Toward General Principles for Resilience Engineering

David J. Yu,[1,2,3,*] Michael L. Schoon,[4,5] Jason K. Hawes,[6,7] Seungyoon Lee,[8] Jeryang Park,[9] P. Suresh C. Rao,[2,10] Laura K. Siebeneck,[11] and Satish V. Ukkusuri[1]

[1]Lyles School of Civil Engineering, Purdue University, West Lafayette, IN, USA.
[2]Department of Political Science, Purdue University, West Lafayette, IN, USA.
[3]Center for the Environment, Purdue University, West Lafayette, IN, USA.
[4]School of Sustainability, Arizona State University, Tempe, AZ, USA.
[5]Center for Behavior, Institutions & the Environment, Arizona State University, Tempe, AZ, USA.
[6]Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN, USA.
[7]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA.
[8]Brian Lamb School of Communication, Purdue University, West Lafayette, IN, USA.
[9]School of Urban and Civil Engineering, Hongik University, Seoul, Republic of Korea.
[10]Department of Agronomy, Purdue University, West Lafayette, IN, USA.
[11]Department of Public Administration, University of North Texas, Denton, TX, USA.

*Address correspondence to David J. Yu, Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., HAMP G175D, West Lafayette, IN 47907; tel: 765-496-0577; davidyu@purdue.edu.

Maintaining the performance of infrastructure-dependent systems in the face of surprises and unknowable risks is a grand challenge. Addressing this issue requires a better understanding of enabling conditions or *principles* that promote system resilience in a universal way. In this study, a set of such principles is interpreted as a group of interrelated conditions or organizational qualities that, taken together, engender system resilience. The field of Resilience Engineering identifies basic system or organizational qualities (e.g., abilities for learning) that are associated with enhanced general resilience and has packaged them into a set of principles that should be fostered. However, supporting conditions that give rise to such first-order system qualities remain elusive in the field. An integrative understanding of how such conditions co-occur and fit together to bring about resilience, therefore, has been less clear. This paper contributes to addressing this gap by identifying a potentially more comprehensive set of principles for building general resilience in infrastructure-dependent systems. In approaching this aim, we organize scattered notions from across the literature. To reflect the partly self-organizing nature of infrastructure-dependent systems, we compare and synthesize two lines of research on resilience: Resilience Engineering and social-ecological system resilience. Although some of the principles discussed within the two fields overlap, there are some nuanced differences. By comparing and synthesizing the knowledge developed in them, we recommend an updated set of resilience-enhancing principles for infrastructure-dependent systems. In addition to proposing an expanded list of principles, we illustrate how these principles can co-occur and their inter-dependencies.

KEY WORDS: Principles for resilience engineering; social-ecological system resilience; self-organization; adaptive management and governance

1. INTRODUCTION

Natural and man-made disasters around the globe have, over recent decades, generated widespread interest in increased resilience of infrastructure-dependent systems in which human society and built components are inextricably linked. The significance of the issue has led to several efforts in the broader safety and risk sciences aimed at identifying various enabling conditions that may be associated with improved resilience in such systems in a universal way (Francis & Bekera, 2014; Erik Hollnagel, 2014; Weick & Sutcliffe, 2001). Some of these conditions have been synthesized into a set of general principles that inform our thinking about what seems wise to do or what needs to be seriously considered for building and assessing resilience (Bruneau et al., 2003; Costella, Saurin, & de Macedo Guimarães, 2009; E. Hollnagel, Woods, & Leveson, 2006). Here, a set of such principles is interpreted as a group of interrelated conditions, rules of thumb, or organizational qualities that, taken together, engender some system-level ability (which in our case is resilience) in an infrastructure-dependent system (e.g., Van Asselt & Renn, 2011). Although there is no single definitive list of principles for enhancing resilience in infrastructure-dependent systems, some common themes run through the body of literature with an eye to the subject: reduce the sensitivity of system performance to shocks and enhance the adaptive capacity of responding organizations under unexpected situations.

In pursuing these broad themes, it is important to not lose sight of the fact that infrastructure-dependent systems are not isolated from the broader social, ecological, and technological contexts within which they are embedded to function, e.g. cities, ecosystems, etc. (Lloyd's Register Foundation, 2015; Meerow, Newell, & Stults, 2016). The discussion about principles for building resilience in such complex systems, therefore, requires a broader perspective that takes into account more than just built systems and organizations involved in operating them. In other words, an infrastructure and its operating organizations may be structured to maintain some functions with a certain level of robustness and reliability and adaptive margins, but actual outcomes may depend on how linked social or ecological components self-organize in response to designed structures, often in unexpected ways and with potential changes to qualitative system behavior (Muneepeerakul & Anderies, 2017; Yu, Qubbaj, Muneepeerakul, Anderies, & Aggarwal, 2015). An example is how levees and dams can be built and operated to contain flooding with a certain recurrence period. Empirical evidence shows that such designs are often associated with a decline in long-term resilience to rarer flooding because of self-organization of societal response, i.e., encroachment of economic activities on floodplains, gradual loss of flood memory among people, and path dependency towards more techno-centric solutions (Di Baldassarre et al., 2015; Logan, Guikema, & Bricker, 2018). Similarly, it has been shown that the building of levees in river deltas can disrupt natural delta-building processes (sand and mud accumulation in regularly flooded wetlands that surround river channels) and cause deltas to self-organize in ways that exacerbate land-sea level difference and flood risk in the long run (Temmerman & Kirwan, 2015). Thus, consideration of an infrastructure and its operating organization in isolation cannot capture the conditions of full resilience. We will argue here that resilience of an infrastructure and the broader system in which it functions *emerges* from the interplay between design and self-organization of societal and ecological responses. Do principles for resilience currently discussed by scholars based in safety and risk sciences, in particular Resilience Engineering (E. Hollnagel et al., 2006), sufficiently reflect this notion? Which additional principles could be considered to better address this partly designed and partly self-organizing nature of infrastructure-dependent systems? Such knowledge, if available, would better inform design of infrastructure-dependent systems in ways that prevent them from self-organizing towards a state with reduced resilience.

Furthermore, given that some principles for Resilience Engineering and related studies tend to be high-level guidelines about organizational and built system qualities (e.g., foster ability for learning, adapting, etc.), it is important to probe deeper to understand which underlying or second-order conditions give rise to such first-order qualities. For example, under what set of supporting conditions are organizational abilities for learning and adaptation encouraged? However, principles that touch on such second-order conditions in an integrative way have been elusive in Resilience Engineering. This difficulty arises in part because, while such supporting conditions tend to be discussed and recognized within safety and risk sciences, they are scattered across the literature, thus hindering an integrative understanding about how they might co-occur or be dependent on one another (see Hollnagel (2014) for an exception, which shows dependencies among some basic organizational abilities). For example, user participation, diversity in stakeholders' views and experience, and elements of social capital such as trust, social network and norms that reduce the cost of exchange tend to co-occur in organizations that effectively co-manage a natural resource system (R. Biggs, Schlüter, & Schoon, 2015). Thus, an approach that (i) organizes scattered discussions about conditions linked to resilience-enhancing basic system qualities and (ii) delineates how such conditions co-occur and collectively fit together to engender resilience would provide an added benefit to this line of research.

The objective of this paper is to contribute to organizing a more comprehensive set of principles that includes various basic and supporting conditions for promoting resilience in infrastructure-dependent systems as discussed in safety and risk sciences. In doing so, we reflect on the partly self-organizing nature of such systems and integrate scattered notions and interrelationships among relevant conditions. In our analysis, we focus on the resilience-enhancing principles discussed within Resilience Engineering (which we hereafter refer to by the abbreviation RE), a field of study that is concerned with how organizations can better manage socio-technical system to deal with change and disruption (Bergström, Winsen, & Henriqson, 2015; E. Hollnagel et al., 2006). Adopting a comparative approach. we also draw on the resilience-enhancing principles discussed in another strand of resilience research, namely the field of social-ecological system resilience (Folke, 2006). We take this approach because the study of social-ecological system resilience has long focused on the self-organizing nature of complex systems and developed extensive prior work that seeks to organize resilience-enhancing principles (R. Biggs et al., 2015), and also because RE scholars often refer back the original definition of ecological or social-ecological resilience in their own discussions (e.g., Erik Hollnagel, 2014). Through a comparative analysis of the two fields, we examine if there are principles currently widely accepted in social-ecological system resilience (and less explicitly recognized or evident within RE) that might benefit the aims and ambitions within RE. We evaluate such principles with respect to what they can bring to the RE field and build on that knowledge to identify a potentially more comprehensive set of resilience-enhancing principles for the field.

1.1. State of the Art: Current Principles and Gaps

Research on the resilience of infrastructure-dependent systems is actively pursued by academics in the field of Resilience Engineering (RE) and related disciplines. RE is a popular paradigm for safety management that appears to blend and extend ideas from multiple lines of research, including C.S. Holling's notion of ecological resilience (Holling & Meffe, 1996), the theory of high-reliability organizations (La Porte, 1996), and Jens Rasmussen's view on the importance of adaptability for dealing with uncertainty in complex systems (J. Rasmussen, 1990). RE was initiated at a symposium in Sweden in 2004 as a complementary approach to the traditional risk perspective, which is largely centered on the notion of robustness, or resistance, to failures based on probabilistic risk assessments, e.g., levees to prevent flooding from a 1-in-200 year flood (although the recent risk analysis approaches have advanced to reflect resilience, governance, and communication aspects) (Bergström et al., 2015; Righi, Saurin, & Wachs, 2015). RE has its roots in the recognition that focusing only on robust, or fail-safe, engineering design may lead to a false sense of security and hidden vulnerabilities that are difficult to detect until they are revealed by a catastrophic failure (Park, Seager, Rao, Convertino, & Linkov, 2013). If and when safety and reliability are taken for granted, complacency sets in, uncertainties in risk assessment are ignored, and changing risk profiles are not examined; all the while, intangible organizational and societal capacities that play a critical role during emergencies gradually wither away. Disastrous consequences of relying on fail-safe systems under changing definitions of acceptable risk were evident in New Orleans (Hurricane Katrina), Houston (Hurricane Harvey), Fukushima (tsunami and nuclear crisis), and New York (Super Storm Sandy), among many others, including non-urban systems like the Space Shuttle Challenger disaster.

In contrast, RE calls for embracing uncertainty and variability as opportunities for fostering an ability to cope with uncertainty and stress (Linkov et al., 2014; D. D. Woods, 2015). The conceptual roots of RE are traced back to process and systems engineering work seeking to enhance safety and improve performance in hazardous manufacturing settings, digging deeper into the traditional and omnipresent label of “human error” (Jens Rasmussen, 1997; D. D. Woods, 2003; D Woods & Wreathall, 2003). It is unsurprising, therefore, that this work has gained traction in fields like infrastructure design and aerospace engineering where total failure of systems comes at extreme cost and rapid recovery is often essential. It is important to realize, however, that RE does not replace risk analysis and that the two approaches are complementary, especially given the fact that the field of risk analysis has progressed to put a greater emphasis on the consequences of an uncertain event—a function of both robustness and recovery (Aven, 2019). In other words, the consequences of an uncertain event on a system are a reflection of both the time period the system state is below a desired level (which pertains to robustness) and the recovery time to return to a desired state and the capacity to shorten this time (which is related to resilience).

