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Engineering meets institutions: an interdisciplinary approach to management of resilience

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Abstract

AQ1 Resilience management stretches across the decoupled domains of community, corporate, and public governance. As a result, fostering resilience needs a governance structure that supports collective actions and integrates fragmented fields with different institutional frameworks. In this study, we carry out a review of three different perspectives on resilience -engineering, social, and organizational- in order to explore resilience management in the context of governance of infrastructure systems. We discuss the common practices to address resilience of engineering systems, the need and current trend for integration of institutions into these practices through formal (e.g., policies and regulations) as well as informal mechanisms (e.g., trust, norms, and shared cognitive structures). To illustrate our theorizing, we provide three illustrative case studies. The cases highlight the barriers and enablers across the three perspectives and highlight the inter-organizational context of management of resilience. We uncovered organizational dynamics such as the necessity of establishing critical functionality through organizational capacity for stakeholder engagement, the need for diverse organizations to address institutional complexity in management of resilience, and the importance of decoupling in aligning the outcomes of resilience management practices with policies. We suggest an agenda for future research on managing practices associated with management of resilience.

Keywords Resilience · Collective action · Governance · Communities · Institutions · Infrastructure systems

1 Introduction

AQ2 Communities constantly face risks and threats, including unexpected natural or man-made events such as extreme weather events or global conflicts. The extent of development and resource utilization has reduced the potential reserve capacity to cope with these often synchronous failures (Homer-Dixon et al. 2015). Given the impossibility of defending against all possible risks, general resilience—the ability to deal with various disturbances and adapt to

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change (Folke 2006)—remains a critical goal across different communities. To date, several advances have been made within academia to develop means for operationalizing resilience, including development of heuristics for enhancing resilience (e.g., Hollnagel and Woods 2006; Walker and Salt 2006; Biggs et al. 2012; Ayyub 2014; Aldrich and Meyer 2015) and metrics for quantifying resilience and impact assessment (e.g., Bruneau et al. 2003; Miles and Chang 2006; Cimellaro et al. 2010; Cutter et al. 2010; Bonstrom and Corotis 2014; McAllister 2015; Hosseini et al. 2016; Choi et al. 2017). However, heuristics and metrics for how to manage resilience still remain largely theoretical.

Management of resilience is an approach that tries to ensure the desired operation of systems under varying conditions (e.g., recovering form shocks or performing under stressors). This approach includes application of means such as resilience heuristics, frameworks, and metrics to counsel practice. In other words, this process includes a shift from theories to policies, then to practices, and finally to outcomes. With respect to the built environment, efforts to manage resilience associated with the infrastructure systems often do not give enough consideration to the role of institutional frameworks within communities and their interplay with the function of infrastructure systems in yielding positive system outcomes (Opdyke et al. 2017a). Current approaches lack social and organizational context of the built environment, especially the institutional regulative, normative, and cognitive elements (Scott 2001). In common language, the term institution is used interchangeably with the term organization. However, it should be noted that in this paper, the term institution is used to refer to social constructs that shape human behaviors and interactions (North 1991; Orr and Scott 2008). To address their absence from existing efforts, models, heuristics, and metrics need to be adapted to further consider the impact of institutions in managing resilience in the context of infrastructure systems.

On the other hand, a systematic approach to resilience is rarely within the boundary of a single organization (Opdyke et al. 2017b, Mian et al. 2018). As a result, the path to operationalize resilience will involve multiple organizations, which often adhere to different sets of institutions such as practices, norms, and values, forming divergent and even conflicting institutional logics (Thornton et al. 2012). For example, metrics developed by an organization based on one interpretation of resilience enhancement principles are prone to be misunderstood in practice by other organizations that have different institutional backgrounds. Therefore, there is a need not to just focus on development of generic and overarching engineering tools, but to account for how the collective process of enhancing resilience should be organized and managed within specific contexts. Addressing this need requires inter-disciplinary approach and acknowledgment of the enabling and constraining power of social institutions as well as opportunities to foster new formal (e.g., laws and regulations) and informal (e.g., shared cognitive structures, norms) institutions to achieve collective action among diverse participants. This interdisciplinary approach should cover the process of theoretical understanding of the concept, or sensemaking of this understanding within each context, up to development of policies according to theories, and finally establishing practices to enhance resilience.

