3*(1). https://doi.org/10.1002/ehs2.1255

Gulf News Staff (2015). RTA Commissions 400 new bus shelters—Phase 2 of air-conditioned bus shelter project to be ready by end of 2017. Retrieved from http://gulfnews.com/news/uae/transport/rta-commissions-400-new-bus-shelters-1.1627849

Haberl, H., Fischer-Kowalski, M., Krausmann, F., & Winiwarter, V. (Eds.) (2016). *Social ecology: Society-nature relations across time and space*. Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-33326-7

Hale, R. L., Armstrong, A., Baker, M. A., Bedingfield, S., Betts, D., Buahin, C., et al. (2015). iSAW: Integrating structure, actors, and water to study socio-hydro-ecological systems. *Earth's Future*, *3*, 110–132. https://doi.org/10.1002/2014EF000295

Hino, M., Field, C. B., & Mach, K. J. (2017). Managed retreat as a response to natural hazard risk. *Nature Climate Change*, *7*(5), 364–370. https://doi.org/10.1038/nclimate3252

Hommels, A. (2005). Studying obduracy in the city: Toward a productive fusion between technology studies and urban studies. *Science, Technology & Human Values*, *30*(3), 323–351. https://doi.org/10.1177/0162243904271759

Howard, B. H., & Millsap, S. (2014). California drought spurs groundwater drilling boom in Central Valley. National Geographic. Retrieved from https://news.nationalgeographic.com/news/2014/08/140815-central-valley-california-drilling-boom-groundwater-drought-wells/

Hummel, D., Jahn, T., Keil, F., Liehr, S., & Stieß, I. (2017). Social ecology as critical, transdisciplinary science—Conceptualizing, analyzing and shaping societal relations to nature. *Sustainability*, *9*(7), 1050. https://doi.org/10.3390/su9071050

Ingraham, C. (2017). Houston is experiencing its third "500-year" flood in 3 years. How is that possible? The Washington Post2. Retrieved from https://www.washingtonpost.com/news/wonk/wp/2017/08/29/houston-is-experiencing-its-third-500-year-flood-in-3-years-how-is-that-possible/?utm_term=.ec10d876aa0b

Iowa Department of Transportation. (2015). Iowa's bridge and highway climate change and extreme weather vulnerability assessment pilot. Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/iowa/final_report/iowa-pilot.pdf

Iwaniec, D., & Wiek, A. (2014). Advancing sustainability visioning practice in planning—The general plan update in Phoenix, Arizona. *Planning Practice and Research*, *29*(5), 543–568. https://doi.org/10.1080/02697459.2014.977004

Jones, S. (2018). Research fit for a King Tide. Retrieved April 19, 2018, from http://www.aoml.noaa.gov/keynotes/keynotes_1014_king_tide.html

Kang, M., & Jackson, R. B. (2016). Salinity of deep groundwater in California: Water quantity, quality, and protection. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(28), 7768-7773. https://doi.org/10.1073/pnas.1600400113

Kim, Y., Eisenberg, D., Bondank, E., Chester, M., Mascaro, G., & Underwood, S. (2017). Fail-safe and safe-to-fail adaptation: Decision-making for urban flooding under climate change. *Climatic Change*, *145*(3–4), 397–412. https://doi.org/10.1007/s10584-017-2090-1

Knickmeyer, E. (2016). In California, a $350 million social experiment over lawns. The Mercury News. Retrieved from https://www.mercurynews.com/2016/10/31/in-california-a-350-million-social-experiment-over-lawns/

Kramm, J., Pichler, M., Schaffartzik, A., & Zimmermann, M. (2017). Societal relations to nature in times of crisis—Social ecology's contributions to interdisciplinary sustainability studies. *Sustainability*, *9*(7), 1042. https://doi.org/10.3390/su9071042

Krumme, K. (2016). Sustainable development and social-ecological-technological systems (SETS): Resilience as a guiding principle in the urban-industrial nexus. *Renewable Energy and Sustainable Development*, *2*(2), 70–90. https://doi.org/10.21622/resd.2016.02.2.070

Labi, S. (2014). *Introduction to civil engineering systems—A systems perspective to the development of civil engineering facilities*. Hoboken, NJ: John Wiley & Sons, Inc.