Returning to our discussion on the emergence of RE, the term resilience was initially adopted by RE theorists as “the intrinsic ability of an organization (system) to maintain or regain a dynamically stable state, which allows it to continue operations after a major mishap and/or in the presence of a continuous stress” (E. Hollnagel et al., 2006). This early definition accepted the bi-stable nature of an organization or system (i.e., a stable functional state and a failed state) and emphasized an ability to maintain or regain the functional state in the face of stress and adversity. This conceptual ground is similar to that of ecological resilience in the social-ecological systems literature, which is also about how systems with multi-stability persist or reorganize in response to change (Folke, 2006).

More recently, three important developments have been observed in RE and the broader safety and risk-related field. First, the ability of a system to extend and adjust to change, termed adaptive capacity, has taken a central stage. This has led to an updated definition of resilience within RE given by “the intrinsic ability of a system to *adjust* its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions” (Erik Hollnagel, Pariès, Woods, & Wreathall, 2010). This revised definition, which is similar to that of social-ecological resilience, underscores that RE is about being able to adapt in response to the unknown and the unknowable and not just about increasing the robustness to anticipated events (Park et al., 2013). Second, there is a growing appreciation of the fact that infrastructure-dependent systems cannot be isolated from their broader context. This is influenced in part by Jens Rasmussen's work on systems view (Jens Rasmussen, 1997) where he showed that multiple organizational levels and analytical perspectives are needed to understand safety management of socio-technical systems. Infrastructure-dependent systems are embedded in social, ecological, and technical elements and processes that are connected and constantly in flux (Lloyd's Register Foundation, 2015; C. Murphy & Gardoni, 2006). Third, much interest has recently developed in the interdependencies of multiple infrastructure systems, i.e., coupling, a two-way relationship in which the state of one infrastructure depends on the state of another infrastructure (Nan & Sansavini, 2017). Amidst complex interactions and given the tightly coupled nature of modern built systems, questions of how vulnerabilities emerge and evolve and how failures cascade through various forms of interdependencies in infrastructures (Rinaldi, Peerenboom, & Kelly, 2001) are gaining traction for diagnosing and understanding resilience.

In light of these developments, there is now a growing consensus among RE theorists that the capacity for resilience as described by the more recent definition (Erik Hollnagel et al., 2010) is determined by several organizational or system-level abilities (Lloyd's Register Foundation, 2015). Hollnagel et al. (2006) provide a group of interrelated basic system abilities (also called cornerstones of RE) and use them to distinguish between systems with differing levels of resilience. These abilities are 1) the ability to monitor internal states and the external environment of a system, 2) the ability to respond to both regular and irregular disruptions using prepared actions as well as adaptive margins, 3) the ability to learn from past experience and adjust monitoring and responses, and 4) the ability to anticipate so that proactive responses can be made before potential failures occur. Related studies share an analogous set of principles. For example, Park et al. (2013) suggest that "safe-fail" systems (as opposed to "fail-safe" systems) are characterized by the abilities to sense, anticipate, adapt, and learn. Synthesizing the work of Rasmussen, Hollnagel, Woods, and others (Hale & Heijer, 2006; E. Hollnagel, 2006; Jens Rasmussen, 1997; Wreathall, 2006), Costella et al. (2009) also packaged a set of RE principles: top management commitment to safety (safety culture), learning from accidents and normal work (learning), increased flexibility in system design to allow for and tolerably respond to variability (flexibility), and awareness of system status through monitoring (awareness). It is also worthwhile to note organizational qualities mentioned by high-reliability organization studies (La Porte, 1996; Roberts, 1989) and the more recent stream of research on reliability-seeking virtual organizations (Grabowski & Roberts, 2016), which are important approaches to crisis mitigation in built systems. These approaches delineate operating organizations' traits for achieving reliability in all circumstances, e.g. organizational culture for safety and vigilance, attention to design and procedures, redundancy, minimization of trial-and-error learning, distributed decision making, and continuous training through simulated exercises (Shrivastava, Sonpar, & Pazzaglia, 2009).

Another well-known approach is the R4 Framework (Bruneau & Reinhorn, 2004), which argues that resilience to both expected and unexpected disturbances is largely determined by the four basic qualities: robustness, resourcefulness, rapidity, and redundancy. Robustness is about resisting or remaining insensitive to disturbances; redundancy is about enabling substitutability among components in case of a component failure; resourcefulness relates to the ability to diagnose problems and mobilize various resources to deal with them; and rapidity concerns the recovery of functionality in a timely way. An important distinction is that while robustness and rapidity are the desired "ends" that are achieved through resilience-enhancing measures taken by actors in a system, redundancy and resourcefulness characterize the general features of these measures or the "means" by which resilience can be improved (Bruneau et al., 2003). Relatedly, it has been suggested that socio-technical resilience is characterized by three abilities: absorptive capacity, adaptive capacity, and restorative or recovery capacity (Francis & Bekera, 2014; Vugrin, Warren, & Ehlen, 2011). Absorptive capacity is the ability to resist or remain insensitive to disturbances. Adaptive capacity is the ability to adjust to changing conditions, especially when the system is maximally challenged to the limit of its absorptive capacity. Restorative capacity is the ability to recover functionality in a timely way. As can be inferred, these abilities are closely related to the four dimensions of the R4 Framework. Namely, a system's robustness and rapidity are manifested through the collective operation of absorptive, adaptive, and restorative abilities. The three abilities, in turn, are facilitated by resourcefulness and redundancy. Resourcefulness encourages adaptive capacity and restorative capacity through mobilization of various forms of assets, ranging from physical and financial resources, to social and human capital. Redundancy supports absorptive capacity through the presence of substitutable components that provide an insurance effect.

The preceding discussion outlined some of the frequently-noted groups of basic system or organizational qualities that are thought to be important for resilience in RE and the broader safety and risk-related field. A corollary is that, at the most fundamental level, it is wise to foster these qualities in order to enhance resilience in infrastructure-dependent systems. The current study builds on this existing foundation to probe what supporting or second-order conditions may be linked to enhancement of these basic qualities as well as what could be common linkages among these qualities. Some such second-order conditions are already recognized within RE, but are scattered across the literature. Thus, our approach is to integrate such notions to the extent possible and suggest a potentially more comprehensive set of RE principles. An underexplored challenge in this regard is that the interplay between design and self-organization in infrastructure-dependent systems is subtle and multi-faceted, and thus it is not obvious how such basic qualities closely associated with resilience can be cultivated (Naikar & Elix, 2019). Specifically, since engineered components such as water and energy infrastructures are often inanimate and thus cannot adapt by themselves, we echo the view of RE that the capacity of human organizations and the broader population to adapt themselves and flexibly manage built components in response to change is what truly makes the overall system resilient (although capacity for adaptive learning can exist in inanimate components of cyber-physical systems). This adaptive capacity, in turn, depends upon a variety of less visible, nonmaterial features such as people's mental models, the design of governance (rules and norms), and social network structures (Folke, Hahn, Olsson, & Norberg, 2005), all of which can influence and can be influenced by designed structures.

To facilitate this synthesis, this paper proceeds as follows. In the following section, we provide the methodological approach used in this study. In section 3, we compare various principles for resilience discussed in the fields of social-ecological systems resilience and RE. We examine if there are principles currently widely accepted in social-ecological system resilience that might benefit the aim and ambitions within RE and their current status in RE. We organize them to suggest an updated list of general principles for RE and further suggest how they might co-occur and fit together.

2. METHODS

Any discussion of approaches to building resilience should start with a clear definition of "resilience of what to what" (Carpenter, Walker, Anderies, & Abel, 2001): what is included in the system boundary, what is a system performance of interest that needs to be maintained, and to which set of disturbances the system performance should develop resilience. Following this ground, we specify our focal system as a socio-technical or infrastructure-dependent system in which the role of built infrastructure is clearly present. The system boundary is, therefore, generalized to include the following multi-layered networks: layers of connected physical (built and natural) components over some spatial extent and one or more layers of social components that operate at some scale and level.

Adding to the complexity, the system boundary can entail coupling of several such multi-layered networks, e.g., interdependent system of human-water, human-power, and human-transportation infrastructure networks in a city.

The system output of interest is some performance measure (e.g., water availability per household per day) based on some benefit stream, the supply of which is largely dependent on but not limited to a shared built infrastructure. For example, residential water supply can be obtained through various means, including the services of specialized infrastructure providers (e.g., water utilities), private infrastructure (e.g., private pumping of groundwater), social capital (e.g., sharing of water among neighbors), and private market mechanisms (e.g., water kiosks, bottled water, etc.). A very broad set of disturbances is considered for resilience, spanning both natural and man-made disruptions, expected and unexpected ones, and ones that are internal (e.g., social conflicts) and external (e.g., extreme climate events) to the system boundary. In essence, we are interested in the principles for *general* resilience, which is about coping with uncertainty in all forms (Folke et al., 2010). Note that general resilience contrasts with *specified* resilience (ibid), which is the system capacity to maintain a certain system-level feature or output to a particular set of disturbances (e.g., those that are known and previously observed).

We also adopt an expanded view towards what can be considered as an infrastructure. Here, an infrastructure is broadly defined to be any physical or non-physical construct that is consciously designed by a society to serve a purpose (Anderies, 2014; Anderies, Janssen, & Ostrom, 2004; Yu et al., 2015). Under this broader definition, an infrastructure can be any physical (e.g., dams, power plants, transportation road networks), cyber (e.g., computerized control of subway trains), or regulatory (e.g., procedures, rules, or norms that are devised to shape human behavior) component that is designed to achieve a particular end. Thus, resilience of an infrastructure-dependent system depends not only on built or physical infrastructures, but also on the design and functioning of non-structural, regulatory components such as operation rules and governance structures crafted by a society. Such components may be understood as the “software” of the infrastructure-dependent system that enables the functioning of “hardware” comprised of physical and cyber components and human interactions with the environment.

2.1. Scoping of Principles for Building Resilience

We investigate what additional insights into the principles for RE can be gained from a comparative analysis with the social-ecological systems literature. The latter literature has a longer-standing discussion on the principles for enhancing resilience in complex self-organizing systems (R. Biggs et al., 2015), and thus can be a source of enrichment for the principles for RE. Despite this cross-learning potential, a recent review study showed that little cross-citation has occurred between RE and other bodies of resilience literature, including social-ecological resilience (Fraccascia, Giannoccaro, & Albino, 2018). But, of course, just because a principle is widely known in the social-ecological systems literature, it cannot be assumed automatically that it also applies to RE. We, therefore, evaluate such a principle based on what it brings to RE and how it might benefit the aims of RE. This will be achieved primarily through assessing whether notions related to such a principle are already recognized in RE and whether they are known to contribute to organizational adaptive capacity. To facilitate our comparative approach, we used a number of criteria to short-list publications that were carefully analyzed to make our analysis tractable. We chose articles, reports, or books that (1) clearly discuss and present a list of heuristics or principles for resilience in one or the other literature that are consistent with the Hollnagel’s definition of resilience (Erik Hollnagel et al., 2010) and the concept of general resilience (Folke et al., 2010); (2) are broad in scope, most often review studies; and (3) are authored by a number of scholars who are recognized and cited in one or the other literature. We combined these criteria and (4) our own experience to select relevant publications.