In this paper, we examine resilience management in view of three different perspectives. First, we provide a review of engineering perspective with a heavy focus on engineering and technical solutions that currently dominates efforts to move resilience from concept to practice. The second two perspectives, which we call "social" and "organizational" are presented to summarize the institutional dimensions that are critical for achieving resilience. To better instantiate our theoretical arguments within the three perspectives, we explore three cases across the world as empirical support for theories regarding management of resilience engineering. Specifically, we limited the scope to discussions on the resilience engineering principles in the context of the development and operation of infrastructure systems. We then conclude our review with proposing a path forward for research and practice towards management of resilience.

2 Three perspective to resilience management

AQ3 Scholars have proposed a wide range of definitions for resilience as a result of a varied application of the term across different disciplines (Baggio et al. 2015; Opdyke et al. 2017a, b). The definition of the concept and its implications has been evolved by numerous disciplines including material science, engineering, ecology, psychology, business, and organizational studies. The majority of the definitions of resilience stem from ecological resilience (Holling 1973) and engineering resilience (Pimm 1984) as an approach to conceptualize system or group response to disturbances (Vale 2014). We explore the implications of definitions within the engineering perspective, before we move to social and organizational perspectives to further understand the path from definitions and theories to outcomes in the context of resilience management.

2.1 Engineering perspective

AQ4 Many scholars based in engineering, ecological, and social resilience domains have taken a reductionist approach to identify principles of resilience (Jackson 2016). These efforts involved substantial progress on what broadly constitutes the principles and systematic attributes of resilience (e.g., Hollnagel and Woods 2006; Walker and Salt 2006;

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MCEER 2010; Aldrich 2012; Biggs et al. 2012; Park et al. 2013; Ayyub 2014; Aldrich and Meyer 2015). The focus on identifying heuristics or principles for enhancing resilience includes a collection of physical and process oriented principles that are posited to dictate system resilience, that among all include redundancy, modularity, loose coupling, and threat detection (Jackson 2016). For example, Bruneau et al. (2003) identifies robustness, redundancy, resourcefulness, and rapidity as key properties of resilient structural systems. These principles can be used in modelling resilience and can be integrated directly into pre-existing systems, particularly in terms of mainstreaming the concept. However, three challenges are observed in the use of these principles in practice, as (i) knowledge generated based on these principles tends to be still theoretical and abstract (Chang et al. 2014), (ii) quantification and simulation of elements of resilience that are not easily parameterized is a barrier in practice, and (iii) shared understanding of the principles across different organizations is not emphasized. These challenges exist despite the fact that definitions of resilience from the engineering perspective acknowledge the human behavioral dimension of resilience (e.g., Hollnagel and Woods 2006). In fact, early work by Timmerman (1981) on engineering resilience acknowledges resilience as a property of communities, not of structures. Therefore, the need for further integration of the social and organizational considerations into the engineering domain has been always integral to the concept of resilience, is still relevant, yet remains mainly undone.

AQ5 In addition, there is a stream of research focusing on the development of metrics to benchmark the level of resilience in the system and provide a shared direction for actions to enhance resilience. These metrics aim to act as tools to institutionalize resilience both in theoretical and practical fields. Metrics in engineering resilience are based on both quantitative data from engineering models, historical records, and qualitative data from experts and diverse stakeholders (Linkov et al. 2016). Existing quantitative approaches to resilience include metrics based on performance level and recovery time (Francis and Bekera 2014; Rad and Jahromi 2014; Chan and Schofer 2015; Levenberg et al. 2016) or input–output models (Haimes et al. 2005; and Pant et al. 2014). Unfortunately, many challenges exist in using metrics-based approaches to characterize resilience. These methods still do not sufficiently reflect the comprehensive picture of the interplay of social and physical systems, as well as organizational context to manage actions based on the interpretation of metrics. The data collection is challenged by lack of quantitative data, reliability of qualitative data, as well as limitations due to ethics and resources for data collection (Linkov et al. 2016). Other issues related to metrics-based approach include difficulty of quantifying emergent dynamics, as well as difficulties in translating the data and analysis into decisions, policies, practices, and changes in behaviors. The emphasis of metrics on attributes of physical or social system still lacks investigation of how such metrics and engineering tools are put into action, which is a matter of organizing the collective action among diverse parties. This lack compromises the practical efficiency of the metrics within and between organizations with diverse institutional structures. This is especially the case in the context of infrastructure systems, as their planning, development, and operation crosses community, corporate, and public domains. As a result, multiple organizations with conflicting institutional backgrounds and logics apply these definitions, principles, and metrics in management of infrastructure systems.