Landry, S. M., & Chakraborty, J. (2009). Street trees and equity: Evaluating the spatial distribution of an urban amenity. *Environment and Planning A*, *41*, 2651–2671. https://doi.org/10.1068/a41236

Layzer, J. A. (2012). Hurricane Katrina hits New Orleans: Disaster, restoration, and eesilience. In *The Environmental Case: Translating values into policy* (3rd ed., pp. 515–556). Washington, DC: CQ Press.

Lind, D. (2017). The "500-year" flood, explained: Why Houston was so underprepared for Hurricane Harvey. Vox. Retrieved from https://www.vox.com/science-and-health/2017/8/28/16211392/100–500-year-flood-meaning

Madrigal, A. C. (2011, May). What we've done to the Mississippi River: An explainer. The Atlantic. Retrieved from https://www.theatlantic.com/technology/archive/2011/05/what-weve-done-to-the-mississippi-river-an-explainer/239058/

Maldonado, A., Collins, T. W., & Grineski, S. E. (2016). Hispanic immigrants' vulnerabilities to flood and hurricane hazards in two United States metropolitan areas. *Geographical Review*, *106*(1), 109–135. https://doi.org/10.1111/j.1931-0846.2015.12103.x

Markolf, S. A., Hoehne, C., Fraser, A., Chester, M., & Underwood, S. (2018). Transportation resilience to climate change and extreme weather events—Beyond risk and robustness. *Transport Policy*. https://doi.org/10.1016/j.tranpol.2018.11.003

McGuire, K. (2016). Houston's development boom and reduction of wetlands leave region flood prone. The Houston Chronicle. Retrieved from https://www.houstonchronicle.com/news/houston-texas/houston/article/Houston-s-development-boom-and-reduction-of-8403838.php?t=cda1a7b013438d9cbb&cmpid=twitter-premium

McKenzie, K. (2015). Interest builds in pulling water from the Central Coast's signature fog. Santa Cruz Sentinel. Retrieved from http://www.santacruzsentinel.com/lifestyle/20150806/interest-builds-in-pulling-water-from-the-central-coasts-signature-fog

McPhail, C., Maier, H. R., Kwakkel, J. H., Giuliani, M., Castelletti, A., & Westra, S. (2018). Robustness metrics: How are they calculated, when should they be used and why do they give different results? *Earth's Future*, 169–191. https://doi.org/10.1002/2017EF000649

McPhearson, T., Haase, D., Kabisch, S., & Gren, A. (2016). Advancing understanding of the complex nature of urban systems. *Ecological Indicators*, *70*, 566–573. https://doi.org/10.1016/j.ecolind.2016.03.054

McPhee, J. (1987). Atchafalaya. The New Yorker. Retrieved from https://www.newyorker.com/magazine/1987/02/23/atchafalaya

McPhee, J. (1989). *The control of nature*. New York: Farrar, Straus and Grioux.

Meerow, S., Newell, J. P., & Stults, M. (2016). Landscape and urban planning defining urban resilience: A review. *Landscape and Urban Planning*, *147*, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

Miami-Dade County Transportation and Public Works (2016). Miami-Dade Transit is testing an air conditioned bus shelter at the Hialeah Metrorail Station to help passengers cool off. Retrieved from http://www.miamidade.gov/releases/2016-8-16-dtpw-ac-busshelter-advisory.asp

Miller, T. R., Chester, M., & Munoz-Erickson, T. (2018). Rethinking infrastructure in an era of unprecedented events. *Issues in Science and Technology*, *34*(2).