For the principles for RE, we selected six publications that meet our criteria: Hollnagel et al.(2006), Bruneau and Reinhorn (2004), Park et al.(2013), Francis and Bekera (2013), Lloyd's Register Foundation (Foundation, 2015), and Costella et al. (2009).These studies, led by scholars who are based in RE and safety and risk sciences, discuss a set of heuristics for enhancing resilience in complex systems dominated by built infrastructures. These studies also cover three major outlets of publication by RE scholars: *Risk Analysis*, *Reliability Engineering and System Safety*, and *Safety Science*. The resilience-enhancing principles given by these studies, which we discussed in the previous section, can be grouped into six recurring themes: reduce sensitivity, build reserve capacity, adapt to change, fast recovery, manage interdependencies in infrastructure, and foster safety culture (Table I).

For the principles discussed within the social-ecological resilience literature, we chose five publications that fit with our criteria: Anderies et al. (2006), Walker et al. (2006), Walker and Salt (2006), Carpenter et al.(2012), and Biggs et al. (2015). These studies are authored by researchers affiliated with the Resilience Alliance (www.resalliance.org), a prominent network of scholars that spearhead the research on social-ecological system resilience, and include a major source of publication for this type of research, *Ecology and Society*. Our review of the selected studies shows the principles suggested by them can be categorized into a few recurring themes (Table II). First, almost all the studies emphasize the importance of maintaining two forms of diversity: response diversity and functional diversity. Second, the importance of striking a balance between modularity and openness in system connectedness is underscored. Third, the presence of organizational abilities for monitoring, learning, and experimentation for adaptive management is highlighted to be important. Fourth, the need for better understanding of and management for complexity of systems to be governed is stressed, especially with respect to nonlinear transitions in system states, cross-scale or cross-level interactions, and potential tradeoffs in vulnerabilities arising from such interactions. Lastly, positive effects of intangible social assets such trust, leadership, social network, and polycentric governance are highlighted.

Before proceeding further, we acknowledge that the selected publications do not constitute an exhaustive list of studies on the subject. Also, the criteria used for selecting the publications and the categorization of principles by theme necessarily involve subjective interpretation. However, the list largely covers the important principles discussed in the two literature. Further, they represent a progression of ideas and capture moments of transition within the two literatures. Most importantly, these studies enable us to take a first step to compare the views of pioneers of RE and prominent Resilience Alliance thinkers for identifying a potentially more integrative set of RE principles.

Table I. Principles for resilience proposed by the Resilience Engineering (RE) community.

Recurring themes	Source	Principles for resilience
Reduce sensitivity	Bruneau & Reinhorn (2004)	Robustness
	Francis and Bekera (2013)	Absorptive capacity
Build reserve capacity	Bruneau & Reinhorn (2004)	Redundancy
Adapt to change	Bruneau & Reinhorn (2004)	Resourcefulness
	Francis and Bekera (2013)	Adaptive capacity
	Hollnagel et al. (E. Hollnagel et al., 2006)	Monitor, learn, respond, and anticipate
	Park et al. (Park et al., 2013)	Sense, learn, adapt, and anticipate

	Costella et al. (Costella et al., 2009)	Awareness, learning, and flexibility
	LRF (Lloyd's Register Foundation, 2015)	Monitor, learn, respond, and anticipate
Fast recovery	Bruneau & Reinhorn (2004)	Rapidity
	Francis and Bekera (2013)	Restorative capacity
Recognize interdependencies	LRF (Lloyd's Register Foundation, 2015)	Interdependencies in critical infrastructure
Foster safety culture	Costella et al. (Costella et al., 2009)	Top management commitment

Table II. Principles for resilience proposed by the social-ecological systems research community.

Recurring themes	Source	Principles for resilience
Maintain diversity	Walker and Salt (B. H. Walker & Salt, 2006) Walker et al.(2006), Carpenter et al. (Carpenter et al., 2012) Biggs et al. (R. Biggs et al., 2015)	Response diversity, functional diversity
	Anderies et al. (Anderies et al., 2006)	Response diversity
Manage connectivity	Walker and Salt (B. H. Walker & Salt, 2006)	Modularity
	Carpenter et al. (Carpenter et al., 2012)	Openness, modularity
	Biggs et al. (R. Biggs et al., 2015)	Connectivity (openness and modularity)
Encourage learning-by-doing	Walker and Salt (B. H. Walker & Salt, 2006)	Tightness in feedbacks (monitor and respond), innovation (learning and experimentation)
	Walker et al.(B Walker et al., 2006)	Learning, experimentation
	Anderies et al. (Anderies et al., 2006)	Interventions (monitor and respond)
	Carpenter et al. (Carpenter et al., 2012)	Monitoring
	Biggs et al. (R. Biggs et al., 2015)	Learning, experimentation
Manage for complexity	Walker and Salt (B. H. Walker & Salt, 2006)	Slow variables
	Walker et al.(B Walker et al., 2006)	Adaptive cycle, cross-scale interactions, fast and slow variables, critical 3-5 variables, tradeoffs in resilience or vulnerability, mental models, multiple stable attractors
	Anderies et al. (Anderies et al., 2006)	Slow variables, cross-scale interactions, tradeoffs in resilience or vulnerability, mental models
	Carpenter et al. (Carpenter et al., 2012)	Feedbacks
	Biggs et al. (R. Biggs et al., 2015)	Slow variables and feedbacks, complex adaptive systems
Foster social capital	Walker and Salt (B. H. Walker & Salt, 2006)	Social capital (trust, social network, leadership)
	Walker et al.(B Walker et al., 2006)	Leadership, trust, social networks
	Anderies et al. (Anderies et al., 2006), Carpenter et al. (Carpenter et al., 2012)	Leadership, trust
	Biggs et al. (R. Biggs et al., 2015)	Participation
Polycentric governance	Walker and Salt (B. H. Walker & Salt, 2006)	Nested governance
	Walker et al.(B Walker et al., 2006)	Overlap in governance
	Carpenter et al. (Carpenter et al., 2012), Biggs et al. (R. Biggs et al., 2015)	Polycentric governance

	Anderies et al. (Anderies et al., 2006)	Flexible and dynamic institutional/governance structures

3. COMPARATIVE ANALYSIS

In the following subsections, we provide a brief introduction to well-established principles for building social-ecological resilience (Table 2) and discuss their current status in and relevance to RE. We end each subsection with our suggestions on whether inclusion of a corresponding principle to RE would be beneficial to the field.

3.1. Maintain Diversity

Maintenance of diversity is regarded as a key foundation for building resilience in complex self-organizing systems. Two types of diversity contribute to resilience. *Response diversity* occurs when multiple components of a system have similar functions (functional redundancy) but respond differently to a given disturbance (Elmqvist et al., 2003). Response diversity provides an insurance effect, i.e., even if a component cannot withstand a disturbance and fails to perform, other components that have the same function may withstand it and still allow the overall system to perform. *Functional diversity* refers to variation in system components' traits or functions. When system components have more diversity in traits or functions, they are more likely to be complementary to one another (Scheffer, 2009). This complementarity may enhance overall system performance, because the more different types of traits or functions there are, the more outputs and activities are likely to be generated in a system through synergistic or complementary combinations of these diverse features. For example, functional diversity can stimulate the capacity for adaptation and innovation. If a group is comprised of individuals with diverse traits, experiences, or resources, it may be able to more effectively deal with unexpected events or complex problems than a homogenous group does. However, too much response or functional diversity can also lead to issues (R. Biggs et al., 2015). That is, these two types of diversity should be maintained at a level that strikes a balance between the danger of rigidity (associated with little diversity) and that of inefficiencies (associated with too much diversity). In social systems, too little diversity can lead to group think and a siloed perspective, whereas too much diversity can result in fragmentation and inability to progress (Elinor Ostrom, 2008).

3.1.1. Importance of Diversity in RE

Redundancy (i.e., functionally redundant components with response diversity to a disruption) has been recognized as one of the key principles for RE and the broader safety and risk sciences (Bruneau et al., 2003; Tierney, 2008), in particular with regards to engineered safety features, such as redundant parts and backup resources, that prevent component failures in systems from causing a system-wide accident. An underlying idea is that, through better engineered safety features and preventive measures, the degree of substitutability among system components are strengthened to enhance robustness to component failures. An example is how most medical care facilities in the US are required to have enough reserve assets (e.g., backup electricity generators, water storage tanks) to remain operational during the first 96 hours after public utility failures caused by a disaster (Commission, 2009). RE also recognizes that non-physical components, such as organizational rules, guidelines, and work procedures, can be designed to build response diversity (Bergström et al., 2015). One of the key characteristics of RE is its focus on how humans (not technical components) deal with difficult tradeoffs in situations characterized by high stakes and complexity. This can include instilling variations or tiered approach into organizational rules, regulations, guidelines, work procedures, etc. to more tolerably respond to a wide variety of disruptions. Rationing of water, electricity, or human resources by applying a set of tiered rules that reflect the severity of situations highlights the point of how rules can be designed to perform a same function but exhibit response diversity (e.g., Xiao, Sanderson, Clayton, & Venkatesh, 2010). For example, some farmer-managed irrigation systems that operate on water diversion structure and distribution networks (weirs and canals) adaptively switch their water distribution rules to buffer the impact of water shortages (Cifdaloz, Regmi, Anderies, & Rodriguez, 2010). When the supply of water from river to irrigation canals is abundant, farmers freely take water anytime (open-flow distribution rule). But when available water gets scarcer, farmers activate a tiered response by taking water in a certain order (sequential distribution rule) or in time-restricted rotations (12-hour and 24-hour rotation distribution rules). These rules are functionally redundant. However, for a given level of water shortage, these variations in rules lead to different outcomes in terms of the total crop yield of the whole system.

Functional diversity is recognized within RE and related studies, in particular with reference to how variations and complementarity in the skills and experience of the front-end staffs and decision makers can contribute to adaptive capacity under complex situations (Bergström et al., 2015; Gomes, Borges, Huber, & Carvalho, 2014). It is important to note that diversity in system components' traits or functions that are other than organizational competence can also lead to complementary effects that otherwise cannot be achieved with homogeneous components. An example is how numerous communities in the US employ a host of different measures to deal with flood hazards (EPA, 2014; Loucks, 2015). Structural measures such as dams and levees contain high waters. Non-structural measures such as forecasting and flood warning, flood insurance, building and planning codes, buy-outs of properties, and rules for evacuation contribute to functions that are not directly related to containing high waters. Yet, these other functions can be just as important for reducing vulnerabilities to flooding. Compared to a community that uniformly relies only on flood control structures, a community that adopts diverse measures from structural and non-structural options is less likely to be vulnerable to floods due to their complementary effects. Aerts et al. found that developing portfolios of infrastructure investments (physical and social) that diversify risk can reduce the overall risk of the system (Aerts, Botzen, Veen, Krywkow, & Werners, 2008).