2.2 Social perspective

While the engineering domain provides a range of means to AQ6 shift from theories to practices, designing and maintaining resilience in the context of infrastructure systems remains as a collective effort (Yu et al. 2015). Therefore, it is not sufficient to build an infrastructure asset to withstand exogenous shocks (e.g., natural disasters), if the community using the asset cannot recover from or learn from and update their strategies for dealing with such shocks. Furthermore, exogenous shocks are not the only threats to the system, but also multiple factors endogenous to the community using the system may lead to malfunction of the system. In the other words, if the rules and norms, which may be understood as the “software” of infrastructure systems, are not collectively defined, followed and enforced, the coupled system (considering social, ecological, and technical entities) may be driven toward chaos. Theories from the institutional economics and political economy can be used to interpret the social context of resilience management.

Parallels has been drawn between many infrastructure AQ7 systems and shared community goods, in which design, operation, and management require collective action (Yu et al. 2015). To work toward collective gain of the whole community, sometimes mechanisms should nudge the individuals to look beyond their short-term self-interest gains. It is assumed that such behavior can be achieved by implementing governance, i.e., defining rules and norms and enforcing them (North 1991). Ostrom (1998) echoes a similar message in her behavioral approach to governance of collective action. Ostrom’s approach underlines the importance of social norms, such as trust and feeling of reciprocity, as potential informal or relational governance mechanisms (e.g., Dietz et al. 2003). The proposed approach recognizes that actors possess agentic capability to self-govern common pool resources by designing governance mechanisms and practices for and that their enforcement is not based only on coercive or legislative pressure but normative pressures, that

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is, what is considered socially acceptable within the community (Ostrom 1990). Such capability to self-organization is an essential hallmark of a resilient system (Holling 1973) or an anti-fragile system (Taleb 2012). Instances of collective governance discussed in Sect. 3, offer lessons for the social actions associated with resilience management in the context of infrastructure systems.

Essentially, self-governance and, therefore, resilience are based on the accumulated social capital within such socio-technical systems (Aldrich 2012). Social capital includes building mutual trust, reputation, and reciprocity between the actors designing, building, operating, and using the service of the systems. Social capital is not just an important enabler of self-governance (through situational or private institutions such as social norms), but also enabler of formal or legislative governance (through public institutions such as laws and regulations). The enabling dimension of social capital may be particularly important in the case of transnational threats to infrastructure systems such as climate change (Adger 2003).

2.3 Organizational perspective

Infrastructure systems are often governed across multiple public and corporate organizations that may not necessarily integrate direct inputs and decisions of the community. Noting that resilience of communities and performance of the associated infrastructure systems is strongly dependent on the actions of different private, public, and non-governmental organizations (Van der Vegt et al. 2015), we see it crucial to include aspects of organizational theory to understand these social constructs in resilience management. Social interaction and human cognition are the core focus of institutions in organizational theory. These views expand the definition of institutions to include also socially constructed cultural elements which, when enacted and reproduced, will maintain, enable, and create meaning to organizational activities and other aspects of social life (Greenwood et al. 2008; Thornton et al. 2012). In these views, it is assumed that organizations are embedded in an organizational field, which comprises for example for profit and non-governmental organizations, regulating agencies and legislators that form social and behavioral structure of the field (DiMaggio and Powell 1983). Organizational actors are seen as not just rationally bounded (March and Simon 1958), but also susceptible to symbolic and often irrational socially constructed and situational prescriptions of legitimacy (Meyer and Rowan 1977; Suchman 1995; Ariely 2008). Therefore, success and survival of organizations depend on their ability to appear legitimate within the field by complying, not just with the governing laws and regulations, but also with the existing socially constructed norms, beliefs, values, and taken-for-granted practices (Suchman 1995). Scott (2001) framed these social constructs as three distinct pillars of institutions, such as regulative (e.g., governing laws), normative (e.g., prevailing moral guidelines), and cultural-cognitive (e.g., socially constructed shared understandings about legitimate practices).