Miller, T. R., Wiek, A., Sarewitz, D., Robinson, J., Olsson, L., Kriebel, D., et al. (2014). The future of sustainability science: A aolutions-oriented agenda. *Sustainability Science*, *9*(2), 239–246.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., et al. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573–574. https://doi.org/10.1126/science.1151915

Muneepeerakul, R., & Anderies, J. M. (2017). Strategic behaviors and governance challenges in social-ecological systems. *Earth's Future*, *5*, 865–876. https://doi.org/10.1002/2017EF000562

Muñoz-Erickson, T. A., Miller, C., & Miller, T. R. (2017). How cities think: Knowledge co-production for urban sustainability and resilience. *Forests*, *8*(6), 203–220. https://doi.org/10.3390/f8060203
Myers, T. A., Nisbet, M. C., Maibach, E. W., & Leiserowitz, A. A. (2012). A public health frame arouses hopeful emotions about climate change. *Climatic Change*, *113*(3–4), 1105–1112. https://doi.org/10.1007/s10584-012-0513-6
National Oceanic and Atmospheric Administration. (2017). What is a living shoreline? Retrieved May 2, 2018, from https://oceanservice.noaa.gov/facts/living-shoreline.html
National Oceanic and Atmospheric Administration National Centers for Environmental Information (2017). U.S. billion-dollar weather and climate disasters. Retrieved from https://www.ncdc.noaa.gov/billions/
Neal, D. J. (2017). Will the arriving Kind Tide flood Miami streets again? Miami Herald. Retrieved from http://www.miamiherald.com/news/local/environment/article173899376.html
Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419–422. https://doi.org/10.1126/science.1172133
Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B., & Policansky, D. (1999). Revisiting the commons: Local lessons, global challenges. *Science*, *284*, 278–283. https://doi.org/10.1126/science.284.5412.278
Park, J., Seager, T. P., Rao, P. S. C., Convertino, M., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, *33*(3), 356–367. https://doi.org/10.1111/j.1539-6924.2012.01885.x
Payo, A., Becker, P., Otto, A., Vervoort, J., & Kingsborough, A. (2016). Experiential lock-in: Characterizing avoidable maladaptation in infrastructure systems. *Journal of Infrastructure Systems*, *22*(1), 2515001. https://doi.org/10.1061/(asce)is.1943-555x.0000268
Peterson, M., & Weiland, N. (2016). A geologist and the war against flooding. Politico. Retrieved from https://www.politico.com/magazine/gallery/2016/03/how-a-miami-researcher-is-changing-the-way-we-test-water-000623?slide=0
Pinter, N., Santos, N., & Hui, R. (2017). Preliminary analysis of Hurricane Harvey flooding in Harris County, Texas. Retrieved from UC Davis Center for Watershed Sciences - California WaterBlog: https://californiawaterblog.com/2017/09/01/preliminary-analysis-of-hurricane-harvey-flooding-in-harris-county-texas/
Po, M., Kaercher, J. D., & Nancarrow, B. E. (2003). Literature review of factors influencing public perceptions of water reuse. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.197.423&rep=rep1&type=pdf
Ramaswami, A., Weible, C., Main, D., Heikkila, T., Siddiki, S., Duvall, A., et al. (2012). A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems: An integrative curriculum across seven major disciplines. *Journal of Industrial Ecology*, *16*(6), 801–813. https://doi.org/10.1111/j.1530-9290.2012.00566.x
Reckdahl, K. (2017). New Orleans Scrambles to eepair drainage system after severe flooding. The New York Times. Retrieved from https://www.nytimes.com/2017/08/11/us/new-orleans-repair-pumping-system-flooding.html
Resnick, B. (2017). Why Houston's flooding got so bad, according to storm experts. Vox. Retrieved from https://www.vox.com/science-and-health/2017/8/29/16216568/hurricane-havery-houston-flooding-experts
Revkin, A. C. (2007). Climate change as news: Challenges in communicating environmental science. In J. F. DiMento & P. Doughman (Eds.), *Climate change: What it means for us, our children, and our grandchildren* (pp. 139–160). Cambridge, MA: MIT Press.