Diversity, both in terms of response and functions, can influence self-organization of societal response. For example, response diversity in infrastructure components can lead to overlaps or redundancies in infrastructure services. This redundancy gives individuals an 'exit' option (Hirschman, 1970) that can have far-reaching effects on the way that these infrastructure services are managed over time. When individuals perceive declining quality in infrastructure service (either in performance or reliability), they will likely exit or switch to another similar infrastructure provider or relocate to where a better performing infrastructure exists, i.e., vote with their feet (Tiebout, 1956). Aggregation of these individual responses can give a powerful feedback to infrastructure providers to enhance the performance and reliability of their infrastructure services. As for functional diversity, variations and complementarity in the skills and experience of organizational staffs and in the coping measures used by them can help infrastructure-dependent systems to self-organize and better adapt under unexpected circumstances (Naikar & Elix, 2019).

In summary, both response and functional diversities are well recognized within RE. Whereas traditional safety management tended to focus on response diversity in the form of engineered safety features and overlook functional diversity in organizational features, RE promotes variations in terms of both response and functions to meet its aim of fostering ability to respond to change and surprise (Bergström et al., 2015). Thus, RE stands to gain from clearer and more explicit incorporation of both forms of diversity into its general principles. An aspect that can be further elaborated and emphasized by RE is that response and functional diversities in rules, work procedures, or institutional arrangements (regulatory infrastructure), not just in technical components (physical or cyber infrastructure) and the front-end staff and management team competence (human capital), can contribute to resilience.

3.2. Manage Connectivity

Connectivity is defined here as a multi-layered network of built components and processes and a nested hierarchy of interacting social units that function to produce and distribute a continuous flow of essential goods and services (e.g., water, energy, mobility, etc.) for the broader society. Two features of connectivity influence resilience in complex systems that provide such essential services. *Modularity* refers to the degree of compartmentalization in a system (B. H. Walker & Salt, 2006). *Openness* refers to the ease with which diffusion can proceed within and across a system (Carpenter et al., 2012). The specifics of how modularity and openness affects resilience depend on the context, i.e., the nature of nodes and links in the connected system structure. When nodes and links represent physical components and flows of resources (e.g., water, energy, or output from a node is an input to another) respectively, modularity can enhance resilience because a highly compartmentalized system is less likely to be impacted by failures of other (sub-) systems due to its low dependency on others. In comparison, an overly open or connected system can be fragile because disturbances can spread more quickly and more broadly across the system (R. Biggs et al., 2015). When nodes and links represent social agents and their interactions (e.g., exchange of information or cooperative relationship among front-end staffs across organizations), openness can support resilience because better flow of knowledge or networks of direct or generalized exchange (Bearman, 1997) can facilitate self-organization towards faster recovery and a more effective response under unexpected disturbances. However, when links deal with the harms that diffuse through social interactions (e.g., false information, computer virus, etc.), too much openness in the system structure can undermine resilience (R. Biggs et al., 2015). As such, regardless of context, identifying the optimal level of modularity and openness is important.

An important related notion is the problem of “fit” in social-ecological networks (Ö. Bodin, 2017; Folke, Pritchard, Berkes, Colding, & Svedin, 2007). The problem of social-ecological fit pertains to how well the structure of a collaborative social network aligns with the specifics of the environmental problem being addressed or with the structure of the biophysical system being governed (ibid). The temporal and spatial extents of ecosystem processes often span beyond the boundaries of a collaborative network of stakeholders. A misfit occurs when the collaborative governance network takes into account only a part of such temporal or spatial extents of ecosystem processes. This can lead to an environmental problem. Further, the level of fit in a social-ecological network may directly affect the capacity of human or social nodes to self-organize, i.e., how well they can coordinate with each other for some objective related to the governance of biophysical nodes (Ö. Bodin & Tengö, 2012).

3.2.1. Importance of Connectivity in RE

Our assessment is that modularity and openness are recognized to be important in the RE and the broader safety literature (e.g., Holmgren, 2006), although these two features are not explicitly mentioned in some of the widely-accepted general principles for RE. This recognition is evident from studies related to resilience of and cascading failures in coupled infrastructure systems. For example, a number of studies investigated how the structure of connectivity in a system (e.g., scale-free, random, etc.) can impact robustness against failures such as blackout of a station in electric power grids (Kim, Eisenberg, Chun, & Park, 2017; Nan & Sansavini, 2017; Schneider, Yazdani, Araújo, Havlin, & Herrmann, 2013; Vespignani, 2010). Furthermore, in systems involving multiple coupled networks (e.g., power and telecommunications networks), interdependencies across those networks can make the system vulnerable to cascading failure (Ash & Newth, 2007; Bashan, Berezin, Buldyrev, & Havlin, 2013). For example, Buldyrev et al. (Buldyrev, Parshani, Paul, Stanley, & Havlin, 2010) present a model of recursive failure between power stations and an Internet network due to the interdependency of nodes within each network as well as across the two networks.

Above examples emphasize how openness combined with certain network structures can induce failures that are more extensive than identified risks in a system design. To overcome these large-scale failures that are difficult to be pre-identified, instilling modularity into the network structure has been suggested to be crucial for resilient infrastructure networks. For example, a micro-grid, which is a module with a group of interconnected loads and distributed energy sources, can be disconnected from the entire grid system and operate as an island-mode in emergency conditions to maintain the power supply to local customers (Hussain, Bui, & Kim, 2019; Li, Shahidehpour, Aminifar, Alabdulwahab, & Al-Turki, 2017). When the earthquake occurred in Fukushima in March 2011, power supply was stopped to the Sendai region, resulting in a three-day power outage. However, the Sendai micro-grid (a prototype grid project located in the Tohoku Fukushi University campus) could continuously supply power to several critical loads within the campus and provide full power service for few days following a blackout (Marnay et al., 2015).

The problem of "fit" of governance in infrastructure-dependent systems and how such a fit affects adaptive capacity of human-related nodes is also recognized within RE and related studies. In this genre of studies, the central nature is how resilience or macro-level performance of a system is affected by the alignment among the collaborative structure of social agents and their incentives and the physical structure of an infrastructure system being managed. For example, Cedergren et al. (2018) examined how the management and operation of a railroad system in Sweden are deregulated among multiple organizations and how this multi-actor setting creates unforeseen coordination problems among involved organizations during emergency situations due to misaligned incentives and consideration among them and the infrastructure characteristics. Another example is Eisenberg et al. (2017), which showed that, by analyzing the betweenness of a power grid and emergency management organizations, the functional hubs of infrastructure and organization network do not always accord with each other. Based on this finding, they suggest ways to improve response to emergency by connecting key components of both networks. Thus, the capacity of human-related nodes in infrastructure networks to self-organize and adapt, including reactivating inactive nodes in times of crisis and improvising nodes or links when they fail to function in the system (Janssen et al., 2006) may depend on achieving the "right fit" among structural and non-structural networks.

To sum it up, system connectedness characteristics and the fit of governance with a system being governed are appreciated within RE because of their influence on adaptive margins and the macro-level outcomes of social interactions in infrastructure-dependent systems. Thus, a more integrative view on these connectedness-related features and how they are combined with other supporting conditions to promote adaptive capacity will be informative to RE. On this ground, we suggest inclusion of system connectedness characteristics and the fit of governance with a system being governed to RE principles.

3.3. Encourage Learning-By-Doing

Resilience Alliance scholars have long highlighted that constant learning and probing of the limits or boundaries of system operation are critical for dealing with uncertainty in the management of complex systems (Polasky, Carpenter, Folke, & Keeler, 2011). Hence, learning-focused management approaches such as adaptive management (Lee, 1993; Walters & Holling, 1990), adaptive co-management (Armitage, Marschke, & Plummer, 2008), and adaptive governance (Folke et al., 2005) have drawn much attention among researchers and practitioners as a method for putting resilience into practice. Core processes that are common to these approaches are monitoring, experimentation, and learning, i.e., learning-by-doing (R. Biggs et al., 2012). *Monitoring* provides information about internal system states and external environment. *Experimentation* involves deliberate small changes to a system process or structure to observe and compare outcomes. *Learning* is the process of updating existing knowledge, governance goals, or management strategies based upon the results of monitoring and experimentation. These three processes work together to operationalize learning-by-doing. Note that learning can be influenced by the structure of connectivity among social nodes (discussed in Sub-section 3.2) because of its effect on the ease of knowledge transfer and opportunities for collaborative learning. However, the aspects of learning discussed in the current Sub-section are distinct in that the focus is on how learning can enable adaptive management (which is a way to deal with uncertainty) and how different types of learning can facilitate the process.

3.3.1. Importance of Learning-By-Doing in RE

Since a key goal of RE is to maintain system performance under both expected and unexpected disturbances, almost all of the existing principles for RE reflect some aspects of learning-by-doing (E. Hollnagel et al., 2006; Park et al., 2013). However, there are two subtle differences. First, whereas the role of experimentation is emphasized in the principles for social-ecological resilience, it is visibly absent in the principles for RE. This is because allowing deliberate small-scale failures or change is difficult, if not impossible, in most physical systems (although modeling can help to some degree) which provide benefit streams such as water, energy, and mobility that are basic to human wellbeing. This absence of experimentation contradicts how RE scholars have called for a paradigm shift from rigid fail-safe systems to more flexible safe-fail systems (Miller, Chester, & Muñoz-Erickson, 2018; Park, Seager, & Rao, 2011).

Second, there is relatively little discussion of the details of how learning should be encouraged to enhance adaptive capacity for resilience, i.e., what type of learning works and under what conditions. This gap has been noted in Hollnagel (2008) who points out that “a concrete solution [on learning] requires careful consideration of which data to learn from, when to learn, and how learning should show itself in the organization” Even beyond this, it is important to see that different types of learning can exist, such as individual learning, social learning, single-loop learning, and double-loop learning (Argyris & Schön, 1978; Reed et al., 2010), and that these can have varying effects on how social groups self-organize in terms of adaptive capacity. Learning can be either individual or social depending on how the learning takes place (Armitage et al., 2008). Individual learning occurs when knowledge is obtained by an individual, not by a collective. Social learning occurs when learning takes place in a group through collaborative interactions and knowledge is internalized and stabilized at a group level (Chudek & Henrich, 2011). Learning-by-doing can also operate at two extents: single-loop and double-loop learning (Pahl-Wostl, 2009). Single-loop learning is about “are we doing things right?” In single-loop learning, monitoring and experimentation take place in order to better meet existing goals. Double-loop learning concerns the question “are we doing the right things?” In double-loop learning, learning processes lead to updating and revising of underlying goals or assumptions. Empirical evidence shows that social groups that frequently underwent double-loop learning tend to be more resilient under extreme disturbances in comparison to groups that focused on single-loop learning (Yu, Shin, Pérez, Anderies, & Janssen, 2016).