We posit at least three reasons why organizational perspective of institutions is beneficial to management of resilience. First, as we already argued, understanding the behavioral patterns that govern the role of institutions as behavioral frameworks is essential to build not only resilient technical systems, but also integrated social, ecological, and technical systems. In other words, one needs to consider institutional resilience of the society (Barin Cruz et al. 2016), or to solve a paradox of how local communities are capable of restoring not just physical infrastructure but the institutional infrastructure (as symbolic frameworks to support behavior and collective action) when the governing rules and regulations collapse or become less effective after a disturbance. For example, Cruz et al. (2016) investigated the attempts of a multinational microfinance organization to recover its cooperative banking operations in post-earthquake Haiti after the collapse of formal frameworks. The organization was able to utilize its strong structural and relational position to re-construct set of informal institutions (e.g., feel of solidarity, mutual trust, and will to cooperate) in helping to revitalize the Haitian cooperative banking sector (ibid.). This observation highlights the importance of deliberate institutional actions (Lawrence et al. 2013) to set up shared value bases and cooperative spirit in addition to building social capital (Aldrich 2012) to facilitate building resilient communities.

Another important topic of the discourse of institutions within organizational theory is to examine why organizations may deviate or decouple their actions from institutional prescriptions. In their seminal article, Meyer and Rowan (1977) argued that so called formal organizational structures may result from rationalized and socially constructed myths about efficiency, prevalent within the organizational field, when organizations often copy non-efficient forms from each other for legitimacy gains (i.e., to receive appraisal from field level organizations). Then to achieve actual efficiency in their operations, an organization decouples its operational practices from the ceremonially appraised formal structure (see Boxenbaum and Jonsson 2017; Bromley and Powell 2012). On the one hand, decoupling can help understand why certain resilience heuristics, metrics, guidelines, regulations, and policies do not necessarily result in the desired actions or outcomes which they target. In addition, decoupling can also prove as a deliberate strategy or form of self-organizing to build up resilience by covertly (or overtly) deviating from guiding rules of social life (Roberts 2004).

Thirdly, the more recent developments of organizational theory have started to account for the pluralism of

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institutional settings and have argued that organizations often face divergent and even conflicting institutional demands (for a recent review see Kraatz and Block 2017). This divergence can lead to institutional complexity, which may turn to problematic situations when organizational actors aim (but often fail) to comply with conflicting institutional requirements (Greenwood et al. 2011). This view can aid in the understanding of inter-institutional conflicts in a situation when two or more parties which are adhered to different prescriptions of legitimate action or institutional logic (Friedland and Alford 1991; Thornton and Ocasio 1999) fail to find shared understanding of the problem or a solution they seek to address. Resilience research as large can be seen as institutionally pluralistic when different research traditions based on different epistemological and ontological assumptions meet and seek to jointly address the concept of resilience (Baggio et al. 2015; Olsson et al. 2015). On the practical level of resilience management, institutional pluralist lens can explain for example why institutionally divergent parties (e.g., disaster recovery NGOs, for-profit companies, or local political parties) may fail to cooperate in situations such as proactive resilience enhancement efforts, or reactive post-disaster management. This explanation will be based on the core idea of institutional complexity or difficulties in constructing consensus on legitimate course of actions (Hällgren et al. 2017).

2.4 Summary

In Table 1, we have summarized these three different theoretical discourse and potential perspective they might offer to management of resilience. As illustrated in the table, we acknowledge that these three perspectives share rather distinct epistemological and ontological stances as well as definitions and key-metaphor of resilience. However, we do not want to get caught in an ontological battle, nor do we want to forcefully combine these three views into a holistic grand theory on resilience. Such forceful actions would, without a doubt, lead to favoring certain perspectives while silencing the voices of others (sometimes referred as scientific imperialism; see, e.g., Dupré 1996). Instead, our quest here is based, more or less, on the philosophical underpinning of instrumentalism, which values problem solving capacity of theoretical claims and is willing to accept unifying alternative and even competing theories and scientific traditions to help solving practical problems (Dewey 1938; Laudan 1977). In the following section, we provide three empirical examples how these views may help us to understand challenges of managing resilience in infrastructure systems.

3 Illustrative empirical cases

In this section, we describe three empirical examples of the management of resilience in the context of the infrastructure systems to further explore the discussed perspectives. We aim to point out how different institutional factors affected management of design, building, operation, and recovery of these systems.