Rijke, J., van Herk, S., Zevenbergen, C., & Ashley, R. (2012). Room for the river: Delivering integrated river basin management in the netherlands. *International Journal of River Basin Management*, *10*(4), 369–382. https://doi.org/10.1080/15715124.2012.739173
Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*, *21*(6), 11–25.
Roth, D., & Warner, J. (2007). Flood risk, uncertainty and changing river protection policy in the Netherlands: The case of "calamity polders." *Journal of Economic and Social Geography*, *98*(4), 519–525. https://doi.org/10.1111/j.1467-9663.2007.00419.x
Rott, N. (2018). California aims to get past the yuck factor of recycled wastewater. National Public Radio. Retrieved from https://www.npr.org/2018/02/20/587195891/california-aims-to-get-past-the-yuck-factor-of-recycled-wastewater
Rubin, E. S. (2001). *Introduction to engineering & the environment*. New York: McGraw-Hill Higher Education.
Sachs, J. D. (2015). *The age of sustainable development*. New York: University of Columbia Press.
San Diego County Water Authority (SDCWA). (2018). Carlsbad Desalination Plant Project Overview. Retrieved April 19, 2018, from http://carlsbaddesal.sdcwa.org/overview/
Schultz, P. W., & Kaiser, F. G. (2012). Promoting pro-environmental behavior. In S. D. Clayton (Ed.), *The Oxford handbook of environmental and conservation psychology* (pp. 556–580). https://doi.org/10.1093/oxfordhb/9780199733026.013.0029
Seager, T. P., Clark, S. S., Eisenberg, D. A., Thomas, J. E., Hinrichs, M. M., Kofron, R., et al. (2017). Redesigning resilient infrastructure research. In I. Linkov & J. M. Palma-Oliveira (Eds.), *Resilience and risk* (pp. 81–119). Dordrecht, Netherlands: Springer.
Shaw, A., Satija, N., & Collier, K. (2016). Boomtown, flood town. ProPublica. Retrieved from https://www.propublica.org/article/boomtown-flood-town-text
Singh, S. J., Haberl, H., Chertow, M., Mirtl, M., & Schmid, M. (2013). *Long term socio-ecological research: Studies in society-nature interactions across spatial and temporal scales*. Netherlands: Springer. https://doi.org/10.1007/978-94-007-1177-8
Slater, L. J., & Villarini, G. (2016). Recent trends in U.S. flood risk. *Geophysical Research Letters*, *43*, 428–436. https://doi.org/10.1002/2016GL071199
South Florida Regional Climate Change Compact. (2015). Unified sea level eise projection for Southeast Florida. Retrieved from http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2015/10/2015-Compact-Unified-Sea-Level-Rise-Projection.pdf
Speth, J. G. (2009). *The bridge at the edge of the world*. New Haven, CT: Yale University Press.
Staletovich, J. (2016a). Miami Beach attacks "sloppy science" on human waste bacteria in bay. Miami Herald. Oxford, UK: Oxford University Press. Retrieved from http://www.miamiherald.com/news/local/environment/article82648642.html
Staletovich, J. (2016b). Miami Beach king tides flush human waste into bay, study finds. Miami Herald. Retrieved from http://www.miamiherald.com/news/local/environment/article77978817.html
Stokols, D. (2018). *Social ecology in the digital age—Solving complex problems in a globalizing world*. London, UK: Elsevier. https://doi.org/10.1016/C2014-0-04300-6
Sweet, W. V., Horton, R., Kopp, R. E., LeGrande, A. N., & Romanou, A. (2017). Chapter 12: Sea level rise. In D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, & T. K. Maycock (Eds.), *Climate sciece special report: Fourth national climate assessment* (Vol. 1, pp. 333–363). Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/J0VM49F2
Swilling, M., Robinson, B., Marvin, S., Hodson, M., Allen, A., Herrero, A. C., et al. (2013). City-level decoupling urban resource flows. Doi:978–92–807-3298-6.
Swim, J., Howard, G., Clayton, S., Reser, J., Doherty, T., Stern, P., et al. (2009). Psychology and global climate change—Addressing a multifaceted phenomenon and set of challenges. Retrieved from http://www.apa.org/science/about/publications/climate-change-booklet.pdf