In summary, RE regards learning to be central for building resilience and coping with uncertainty. RE explicitly mentions capacity for learning as one of cornerstones of resilient systems. Notions that can be further elaborated and emphasized by RE principles include: there are nuances among different types of learning and their varying effects; probing boundaries of system operation through deliberate management experiments and learning from the experience (i.e., adaptive management) can be helpful for building resilience; and promotion of social learning is important in nurturing adaptive capacity at a collective level.

3.4. Manage for Complexity

Awareness among actors of the properties of complex adaptive systems (Holland, 2006) is important in nurturing the capacity of the actors to manage for resilience (R. Biggs et al., 2015). Properties of complex adaptive systems relevant to social-ecological systems include self-organization, the existence of alternate stable states and thresholds that separate them, rapid non-linear transitions between such alternate states, slow-varying variables that determine when critical feedbacks lead to alternate stable states, multi-level and multi-scale interactions, tradeoffs in resilience, and power-law scaling behavior (Folke, 2006; Folke et al., 2010; Mitchell, 2009; Scheffer, 2009). The lack of appreciation among decision makers of these properties is often the reason why attempts are made to tightly regulate social-ecological systems under the idealistic assumption that these systems are tractable and predictable in the long-run. This kind of command-and-control approach is attributed as the key reason why self-organizing systems gradually lose resilience (Holling & Meffe, 1996).

An important property of complexity is the potential presence of alternate stable states and the critical thresholds that mark rapid transitions between these states. Alternate stable states, which may exhibit hysteresis or not-easily-reversible changes, are a hallmark of ecological resilience and arise as a result of a system's self-organization into qualitatively different configurations. Classic examples of resilience are derived from this phenomenon, e.g., critical transitions between clear and eutrophic states of lakes and grassy and shrubby states of rangelands (Folke et al., 2004). The existence of thresholds or tipping points, the locations of non-linear transitions between those states, has long been recognized in complex systems modeling, but it is still challenging to predict such points in real-world systems. As a result, scholars have sought to identify early warning signs that indicate that a system may be approaching such a point, and recent work has generated a variety of signals that have consistently appeared in a variety of complex systems (Dakos, Carpenter, Nes, Scheffer, & Dakos, 2015). Several of those indicators are collectively referred to as "critical slowing down" (Scheffer et al., 2009) and can be statistically identified as increased autocorrelation, slower recovery, increased variance, flickering, and skewness in system states after small perturbations.

The concepts of multi-scale and multi-level processes and panarchy also indicate how complex social-ecological systems can be (Allen, Angeler, Garmestani, Gunderson, & Holling, 2014; Brian Walker, Holling, Carpenter, & Kinzig, 2004). More often than not, these systems are managed with a narrow scope, i.e., at a particular scale or level of dynamics that is of interest to managers. However, complexity can be much higher in reality because these systems are connected to processes and feedbacks that operate at other scales and levels (e.g., global system processes, household-level processes, etc.). These feedbacks can originate at both higher and lower scales and can lead to surprises and unintended outcomes in the system of interest. Panarchy highlights the importance of cross-level or cross-scale interactions in determining outcomes in social-ecological systems, i.e., how a dynamics at a focal scale and level is shaped by processes operating at the level above or below. A classic example is how the long-term dynamics of a forest ecosystem (cycle of destruction by forest-wide fire, revegetation, and maturation into a dense forest) is influenced by the memories from above (surviving species found in the wider landscape) and the revolts from below (patch-level burning by wildfire) (Allen et al., 2014; L. H. Gunderson & Holling, 2001).

It is also important to realize that tradeoffs among different vulnerabilities can occur in social-ecological systems as a result of design choices. Decisions to alter system design to reduce vulnerability to a particular disturbance regime may lead to amplified vulnerabilities to disturbances in other domains because of the interplay between design and self-organization (Csete & Doyle, 2002; Janssen & Anderies, 2007). One of the underlying questions of social-ecological resilience thinking asks “resilience of what to what” (Carpenter et al., 2001), and this implicitly acknowledges that strategies to increase the resilience (or reduce the vulnerability) of a particular aspect of social-ecological system to a specific set of disturbances may cause the system to be more vulnerable in other ways. Thus, vulnerabilities cannot be eliminated; they are merely shifted around different domains with design choice (Anderies, 2015). This notion is particularly true in light of the previous principle of multi-scalar feedbacks and interactions; focusing on the short-term resilience of a system output over narrow spatial scale has been cited as particularly problematic for losing long-term resilience (Carpenter, Brock, Folke, van Nes, & Scheffer, 2015; Chelleri, Waters, Olazabal, & Minucci, 2015).

Further, phenomena from various natural, social, or engineered systems have shown to exhibit power-law distributions and scaling behavior: a relatively small number of extremely large-scale events, a very large number of events with a wide range of diversity in impact or size, and self-similarity or scale-free pattern in the size distributions of such events (Mitchell, 2009). Although such phenomena are very different in nature and origin (e.g., income distribution, disasters, river networks, drainage infrastructure networks, etc.), the power-law is a regularity that can be held to hold among them (Levin, 1998). Power-law distributions mean that such phenomena do not have meaningful averages, signifying that there will be low-probability, large-scale events that are inherently unpredictable. Several generative mechanisms have been proposed to explain power-law distributions, including positive feedback loops or preferential attachment (i.e., “rich gets richer” process), self-organized criticality (i.e., how a system drives itself over time to a critical state beyond which outbursts of activity occur), and highly-optimized tolerance (i.e., how system vulnerabilities are shifted around different domains as a result of fine-tuning system design) (Carlson & Doyle, 2002; Mitchell, 2009).

3.4.1. Importance of Managing for Complexity in RE

Complexity of socio-technical system is well recognized by RE and related studies (Lloyd’s Register Foundation, 2015). The multi-scale and multi-level nature of such systems involved in risk management is at the core of RE. For example, Rasmussen (Jens Rasmussen, 1997) and subsequent studies (Costella et al., 2009) highlight that multiple organizational levels and different disciplinary perspectives or unit of analysis are often involved in socio-technical system dynamics. Feedback loops or interactions across several such scales and levels in a system imply that one cannot fully comprehend, anticipate or prevent system accidents. In line with this notion is Normal Accident Theory (Perrow, 1981, 1999), a well-known concept in the safety science community. Based on the analysis of organizational features of those involved in a major nuclear accident, Normal Accident Theory concludes that accidents or failures are inevitable (or ‘normal’) and cannot be anticipated in some types of technological systems because of two system properties: complex interactions and tightly coupled nature. According to this theory, complex interactions in a system are driven by factors such as the presence of multi-functionality components, specialized knowledge of front-end staff that limit their awareness of inter-dependencies, physical proximity of components; and unfamiliar or unintended feedback loops that make analysis difficult. Tight coupling occurs when there is little leeway in terms of time system processes, little variation in the sequence of system processing, little buffer or slack is available in resources and equipment, and little flexibility and redundancy in system design, components, and personnel, among others (Perrow, 1999; Shrivastava et al., 2009). Typically, tight coupling is exacerbated when only efficiency is pursued, making systems management locked in a rigidity trap (L. Gunderson & Holling, 2002). On a different note, a recently study on urban water systems security also showed that focusing entirely on local level resilience and ignoring interactions across multiple scales can lead to an incomplete analysis of system dynamics (E. H. Krueger, Borchardt, Jawitz, & Rao, 2020; E. Krueger, Rao, & Borchardt, 2019). Only when multi-level and multi-scale dynamics are considered, a more complete characterization of urban water system dynamics is possible in terms of security, resilience, and sustainability.

Also relevant to RE and safety and risk sciences are difficult tradeoffs (often between safety objectives and economic objectives) in situations characterized by high stakes and complexity. Such tradeoffs exist not only between costs and risks stemming from different engineering design choices but also among different risks or vulnerabilities (Aven, 2017; Carlson & Doyle, 2002; David Woods, Schenk, & Allen, 2008). Risk or vulnerability tradeoffs can emerge through interplays between engineering design and self-organization in the long-run (Ishtiaque, Sangwan, & Yu, 2017). Logan et al. (Logan et al., 2018) makes this point clear by illustrating that quantitative risk assessments around hard-adaptive measures that ignore behavioral feedbacks (e.g., increased economic activities on floodplains) and long-term changes in natural system states (e.g., increased land-sea level difference) can lead to an inaccurate assessment of flood risk in the long-run. Another case in point is how an extended period of drought caused a change in operation rules of a reservoir infrastructure to put greater operational focus on water conservation than flood prevention (Di Baldassarre, Martinez, Kalantari, & Viglione, 2017). This study argues that while such a change might have reduced risks to droughts, it can also increase risks to extreme flood events.

In contrast, there is little discussion within RE about the potential for alternate stable states and critical transitions between them, presumably because these are thought to be irrelevant to the built or technological components and organizations directly involved in their daily operations and management. However, if and when time scale of analysis is extended to decadal, centennial or longer time levels, aspects of alternate stable states and critical transitions may matter to infrastructure-dependent systems (e.g., Anderies, 2006; Kuil, Carr, Viglione, Prskawetz, & Blöschl, 2016). For example, Anderies (Anderies, 2006) uses a mathematical model to explain why an agricultural society that constructed, expanded, and heavily relied on a complex network of irrigation infrastructure might have collapsed in the past. He argues that the presence of water infrastructure might have caused a path dependency or lock-in towards continued expansion of canals and greater reliance on the infrastructure to increase and stabilize agricultural production in order to keep up with increasing population. This might have created two alternate stable states (functional vs. collapsed) and caused gradual erosion of the resilience of the functional regime, making the system especially vulnerable to extended droughts. In infrastructure-dependent systems, an infrastructure might induce a path dependency or lock-in towards alternate stable states and gradual loss of resilience (Markolf et al., 2018).

In summary, different features of complexity are acknowledged within RE and regarded as a chief cause of irreducible uncertainty in the dynamics of infrastructure-dependent systems. Notions about these features motivate the significance of RE and why the perspectives of RE can complement the approach of traditional safety management. As such, awareness among decision makers about the complex adaptive systems nature (Holland, 2006) of infrastructure-dependent systems is important to nurturing safety culture and organizational ability for resilience. On this ground, we suggest that RE stands to gain from incorporating into its general principles aspects about complex interactions (multi-scale and multi-level) and tradeoffs in risks or vulnerability stemming from design choices and self-organization. However, aspects of alternate stable states, which are integral to social-ecological systems resilience, seem to be of less relevance to RE and, thus, we think that they are unnecessary for inclusion in RE principles.