3.1 Case 1: Fukushima: institutional misfits in designing the power plant and responding to the nuclear catastrophe

Japan suffered compounded disasters on 11 March 2011 involving a massive 9.0 magnitude earthquake, a major tsunami, and subsequent meltdowns at the Fukushima Daiichi Nuclear Power Plant. Nuclear safety is a critical issue in Japan, which has strong regulations and a long history of developing and operating nuclear power plants. Furthermore, Japanese nuclear engineers regularly travel around the world to provide training on issues of nuclear safety and management and have sought to sell training and technology in countries like Turkey, Korea, Ghana, and Vietnam. Despite safety systems and the hard work of management and personnel at the Fukushima Dai-ichi Plant, nuclear

Table 1 Three perspectives to resilience

	Engineering perspective	Social perspective	Organizational perspective
Generic characteristic	Rational	Bounded rational	Social constructivist
Basic metaphor	Resilience as designable process	Resilience as governance of collective action (formal and informal)	Resilience as shared meaning within and among organizations
Key argument	Return to the steady-stable state after disruption	Social capital and collective governance	Institutional complexity, Institutional logic, Decoupling
Fundamental theory	Decision making, Systems theory	Institutional economics/ Political economics	Organizational sociology/ Neo-institutional theory
Key references	Hollnagel and Woods (2006)	Ostrom (1998), Aldrich (2012)	Thornton et al. (2012)
Potential discourse in the context of resilience	Metrics, Heuristics	Policies	Strategies

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meltdowns at three of the six reactors forced the evacuation of more than 150,000 people from Fukushima prefecture and requires a decades' long process to decommission and decontaminate the facility. Many of the nearby villages, such as Futaba and Okuma, remain uninhabited 7 years after the disaster. We look into the Fukushima nuclear meltdowns to underscore the critical role played by regulatory and governance institutions in resilience.

At 3:37 p.m. on 11 March 2011, after a series of smaller waves, a 13 m (42 feet) tsunami overtopped the 5.5 m (18 foot) seawalls at the Fukushima Dai-ichi Nuclear Power Plant and flooded the entire site, which sat at sea level right next to the ocean. Tokyo Electric Power Company, or TEPCO, had worked with central government bureaucrats to site the facility on the coast because of a lack of opposition to the plant and weakening civil society organizations in the area (Aldrich 2008). In the late 1960s, engineers set up backup cooling mechanisms at Fukushima based on the typical North American approach to disasters; the placement of the cooling systems could prevent a meltdown in the event of a power loss to the main cooling systems. In the United States, risks to nuclear power plants were extreme weather events such as tornadoes. As a result, the diesel generators at Fukushima Dai-ichi sat on the first floor of a seaside building with the alternating current (AC) batteries in the basement. The flood waters destroyed these secondary systems that could have prevented the cores from overheating.

With power out, and active backup systems damaged by inundation, there was still a third line of defense to prevent meltdowns. Passive cooling mechanisms known as isolation condensers at reactor 1 and throughout the plant could have continued to cool the reactors even without power. Unfortunately, TEPCO personnel had shut them off just before they lost electricity. Without indicator lights to confirm their status, they mistakenly believed that they were still working as temperatures rose for several hours, losing the chance to slow or halt the progressing meltdown in reactor 1 (RJIF 2015, p. 18). Water no longer circulated through the reactor to cover the fuel rods, and active and passive backup systems were offline; as a result, the temperature inside the reactors began to surge upward. The Fukushima Dai-ichi Nuclear Power Plant experienced, what engineers call, total station blackout without any power to operate pumps or sensors (Osnos 2011). Plant operators struggled to reduce the massive heat buildup in the reactors without full sensor readings, external power, or clear communication channels to each other or the outside.

TEPCO engineers lacked disaster response training and experience that would have enhanced their stabilization efforts. They did not recognize that the weak puffs of steam coming from the isolation condensers indicated that they were not working. Staff at Fukushima Dai-ichi had never practiced pumping in water using external mechanisms like fire trucks and did not efficiently set up the pipes inside the facility to deliver several 100 tons into the reactor. Efforts to open safety release valves to vent pressure and radioactivity and to pump water into the reactors from fire trucks brought in to assist early in the morning on March 12th had little impact. While the hydrogen explosions caused by a chemical reaction between the fuel rods and salt water that blew the facades off of reactors 1, 3, and 4 made for impressive television news loops, in reality the more pressing environmental problems were not visible to the world. Without cooling water in place for more than 14 h, the radioactive fuel inside the Fukushima Dai-ichi plants melted through the seven inch steel reactor cores into the basements as temperatures in the core reached 2800 °C (5000 F), melting the fuel pellets.