Syvitski, J. (2012). Anthropocene: An epoch of our making. *Global Change Magazine*, *78*, 12–15.
Taleb, N. N. (2012). *Antifragile: Things that gain from disorder*. New York: Random House.
Tanner, E. V. J., Kapos, V., & Healey, J. R. (1991). Hurricane effects on forest ecosystems in the Caribbean. *Biotropica*, *23*(4), 513–521. https://doi.org/10.2307/2388274
Tellman, B., Bausch, J. C., Eakin, H., Anderies, J. M., Mazari-hiriart, M., & Manuel-navarrete, D. (2018). Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City. *Ecology and Society*, *23*(1). https://doi.org/10.5751/ES-09712-230101
Thomas, W. L. (1956). *Man's role in changing the face of the Earth*. Chicago, IL: University of Chicago Press.
Tomlinson, B., Nardi, B., Patterson, D. J., Raturi, A., Richardson, D., Saphores, J.-D., et al. (2015). Toward alternative decentralized infrastructures. In *Proceedings of the 6th annual Symposium on computing for development* (pp. 33–40). London: ACM DEV. https://doi.org/10.1145/2830629.2830648
Turner, B. L. (1993). *The Earth as transformed by human action: Global and regional changes in the biosphere over the past 300 years*. Cambridge, UK: Cambridge University Press.
U.S. Army Corps of Engineers (USACE). (2013a). Seabrook Floodgate Complex. Retrieved from http://www.mvn.usace.army.mil/Portals/56/docs/PAO/FactSheets/SeabrookFloodgateComplex.pdf
U.S. Army Corps of Engineers (USACE). (2013b). IHNC-Lake Borgne Surge Barrier. Retrieved from http://www.mvn.usace.army.mil/Portals/56/docs/PAO/FactSheets/IHNC-LakeBorgneSurgeBarrier.pdf
U.S. Army Corps of Engineers (USACE). (2015). West Closure Complex. Retrieved from http://www.mvn.usace.army.mil/Portals/56/docs/PAO/FactSheets/Fact Sheet update 10_15/WCC Fact Sheet (August 2015).pdf.
U.S. Environmental Protection Agency (EPA). (2008). Reducing urban heat islands: compendium of strategies, Chapter 5, "Cool Pavements," Retrieved from http://www.epa.gov/heatisld/resources/compendium.htm
U.S. Environmental Protection Agency (EPA). (2017a). What is green infrastructure? Retrieved from https://www.epa.gov/green-infrastructure/what-green-infrastructure#bioswales
U.S. Environmental Protection Agency (EPA). (2017b). Constructed wetlands. Retrieved from https://www.epa.gov/wetlands/constructed-wetlands
Underwood, E. (2016). First study of California's deep groundwater sparks debate. *Science*. https://doi.org/10.1126/science.aag0628
United Nations Development Programme (UNDP). (2018). Sustainable development goals. Retrieved from http://www.undp.org/content/undp/en/home/sustainable-development-goals.html
Unruh, G. C., & Carrillo-Hermosilla, J. (2006). Globalizing carbon lock-in. *Energy Policy*, *34*(10), 1185–1197. https://doi.org/10.1016/j.enpol.2004.10.013
US Army Corps of Engineers (USACE): New Orleans District. (2009). Old River Control. Retrieved from http://www.mvn.usace.army.mil/Portals/56/docs/PAO/Brochures/OldRiverControlBrochure.pdf
Valley Metro. (2018). Keeping your cool during the sizzling summer heat. Retrieved April 19, 2018, from https://www.valleymetro.org/keeping-your-cool-during-the-sizzling-summer
Voiland, A. (2017). Why Caribbean Islands went brown and how long will they stay that way? Retrieved April 24, 2018, from https://earthobservatory.nasa.gov/blogs/earthmatters/2017/09/18/why-caribbean-islands-went-brown-and-how-long-will-they-stay-that-way/