3.5. Foster Social Capital

The resilience literature refers to social capital in several inter-related ways—as a form of capital, as trust and leadership, as a social network, and as participation (R. Biggs et al., 2015; Brondizio, Ostrom, & Young, 2009). These features of social organization facilitate cooperation for mutual benefits and, thus, enhance the ability of groups to solve collective action problems (E Ostrom & Ahn, 2003; Putnam, 1993) and gain the resources essential for restoring services and meeting the needs of disaster survivors (Mayunga, 2007). Social capital can also be understood as the positive effects and outcomes achieved through the development and nurturing of relationships and interactions among various individuals, social groups, organizations, and entities within a community (Aldrich & Meyer, 2015; Cutter, Burton, & Emrich, 2010) that are derived through formal and informal ties or networks that form before, during, or after disturbances (Aldrich, 2010). The degree of cooperation and collaboration resulting from these ties partially determines the extent to which individuals and organizations are able to collectively enhance social capital (Mayunga, 2007). Such social ties can take three forms: bonding, bridging, or linking (Aldrich & Meyer, 2015; Hawkins & Maurer, 2010; Woolcock, 2002). Previous research has defined and measured these ties in various ways and some of the more widely applied definitions, such as those offered by Woodcock (2002) and Nakagawa and Shaw (2004), describe the types of actors and how their interactions serve to address a diverse range of post-disaster issues. They, along with other scholars, define bonding as ties that exist between familiar individuals and organizations that facilitate the existence of a strong sense of community. These ties often exist between an individual's close relatives, friends, or those one frequently interacts with in a community such as a neighbor, teacher, or co-worker (Molinas, 2002; Nakagawa & Shaw, 2004). Bridging includes social capital stemming from established networks between more distant individuals, such as acquaintances, that are often dissimilar in terms of their geographic location or socio-demographic characteristics, but still have comparable social status and values (Aldrich & Meyer, 2015; Nakagawa & Shaw, 2004; Newell, Tansley, & Huang, 2004). Previous studies suggest that these types of collaborations can enhance social capital through the diversification of information availability, resources, and services that may be needed in the aftermath of a disaster (Andrew, Arlikatti, Siebeneck, Pongponrat, & Jaikampan, 2016). Lastly, linking refers to the establishment of alliances or relationships between individuals or communities and formal organizations such as public agencies, private entities, and non-profit stakeholders in positions of power or authority (Molinas, 2002; Woolcock, 2002).

The social capacity derived through these social network-based capital is essential in the enhancement of social-ecological resilience to disasters, as these relationships provide individuals, organizations, and communities access to resources that may otherwise not be available through other means (W Neil Adger, Hughes, Folke, Carpenter, & Rockström, 2005). Adger (N. W. Adger, 2003) argues that networks and capacities fostered through these ties promote a shared management of social capital, which in-turn enhances the ability of individuals and communities to coordinate and share resources needed when carrying out mitigation, preparedness, response, and recovery activities. As such, social capital can be thought of a key enabler of the ability to meet ones needs and access resources by leveraging relationships. In this sense, one could argue that social capital promotes response diversity and redundancy in social systems, i.e., such relationships allow disaster-affected people to achieve the same function (meeting their needs) even when individuals do not have their own resources.

Trust and leadership facilitate cooperative behavior and reduce the cost of working together. As a result, they enable innovation and adaptive decision-making (Gutiérrez, Hilborn, & Defeo, 2011). All resilience-building principles discussed in this paper that relate to governance—not just in the title, like polycentricity, but also learning-by-doing, building connectivity and diversity in decision-making—require strong leadership for shaping desired outcomes. Leadership facilitates involvement and improves decision-making. Olsson et al.(2004) discuss the importance of leadership in the transformation of social-ecological systems, where transformation is a radical change to a more sustainable regime. Experimentation, whether adaptive or transformative, requires trust and leadership (Cundill, 2010).

Institutional arrangements are also part of social capital. Institutional arrangements are formal and informal rules of the game that guide what actions are allowed or prohibited, by whom, and under what conditions during human interactions with one another (North, 1990). They are crafted and used by human society because they bring structure and predictability to such interactions, thereby reducing the transaction cost of exchange among parties and supporting functioning of societal systems (ibid). Further, institutional arrangements are also developed to govern how humans use technological and ecological systems that are shared by many, e.g., rules for operating transportation road networks, levees and reservoirs (Anderies, Janssen, & Schlager, 2016; Yu et al., 2015; Yu, Sangwan, Sung, Chen, & Merwade, 2017).

3.5.1. Importance of Social Capital in RE

Several studies related to RE acknowledge and discuss the beneficial roles of trust, leadership, or social networks for resilience (Aldrich, 2012; Costella et al., 2009; Davoudi, Brooks, & Mehmood, 2013). The role and importance of institutional arrangements for the rapid recovery of infrastructure-dependent systems is also noted within RE (Cedergren et al., 2018). However, the consideration of such social capital elements tend to be scattered across the literature and are yet to be explicitly included as part of RE principles.

One primary goal of RE is to improve the safety and functionality of the various systems within a given environment to withstand the effect of chronic or sudden adverse events (D. D. Woods & Hollnagel, 2017). The environment, regardless of scale, is comprised of various systems that are often interdependent with one another. While RE places emphasis on the restoration of various systems and infrastructure in response to disruptions, such as disasters, it also recognizes that these processes are closely tied to the human and social systems that are embedded within the environment (Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008). Within emergency management and hazards literature, Murphy (2007) proposed that social capital, which can be derived from networks of strong and weak ties, is a vital resource for improving community resilience. Wickes et al. (2015) suggested that the level of social capital in communities, in combination with the structure of vulnerability, is associated with perceived community resilience. Manifested through specific indicators such as associational relationships, community belonging, social norms, and trust, social capital provides a mechanism for community members to become active agents in organizing their activities and gaining access to resources (W. N. Adger, 2000; Barton, 1969). The capacity of a location to withstand the adverse impacts of disaster is highly dependent on the "networked social communities and lifeline systems" existing within that community…" (Godschalk, 2003). To that end, linkages between various social networks play a critical role in the strengthening of social capital and the resilience of the physical environment within a community.

In understanding the effects of social capital on the resilience of an infrastructure-dependent system, we see multiple causal connections. Many of the other principles for influencing resilience affect social capital. For instance, the multiple perspectives engendered by increasing diversity—through strengthening social networks, expanding on diversity of knowledge and ways of knowing, or engaging diverse stakeholder groups—can build social capital. Likewise, increasing connectivity through bonding and bridging relationships in a network can build social capital. Broadening participation, in general, may also increase social capital (Cundill, 2010). Strengthening the social capital of individuals, communities, organizations, and stakeholders can also introduce redundancy into social and physical systems, thereby enhancing disaster resilience (Tierney, 2008). Building on the ideas mentioned previously, broadened participation increases diversity of perspectives and builds knowledge. All of these are seen as enhancing resilience (R. Biggs et al., 2015).

At the same time, social capital facilitates other resilience-building principles. Social capital builds the trust between groups of people that is required to allow for experimentation and learning-by-doing (N. W. Adger, 2003). Similarly, accountability increases trust and social capital through the building of legitimacy, and characteristics are essential for effective polycentric governance (R. Biggs et al., 2015). In short, social capital facilitates collective action which in turn improves many of the other variables—connectivity of groups of people, broadening diversity of knowledge, world views, and alternative mental models. These variables undergird the foundation for polycentric governance systems which will be discussed in the next subsection.

In a nutshell, various elements of social capital reduce the cost of collaboration or exchange among actors within and across multiple levels of organizations working towards a related task. Since prevention and recovery of many system accidents and failures often involve multiple stakeholders' participation and collaboration, social capital can play a central role in promoting system resilience through facilitation of such coordinated group actions. Furthermore, given that one of the key characteristics of RE is its focus on human organizational ability for variability management, social capital with its positive effects on collaborative group actions is highly relevant to RE. On this ground, we suggest formal inclusion of social capital into RE principles.

3.6. Polycentric Governance

A form of governance structure termed *polycentricity* is thought to be an important contextual condition relevant to system resilience (R. Biggs et al., 2015). Polycentric governance systems are characterized by multiple centers of decision making which operate semi-independently but with the ability to interact and affect one another (Carlisle & Gruby, 2017). These centers operate at multiple levels, leading to a nested, overlapping structure with horizontal (at the same scale) and vertical (across scale) ties. It has been suggested that this structure may offer a middle-ground between completely centralized and truly decentralized or community-based governance (Imperial, 1999). Most importantly, the components of a polycentric governance system are able to consider each other and react, both cooperatively and competitively (V. Ostrom, Tiebout, & Warren, 1961). Polycentric governance systems have been lauded in the social-ecological resilience literature for a variety of reasons, with much attention paid to: the ability of polycentric systems to adapt to change, the "goodness of institutional fit" provided by polycentric systems, and the "safe-fail" nature of semi-redundant governance systems (R. Biggs et al., 2015).

3.6.1 Importance of Polycentric Governance in RE

The role and importance of governance is noted by the risk literature, so much so that there is a strand of research called risk governance (Van Asselt & Renn, 2011). A particular structure of governance, termed polycentric governance, is also recognized by some conceptual studies within RE. These studies refer to the concept as *polycentric control architecture* and acknowledge the beneficial effects of the architecture on the adaptive operation of infrastructure systems under uncertainty (Branlat & Woods, 2010; D. D. Woods & Branlat, 2010). These studies view polycentric control architecture as the presence of multiple centers of control that are interdependent and situated at different scales or levels of an overall system, each of which operates with some degree of autonomy. This allows various decision centers to independently set and adapt their goals and associated plans and make decisions by taking the relationships with other centers into consideration (ibid). As a result, polycentric architecture facilitates better "fit" or matching between control and local context through empowerment of local control centers.

This type of control architecture is likely to be effective under disaster situations because of the need to match disaster responses to local context, a high degree of uncertainty and chaos that require autonomous adaptations (Forsyth & Evans, 2013), and the need to coordinate numerous control units at local level over wider geographic and jurisdictional extents and the involvement of control units at higher levels of organization (D. D. Woods & Shattuck, 2000). Further, polycentricity allows each control center to create and maintain some margin of maneuverability in ways that reflect its own circumstances, a buffering cushion of actions and resources that help each subsystem as well as the overarching system to continue functioning in the face of unexpected situations (David Woods & Branlat, 2011). Failure to maintain margin leaves the overall system with little resourcefulness when prompt responses are needed to deal with acute, low-probability events.

Polycentric governance matters to the resilience of infrastructure-dependent systems because such systems are often part of polycentric nexus of interconnected semi-autonomous organizations, engineering infrastructures and natural processes. As Wood and Branlat (D. D. Woods & Branlat, 2010) suggest, centralized control of such a system can be problematic because of the risk of over-homogenizing responses to system components that are disparate (i.e., the problem of fit) and the risk of information and decision bottlenecks in the apex control center in times of crisis. Fully decentralized control can be also problematic because of the risk of system components operating in silos and the risk of missing links in vertical and horizontal interactions that can prove to be fatal in times of crisis. Polycentric control or governance structure offers a middle-ground between the two architectures and contributes to resilience due to its advantages in matching governance levels to the scale of the problem and in inducing self-correcting mechanisms through overlaps and diversity in responses (R. Biggs et al., 2015). Of course, these strengths of polycentricity come with related costs (Schoon, Robards, Meek, & Galaz, 2015). The primary challenge is in balancing the benefits of redundancy with the costs of this duplicative effort. There are also increases in transaction costs required to coordinate between multiple governing bodies.

These costs come both from the added redundancy and focus on place-based decision-making within a center of decision-making.