In short, the nuclear meltdowns at Fukushima Dai-ichi came about because of several interconnected institutional factors. The placement of the cooling systems at sea level, according to the North American design standard, in an area which had a long history of earthquakes and tsunami showed a lack of integration of local knowledge. Nuclear engineers designing the Fukushima Dai-ichi Nuclear Power Plant thought about systems resilience primarily in terms redundancy, i.e., backup cooling systems. Standard procedures in such facilities involved the installation of battery packs and diesel generators. But engineers ignored indigenous knowledge or local institutions on past tsunami events and installed these backup systems at sea level. This is an instance of misfit between institutions and local context. TEPCO engineers had internal discussions about the possibility of a tsunami, but a lack of pressure from regulators and a belief in the infallibility of the system prevented any changes in design. In other words, the institutional infrastructure was not in place to allow designing of resilient system since neither the regulations (i.e., regulative pillar), the common industry standards, or design practices (i.e., normative pillar) nor the shared understanding (i.e., cultural cognitive dimension) supported context-specificity. Quite the contrary, the Japanese hierarchical working culture may have exacerbated the problems by deterring local workers, that hold the best available information about risks, from questioning the top-down design.

As the plant went into station blackout, engineers lacked training in identifying the failure of isolation condensers. Institutional arrangements for and organizations working in low probability but high consequence fields, such as nuclear power plants and air transportation, need to regularly re-evaluate potential risks, secure the input of outsiders, and continuously train staff in emergency procedures. Had engineers been able to re-activate the isolation condensers, they may have been able to slow down or even prevent the meltdowns.

Next, a lack of knowledge exchange between team members at the plant and local emergency responders meant that

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existing personnel did not interact with their counterparts in local emergency response teams, such as firefighters. This failure to collaborate might stem from the profound differences of operating (or institutional) logics between these two professional groups (Hällgren et al. 2017) leading to high variation in emergency response practices such as insufficient attempts to use fire-fighting equipment such as hoses and cranes to bring water into the overheating cores. These barriers can be explored in view of organizational sensemaking (as described by Weick 1993) and knowledge transfer across organizations in the context of resilience. While Japanese engineers imagined that the facility would be resilient to shocks, their lack of governance and cultural frameworks in their planning process resulted in the second worst nuclear disaster in history.

3.2 Case 2: institutions for flood resilience in southwest Bangladesh

The coastal region of southwest Bangladesh is comprised of vast stretches of deltaic floodplains that are hydrologically associated with the Ganges and Brahmaputra rivers. This low-lying area is one of the most vulnerable places in the world to flood-related natural hazards (Department of Disaster Management 2014). In the 1960s and 1970s, the Bangladesh government constructed large-scale infrastructures (37 polders with 1556 km of embankments) in the region to protect the low-lying area from riverine flooding and tropical storm surges (Ishtiaque et al. 2017). A polder is an engineered hydrologic unit where a tract of floodplain is enclosed by embankments and sluice gates. Embankments shield the enclosed area from being flooded by surrounding bodies of water and sluice gates are used to bring water in and out of polder. The polders have helped to create a more stable and predictable living environment, and thus greatly contributed to increased agricultural production and population growth in southwest Bangladesh.

To be operational, these polders need to be repaired or maintained regularly as well as on emergency basis because of natural erosion of the embankments and embankment breakdowns that occasionally occur when storm surges hit the coasts (Yu et al. 2017). Because insufficient or delayed support from the government is quite common, the local communities in the region often take on the repair work themselves, knowing that if they waited for external assistance, their safety would be in jeopardy (Afroz et al. 2016). This has forced the communities to organize collective action, or mass social action with a common goal, to tackle the repair work (i.e., participation by only a few individuals is insufficient to complete the repair work). As such, community resilience to flooding in the region critically depends upon the community capacity to self-organize and maintain collective action. It is also imperative to realize that a set of institutions (rules and norms) regarding the embankment repair is often devised by the communities to regulate people's behavior during collective action. In normal situations, the community rule is that people need to work together annually during a predetermined period to counter the natural erosion of the embankments. In emergency situations caused by embankment breakdowns, the community rule is that people must work together around the clock to fill the breached portions of the embankments. There is also a social cost or pressure (e.g., social disgrace or ostracism) when a community member does not adhere to the institutions for polder maintenance (Afroz et al. 2016). It has been reported that in times of an embankment breach, as many as 500–600 people from several villages work together for 2–3 weeks to repair the breached portions of the embankments. People in the affected communities participate in the collective repair work by providing labor, food, and/or funds.