Waldheim, C., Barbar, A., Elkin, R., Kongsgaard, H., Yang, J., Ors-Austin, J., et al. (2017). South Florida and sea level—The case of Miami Beach. Retrieved from http://www.mbrisingabove.com/wp-content/uploads/2017/08/South-Florida-and-Sea-Level-The-Case-of-Miami-Beach.pdf
Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., et al. (2002). Resilience management in social-ecological systems: A working hypothesis for a participatory approach. *Conservation Ecology*, *6*(1). Retrieved from http://www.consecol.org/vol6/iss1/art14
Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., et al. (2018). Resilience management in social-ecological systems: A working hypothesis for a participatory approach. *Ecology and Society*, *6*(1).
Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, *11*(1), 13.
Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, *9*(2).
Walker, G. (2015). Come back sociotechnical systems theory, all is forgiven. *Civil Engineering and Environmental Systems*, *32*, 170–179. https://doi.org/10.1080/10286608.2015.1024112
Wallace, T., Watkins, D., Park, H., Singhvi, A., & Williams, J. (2018). How one Houston suburb ended up in a reservoir, New York Times. Retrieved from https://www.nytimes.com/interactive/2018/03/22/us/houston-harvey-flooding-reservoir.html
Wang, R., Eckelman, M. J., & Zimmerman, J. B. (2013). Consequential environmental and economic life cycle assessment of green and gray stormwater infrastructures for combined sewer systems. *Environmental Science & Technology*, *47*(19), 11,189–11,198. https://doi.org/10.1021/es4026547
Warner, J., & van Buuren, A. (2011). Implementing room for the river: Narratives of success and failure in Kampen, the Netherlands. *International Review of Administrative Sciences*, *77*(4), 779–801. https://doi.org/10.1177/0020852311419387
Weiss-penzias, P., Fernandez, D., Moranville, R., & Saltikov, C. (2016). A low cost system for detecting fog events and triggering an active fog water collector. *Aerosol and Air Quality Research*, 1–10. https://doi.org/10.4209/aaqr.2016.11.0508
Wendel, J. (2016). Dirty water: Unintended consequence of climate resilience. *Eos*, *97*. https://doi.org/10.1029/2016EO047061
Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability Science*, *6*(2), 203–218. http://doi.org/10.1007/s11625-011-0132-6
Wiering, M. A., & Arts, B. J. M. (2006). Discursive shifts in dutch river management: 'Deep' institutional change or adaptation strategy? *Hydrobiologia*, *565*(1), 327–338. https://doi.org/10.1007/s10750-005-5923-2
Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Landscape and urban planning urban green space, public health, and environmental justice: The challenge of making cities "just green enough". *Landscape and Urban Planning*, *125*, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017
Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety*, *141*, 5–9. https://doi.org/10.1016/j.ress.2015.03.018
Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for smart cities. *IEEE Internet of Things Journal*, *1*(1), 22–32. https://doi.org/10.1109/JIOT.2014.2306328

Zimmerman, R., Zhu, Q., de Leon, F., & Guo, Z. (2017). Conceptual modeling framework to integrate resilient and interdependent infrastructure in extreme weather. *Journal of Infrastructure Systems*, *23*(4), 04017034. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000394

Zimmerman, R., Zhu, Q., & Dimitri, C. (2016). Promoting resilience for food, energy and water interdependencies. *Journal of Environmental Studies and Sciences*, *6*(1), 50–61. https://doi.org/10.1007/s13412-016-0362-0