Polycentric governance affects resilience in other ways too. Like the earlier discussion about social capital, polycentric governance both affects and is affected by other resilience-enabling principles. As with building social capital, polycentric governance facilitates learning and experimentation, enabling failures in one sphere of governance to rebuild off of the experience of other spheres at similar levels or others. It provides a mechanism, similar to federalism, in that multiple experiments can be tried, and successes emulated (Schoon et al., 2015). In effect, it adds in redundancy to minimize failure and correct mistakes that are inevitable in the process of governance in complex systems. This, in effect, provides a means of increasing response diversity. Additionally, in its structure, polycentric governance improves connectivity while building modularity.

In summary, although the notion of polycentric structure of governance is not widespread in RE, it is certainly noted and discussed in the field. Polycentricity is relevant to RE given its advantages in matching governance levels to the scale of the problem and in inducing self-correcting mechanisms through overlaps and diversity in responses. Because of the integral role of polycentricity in supporting other conditions related to adaptive capacity, promotion of polycentricity in an infrastructure-dependent system presents a strong case for inclusion into RE principles.

4. IMPLICATIONS FOR PRINCIPLES FOR RESILIENCE ENGINEERING

Our comparative analysis of the resilience-enhancing principles in the preceding section reveals the following points about the state-of-the-art in RE and the broader risk and safety-related field in comparison to the social-ecological systems resilience community. The importance of redundancy (response diversity) and learning and adaptation are both well recognized and explicitly mentioned as part of resilience-enhancing principles. The effects of different system connectedness characteristics (openness, modularity, and coupling of networks) and different forms of social capital (trust, participation, and collaborative social network) are well recognized and discussed within the field, but they are yet to be clearly packaged into RE principles. A similar pattern is observed with regards to polycentric governance, functional diversity, experimentation and social learning, the role of institutional arrangements, and the problem of fit involving social networks and governance. These aspects are noted by RE and the broader risk and safety sciences but yet to clearly appear as RE principles. Also, how all these various conditions collectively fit together to bring about resilience has been elusive in the field.

How can the lessons and the opportunities presented by this comparative analysis be applied to better inform future RE studies and practices? We contend that organizing a more comprehensive set of resilience-enhancing principles that incorporate the results of our analysis can be useful in this regard. The rationale is that the conditions discussed here are consistently suggested to be relevant for resilience because of their positive influence on the adaptive capacity of social systems (R. Biggs et al., 2015; Ö. Bodin, 2017; R. Bodin, 2006; Carpenter et al., 2012; Polasky et al., 2011; D. D. Woods & Branlat, 2010). As a start and building on the pioneering work of RE and Resilience Alliance theorists, the following tentative messages for RE principles emerge from our work:

- **Recognize that system context matters (P1).** An infrastructure and its operating organization in isolation cannot fully reflect resilience—they are embedded within broader social, ecological, and technological contexts that are constantly in flux with infrastructure systems. Focusing on built systems and operating organizations only and failure to account for feedbacks involving broader systems are a cause of many of the recurring problems in infrastructure-dependent systems. Thus, system boundaries under consideration should not only cover the focal infrastructure and organizations directly responsible for operation, but should also reflect linkages with other technical networks, natural processes, and linked user and governance organizations at levels above or below the focal organizational scale. Further, this principle warns against blueprint panacea types of interventions or thinking, i.e., technical designs or regulatory designs (design of rules, regulations, and work procedures) that work in one setting do not necessarily mean they will also work in other contextual settings.

- **Foster social capital (P2).** Social capital includes intangible, but important, group-shared assets such as trust, broad participation, collaborative social networks, and formal and informal institutional arrangements. Social capital matters for resilience because of the beneficial effects on the links that connect social-to-social or social-to-physical (built or natural) nodes. These effects take on various forms, including capacity for reactivating inactive nodes in times of crisis, capacity for improvising and adapting nodes or links when they fail to function, and protocols of interaction that increase the predictability (hence, reduce the cost) of such interactions. Thus, social capital enables infrastructure-dependent systems to extend capacity, self-organize, and still function when disturbances push them to the brink of or beyond the limits of their designed robustness.

- **Maintain diversity (P3)**. Redundancy (response diversity) and functional diversity matter for resilience because of their insurance and complementary effects, respectively. Systems with high levels of redundancy and functional diversity are generally more resilient than ones that are low in these two attributes. However, too much heterogeneity (high levels of redundancy or functional diversity) can also lead to inefficiencies, which may undermine adaptive capacity. It is also important to note that redundancy and functional diversity not only exist in physical components but also in social capital or regulatory infrastructure (e.g., redundancy or diversity in institutional arrangements and social ties) and human capital (e.g., diversity in actors' backgrounds and experience).

- **Manage connectivity (P4).** Connectivity enhances resilience by facilitating exchange of knowledge and resources and collaborative interactions among social nodes, all of which can contribute to rapid recovery after disruptions and adaptive capacity to deal with unexpected disturbances. However, a caveat is that an overly connected system can also be vulnerable because disturbances can spread more quickly across built or cyber nodes and because of potential homogenization or loss of diversity in social nodes. Context matters for specific aspects of connectivity structure ideal for resilience. Openness in connectivity is generally beneficial to resilience when connectivity concerns exchange of knowledge, resources for recovery, or cooperative relationships. Modularity in connectivity is better for resilience when it concerns functional interdependency, i.e., situations where an input critical to the functioning of each node depends on an output from or the state of another. Modularity is also better for resilience when connectivity involves diffusion processes that are potentially harmful (e.g., epidemic disease, software viruses, erroneous information, etc.).

- **Encourage learning-by-doing (P5).** Learning contributes to resilience because of its beneficial role in decision-making under uncertainty. Important features of learning that should be noted more by RE are experimentation and social learning. Experimentation involves deliberate allowance of small-scale failures for awareness raising and for probing the boundaries or limits of system resilience. Social learning is a type of learning that occurs when knowledge is gained and shared collectively by a group. Social learning is critical for the updating of institutional arrangements and social goals and underlying assumptions. Experimentation and social learning jointly work for building resilience.

- **Embrace polycentric control (P6).** Polycentric structure in governance or system control means that there are multiple decision units operating in a specific geographic area or level of jurisdiction, each of which operates with some degree of autonomy. Each unit may be connected horizontally with other units to work on a common issue or interact vertically with other units that are nested within a hierarchical governance system. Polycentric governance has been considered a key principle for building resilience because of its advantages in matching governance levels to the scale of the problem and in encouraging self-correcting mechanisms through redundancy and diversity in governance structures.

- **Address the problem of fit (P7).** The problem of fit pertains to how well the structure of a collaborative social network aligns with the structure of the built or natural system being governed (fit involving social networks) or how well the design of institutional arrangements matches with the scale or nature of the problem being addressed (fit involving institutional arrangements). A lack of such a fit can lead to problems and erosions in resilience because it means that a governance system only manages a part of the physical world or does not fully account for the extents of ecological processes or technical aspects. A high level of fit can enable social nodes to better coordinate with one another and appropriately respond to a problem.

- **Manage for complexity (P8)**. A step towards building resilience requires a shift in actors' underlying mental models that acknowledge the complex adaptive systems nature of an infrastructure-dependent system being governed. Approaches based on the linear, reductionist thinking is often a root cause of erosions in resilience. Relevant sub-principles are as follows.

  Consider multiple scales and levels and their linkages. It is important to understand how the focal scale of interest is linked to other scales, e.g., approaches that increase a localized system's efficiency and robustness in a short-time scale might increase long-term vulnerability to processes that operate at a larger spatial or longer time scale. It is also important to understand how the focal level of a scale influences the levels above or below, e.g., approaches that reduce vulnerability at household level might undermine resilience at community level.

  Understand robustness-vulnerability tradeoffs. While engineering for robustness is certainly important and required, it is also important to realize that enhancing robustness (or reducing vulnerability) to particular types of shocks can lead to increased vulnerabilities in other domains because of self-organization. That is, vulnerabilities cannot be eliminated. They are merely shifted across domains. Such robustness-vulnerability tradeoffs are an inherent feature of systems governed by regulatory feedback controls. Thus, social systems should nurture capacity for detecting and navigating through robustness-vulnerability tradeoffs that inevitably appear as risk profiles change.

  Pay attention to interdependencies or coupling of multiple infrastructure networks. Interdependencies of infrastructure networks can take various forms, including physical (the state of each infrastructure depends on the output from or the state of the other), geographic (parts of two or more infrastructure networks are co-located or in close proximity), cyber (the state of an infrastructure depends on information generated by information infrastructure), and logical (two infrastructures affect the state of each other via human decisions or social processes). These interdependencies affect resilience because of their influence on how localized failures might cascade through the system.

Equally important is understanding how these principles work collectively to influence resilience. Implementing any one principle in isolation will likely not lead to increased resilience of infrastructure-dependent systems (R. Biggs et al., 2015). In this respect, we contend that the principles listed above can be thought of as a set of enabling or second-order conditions under which the first-order system abilities associated with resilience emerge. Although exploratory, we suggest that the following conceptual model (Fig. 1) can be useful to illustrate potential relationships among various RE principles and that these tend to be consistent with the notions and findings from a variety of disciplines (R. Biggs et al., 2015; Francis & Bekera, 2014; SRA, 2018).

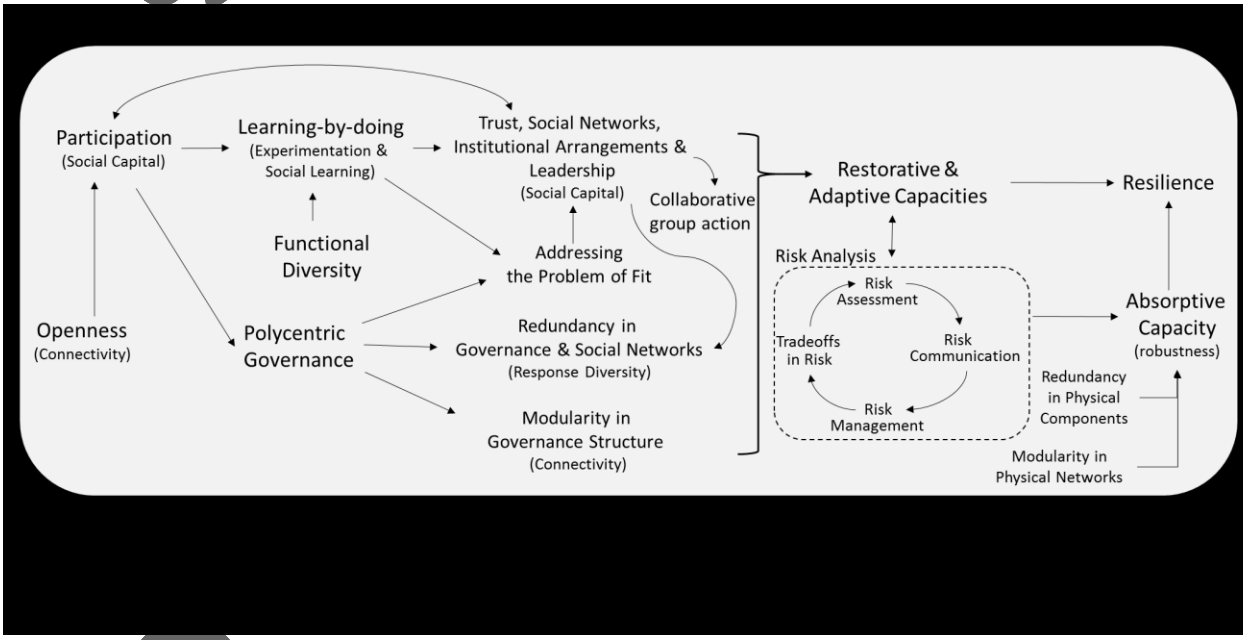

Fig. 1. Interrelationships among the principles towards building resilience in infrastructure-dependent systems. The figure shows a plausible set of interconnected second-order conditions through which three first-order system abilities for resilience (robustness or absorptive capacity, adaptive capacity, and restorative capacity) emerge.