Taken together, the institutions for collective polder maintenance and the presence of social pressure that motivates people to abide by the institutions form a critical social infrastructure that has greatly contributed to the resilience of the communities to flood-related natural hazards. Just like the physical structure of polders provides resistance to flooding, a social asset in the form of shared community rules and norms can extend the coping capacity of communities to deal with natural hazards.

3.3 Case 3: irrigation institutions for coping with climate variability in Nepal

The Pumpa irrigation system, a small-scale irrigation system located in the Chitwan Province of Nepal, presents an interesting case of how institutions can help to reduce the sensitivity of crop production to climate variability. The Pumpa system serves a community of 140 households that cultivate 70 hectares of land. Most of the households are small-holder farmers who depend on agriculture for livelihood, i.e., 75% of households own and cultivate 0.3–0.7 hectares of land (Cifdaloz et al. 2010). The Pumpa system is located on the foothills of a mountain range and thus is characterized by hilly terrains, and is a farmer-managed system, i.e., the operation and maintenance of the irrigation system is managed by the community similarly to the polder system in Bangladesh. The irrigation system is comprised of headworks, canals, and water allocation devices that are used to divert water from a river to cultivated areas. It is imperative to realize that the physical structure of an irrigation system helps to smooth out temporal variability of irrigation water. Whereas rain-fed agriculture causes crop output to be extremely sensitive to the amount and timing of rainfall, irrigated agriculture, and its physical infrastructure allow the crop output to be less sensitive to rainfall

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variability by diverting, storing, and conveying water from flowing bodies of water.

The Pumpa system is exposed to several climate-related disturbances: flash-floods in the monsoon season that wash out and destroy the headworks, variability in the amount of river discharge (i.e., increase and decrease in rainfall), temporal shifts in river discharge (i.e., early and late onset of the monsoon season), and variability in river discharge distribution (i.e., short and long time-duration of the monsoon season) (Pérez et al. 2016). To reduce the sensitivity of crop output to these disturbances, the local community has developed and used an elaborate scheme of adaptive institutional arrangements or rules related to water distribution and emergency repair work (Cifdaloz et al. 2010). Whenever irrigation infrastructure is damaged by flash-floods, the community rule is that people need to work together to repair it. The community also adaptively switches among three water distribution rules (open-flow, sequential, 12-h rotation, and 24-h rotation) depending upon system condition. For example, when mean river water discharge is reduced to below 45% of the normal level, the community switches to the sequential water distribution (i.e., water is supplied to each irrigation sectors sequentially) from the open-flow distribution (i.e., all irrigation sectors extract water simultaneously). These rules can be understood as the “software” of the irrigation system which controls the “hardware” comprised of water diversion structures, canals, and gates.

The resilience of the Pumpa system or its capability to adapt to changes in environmental conditions (e.g., the river flow) has been modelled using a dynamic system model (see Cifdaloz et al. 2010). The model results show that the adaptive irrigation rules used by the community are indeed effective at reducing the sensitivity of crop output to the climate-related disturbances. Consistent with the model results, the community managing the Pumpa system actually adhere to these rules to cope with the disturbances.

Similar to the case of southwest Bangladesh, the case of the Pumpa irrigation system speaks a volume about the importance of collective formed institutions or social rules for enhancing the capacity of communities to deal with disturbances. Compared to solely relying on physical infrastructure (e.g., irrigation infrastructure, polder embankments, etc.), the co-presence of institutions and their effects on the human interactions with the infrastructure can substantially enhance the coping capacity of a community. The case further shows the applicability of different modelling approaches and engineering tools, such as dynamic system models, in validating these human-devised institutions.