As can be seen in Fig. 1, high levels of trust among social actors and openness in social connectivity provide an environment where active stakeholder participation or co-management occurs. Such participation is a precondition for learning-by-doing, especially in the form of social learning. However, participation alone is not sufficient for effective learning to arise. When participation occurs in combination with functional diversity in social actors, more effective learning becomes possible. When this type of learning occurs systematically through cycles of experimentation and social learning, knowledge and experience are attained at group or collective level. This enables groups to further accumulate social capital—trust, broad participation, formal and informal rules, shared goals and underlying assumptions, collaborative social ties, among others. The resulting gain in social capital not only promotes cooperation (which is critical for social capacity for adaptation and fast recovery) and redundancy in social networks (through more collaborative social ties and bonding) but also feeds back to reinforce learning by encouraging greater participation. Participation is also a precondition for implementing polycentric governance. Modular governance structures associated with polycentricity generate overlaps or redundancy in the services and functions of governance. This redundancy in the governance layer enhances resilience because when a governance unit at a particular level fails, vertically-linked broader levels of governance or horizontally-linked units at the same level can step in and provide support. Next, polycentric governance and learning-by-doing act together to provide an environment where potential problems of fit between governance design or social network and technological system being governed can be proactively detected and addressed. What emerge holistically from these dependencies among principles are more adaptive capacity for the unknown and unknowable and more capacity for rapid recovery following great stress. Of course, the full manifestation of the pathways described is not an inevitable result of any of the first-order principles described above. For example, again drawing on work in cities as infrastructure-dependent systems, we see that stakeholder engagement in agenda-setting initiatives is as power-laden as any contested process (Bryson & Slotterback, 2016; Dahl, 1989; Jacobs, 2014). Therefore, scholars of resilience must seek openness, trust, and learning-by-doing with a constant eye to participatory justice in negotiated system dynamics.

With respect to the built system or technological part, absorptive capacity (and hence, robustness) can be imbued into physical infrastructure through engineering design based on a probabilistic risk assessment and some acceptable level of risk to a set of anticipated hazards, e.g., design of a levee system protecting a riverine city based on past records. Absorptive capacity can be further enhanced by instilling redundancy and modularity in the connectedness of physical components, e.g., improved engineered safety features of a production system. Note that these properties of redundancy and modularity in physical components are distinct from redundancy and modularity in governance and social networks (which, in most part, contribute to adaptive and restorative capacities). Furthermore, with shifting risk profiles under the changing environment and society, new risks and vulnerabilities emerge and may make existing design no longer effective or even a source of the problem itself (Carlson & Doyle, 2002; D. D. Woods, 2016). Thus, capacity for timely and effective risk analysis, which includes assessment and characterization of emergent risks, risk communication, and risk management (e.g., updating of engineering design in a timely manner to respond to changes in risk), becomes extremely important for maintaining absorptive capacity. Organizational adaptive capacity can facilitate a cycle of continuous risk analysis to effectively navigate through such tradeoffs in risk, i.e., ability to anticipate and take proactive measures to engineered systems to update absorptive capacity. Finally, the principle for recognizing that system context matters and the principle for managing for complexity contribute to all other principles. These two principles facilitate actors to better appreciate other principles and to more effectively implement them.

Putting all these pieces together, we have portrayed a more encompassing map on how the first-order abilities described by the R4 Framework (absorptive capacity, adaptive capacity, and capacity for fast recovery) and the four cornerstones of RE (abilities for monitoring, learning, adapting, and anticipation) and their variants may be facilitated by co-occurrences and dependencies among various supporting conditions reflected in the RE principles we organized. This second-order insight provides a clearer picture of plausible conditions under which infrastructure-dependent systems can self-organize to develop more general resilience.

5. CONCLUSIONS AND WAYS FORWARD

Maintaining the performance of infrastructure-dependent systems under known and unknown threats is a grand challenge. Addressing this challenge requires enhancement of general resilience in these systems, which is about building capacity to deal with a broad range of shocks, including unexpected and extreme ones (Folke, 2016). Hence, we argue that better understanding of general principles that promote resilience in a universal way and bringing them to the forefront of Resilience Engineering (RE) can make a valuable contribution to meeting this important goal.

There is a growing body of work about the principles for resilience in both RE and social-ecological system studies (R. Biggs et al., 2015; Lloyd's Register Foundation, 2015). Although some of the principles do overlap, there are distinct differences in the two lines of research. By comparing and synthesizing the knowledge developed in them, we made some tentative suggestions about a more comprehensive set of resilience-enhancing principles for RE. We examined whether there are principles currently widely accepted in social-ecological system resilience that might benefit the aim and ambitions within RE and whether and how such principles are currently discussed in RE and safety sciences. We took this approach because of the partly self-organizing nature of infrastructure-dependent systems. Thus, the field of RE stands to gain from incorporating the principles-related insights from the field of social-ecological system resilience (which focuses on the dynamics of complex self-organized systems). Specifically, our approach has been to organize scattered discussions about supporting conditions linked to basic system or organizational qualities related to resilience and delineate how such conditions are dependent on one another and collectively fit together to engender resilience. The following tentative propositions for RE principles emerged from our comparative analysis: (P1) recognize that system context matters, (P2) foster social capital, (P3) maintain diversity, (P4) manage connectivity, (P5) encourage learning-by-doing, (P6) embrace polycentric control, (P7) address the problem of fit or match the scale of a problem to that of governance and collaborative networks, and (P8) manage for complexity by considering multiple scales and levels involved in system dynamics, potential robustness-vulnerability tradeoffs, and interdependencies among multiple infrastructure networks. We also argued that these principles do not occur in isolation and that they tend to influence one another. For example, presence of a polycentric control can affect diversity, connectivity, and the problem of fit in a system because of potential overlaps and nestedness in involved governance units. In this spirit, we presented an exploratory conceptual model (Fig. 1) of potential interlinkages among the proposed RE principles and how they may operate in combination with one another and with risk analysis to engender general resilience.

We also suggest multiple ways forward for future research. Future studies should investigate how the RE principles can be applied in diverse contexts. At the most basic level, there is a need for identifying practical strategies for implementing the principles in ways that fit with local situation and capacity. One can also investigate the necessity and sufficiency conditions of these RE principles. For example, are all of these principles necessary to build general resilience? Or are some RE principles particularly more relevant for building resilience for certain types of infrastructure-dependent systems? Empirical studies on how the specifics of a RE principle influence the interplay of design and self-organization is another important area of research. For example, a recent study used a controlled behavioral experiment with human participants to develop insights into what type of learning works and under what conditions for fostering resilience in an infrastructure-dependent system (Yu, Shin, et al., 2016). In addition, quantification of general resilience in infrastructure-dependent systems is a much needed research area that could benefit from a more comprehensive set of RE principles. For example, the general resilience of an urban water system can be quantified using a set of capital portfolios (e.g., physical capital, social capital, governance capital, etc.) in ways that reflect some of the RE principles discussed here (e.g., E. Krueger et al., 2019).

Another important consideration for future research is that achieving general resilience to a broad range of disturbances is likely to be too costly or even infeasible compared achieving specified resilience to a well-defined set of disturbances. Limited budgets often force decision makers to navigate difficult tradeoffs regarding how much resilience is needed in what dimensions and to what disturbances. Thus, a more realistic option could be a complementary use of both risk analysis and resilience approach (Anderies, Folke, Walker, & Ostrom, 2013; Aven, 2019; Yu, Rao, et al., 2016). For example, in a foreseeable time period, decision makers can achieve robustness or specified resilience (if the system has multi-stability behavior) by carefully considering disturbances that are known. A probabilistic risk assessment as part of risk analysis is and will continue to be important for informing this process. However, decision makers in resilient systems would not remain idle or satisfied with just achieving short-term robustness. In parallel, they would engage in a cycle of continuous risk analyses with resilience principles to dynamically update system robustness to deal with emerging risks. In the process, they would actively communicate and engage with other stakeholders to co-implement anticipatory or recovery measures. This continual updating of short-term robustness (or specified resilience) to changing conditions can approximate general resilience in the long-run. Future studies should look into how risk analysis and resilience strategies can be applied in tandem to operationalize general resilience and how RE principles can be put into practice to facilitate this complementary use.

One aspect that has been little discussed in this study is how RE principles might influence the transformability of an infrastructure-dependent system, the “capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable” (Brian Walker et al., 2004). Transformability is part of the three core dimensions of resilience that are widely recognized in the field of social-ecological system resilience (persistence, adaptability, and transformability) (Folke, 2016). Is transformability also relevant to RE? It is important to realize that, just like social-ecological systems, infrastructure-dependent systems can undergo transformations to have new identity and function. For example, a former railway overpass in New York and a former highway overpass in Seoul, South Korea have been transformed into elevated linear parks and greenways to serve a new purpose (provision of an environmental amenity) because their former function (provision of a transportation space) became obsolete or untenable (Millington, 2015; Shafray, 2018). Infrastructure-dependent systems can also undergo transformations for a limited time period, e.g., temporary conversions of large public facilities such as community centers into shelters for housing evacuees in times of disasters (Arlikatti, Andrew, Kendra, & Prater, 2015). Because built components cannot transform themselves to have new identity and function, social systems’ ability to initiate and implement such a transformative change becomes extremely important when situations call for drastic changes.

Future research, therefore, should focus on uncovering empirical cases of transformations in infrastructure-dependent systems in diverse contexts and potential effects that RE principles may have had on the transformability of these systems. We conjecture that the same RE principles for adaptability are also applicable to transformability (e.g., functional diversity, openness in social connectivity, etc.). This is because whether a system change is perceived as a transformation or adaptation depends on how the focal system boundary is defined (Johnson et al., 2018). For example, in the case of the conversion of a highway overpass in Seoul, it can be viewed as a transformation if the system boundary for analysis is narrowly defined to focus on the highway overpass and communities immediately surrounding the structure. However, the same change can be also viewed as an adaptation if the system boundary for analysis is expanded to cover the entire city. This is because the identity and function of the city remain qualitatively the same. As such, there is only a fine line between what constitutes transformability and adaptability.

Finally, we hope that we have clearly communicated that building general resilience has no magic formula or blueprint panacea. Rather, we have identified principles for building resilience in the design, management and governance of a system. Implementation is not simple, nor is success ensured, however, reaching goals benefits from a clear map. Our intent has been to provide one.

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