4 Discussion

These case studies illustrate the short-comings of standard engineering frameworks compared to more holistic ones that explicitly incorporate the role of institutions (i.e., the socially constructed rules of the game that shape human interactions in repetitive, structured situations). In the Fukushima nuclear disaster, we noticed a number of challenges, including the neglect of social networks in recovery and adaptation and institutional misfits in both the design practices of the nuclear power plant as well as emergency response potentially caused by presence of multiple diverging institutional logics among the associated organizations. In the case of southwest Bangladesh, we recognize the importance of collective action for enabling community resilience and the role of institutions in regulating people’s behavior. Without a proper set of institutions including regulative elements to enforce resilience engineering in plans, designs, and operation guidelines, the presence of social norms that enforces them, and shared belief and mindsets to facilitate their communication, many communities may not be able to effectively cope with and recover from natural hazards. The Pumpa irrigation system and the adaptive irrigation rules used by the Nepali community also demonstrate the importance of institutions for enhancing community resilience but also emphasizes the engineering and modelling perspective in creating such institutional rules. By dynamically switching among different water distribution rules (e.g., open-flow, sequential, 12-h rotation, 24-h rotation) depending upon changing system condition, the community can reduce the sensitivity of its crop output in the face of climate-related disturbances.

Across these cases, we have seen how engineers and managers have not sufficiently considered the elements we propose, namely regulative (e.g., laws, regulations, and policies), normative (e.g., norms and moral values), and cognitive elements (e.g., shared cognitive schemas). In cases that the planners have failed to include regulative elements, we observed a lack of institutional arrangements for resilience enhancement principles to plan, absorb, recover, and adapt. Just like how physical infrastructure can provide improved resistance to an external shock, use of proper institutional and organizational arrangements can lessen the impact of such shocks on a community exercising them. In cases that the designers have missed normative elements, social norms were not fully integrated in resilience enhancement policies and strategies. Norms of conduct reinforce institutions by attaching social cost to disregarding them, which helps to increase people’s conformity to institutions and thus leading to enhanced community resilience. Finally, we have seen how cognitive

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elements have been neglected, leading to fragmented and multi-directional approach to definitions, as well as lack of shared understanding on safety practices and institutional complexity between nuclear engineers having diverse institutional and national backgrounds.

A path to integrate these elements can be based on a heuristic proposed by Linkov et al. (2013) to characterize system's capability to its functions in the face of disturbances. The proposed matrix by Linkov et al. (2013) is used to frame the landscape of capabilities from which disaster outcomes emerge resilient or otherwise. System capabilities to maintain critical functions exist across a range of domains (physical/engineering, informational, cognitive, and social) and need to be leveraged at different points in a disaster life-cycle, i.e., prior to, during, recovering from, and adapting cycles. This matrix is an effort to put the National Academy of Science (2012) resilience definition into practice. It can form a basis to more explicitly integrate institutional capacities and connections into resilience assessment. While including organizations as one of the components in this framework is a valuable step, future research needs to address the need to further explore institutional context of resilience management and how to use such frameworks in practice across different organizations.

We have summarized the three different perspectives into a conceptual model illustrated in Fig. 1. The model emphasizes the nested nature of social structures (e.g., institutional field, local community, organizations) which are involved in development and operation of infrastructure systems. The different institutional pressures (regulative, normative, and cognitive) cross through these multiple levels shaping more localized institutions (within the community and/or inside the organizations), which become to govern behavior of actors when they engage into designing or using the infrastructure system. This is illustrated through the two-way arrows crossing each level, which shows how higher-level institutional structures (e.g., laws) become interpreted within organizations and local communities but also how this interpretation can produce change on the field-level structures (i.e., institutional change). Resilience engineering metrics and heuristics are then positioned to take place within organizations but affect and are affected the external institutions (e.g., policies and national design guidelines).

Furthermore, we want to emphasize that some of organizations participating in design and operation of the infrastructure may be positioned outside the local community or the whole institutional field (e.g., transnational participants). In Figure organization three and four represent such cases. The engineering metrics and heuristics as well as other resilience enhancing practices can then act as boundary spanning elements helping organizations with diverse institutional backgrounds to work together. However, there always exist a risk of institutional complexity in such situations. One should also note that institutional elements (e.g., design guidelines) affecting infrastructure system may come outside the institutional field in which the system is embedded which occurred for example in the Fukushima case. This underlines the importance of different boundary spanning organizations who might be familiar with the institutions of

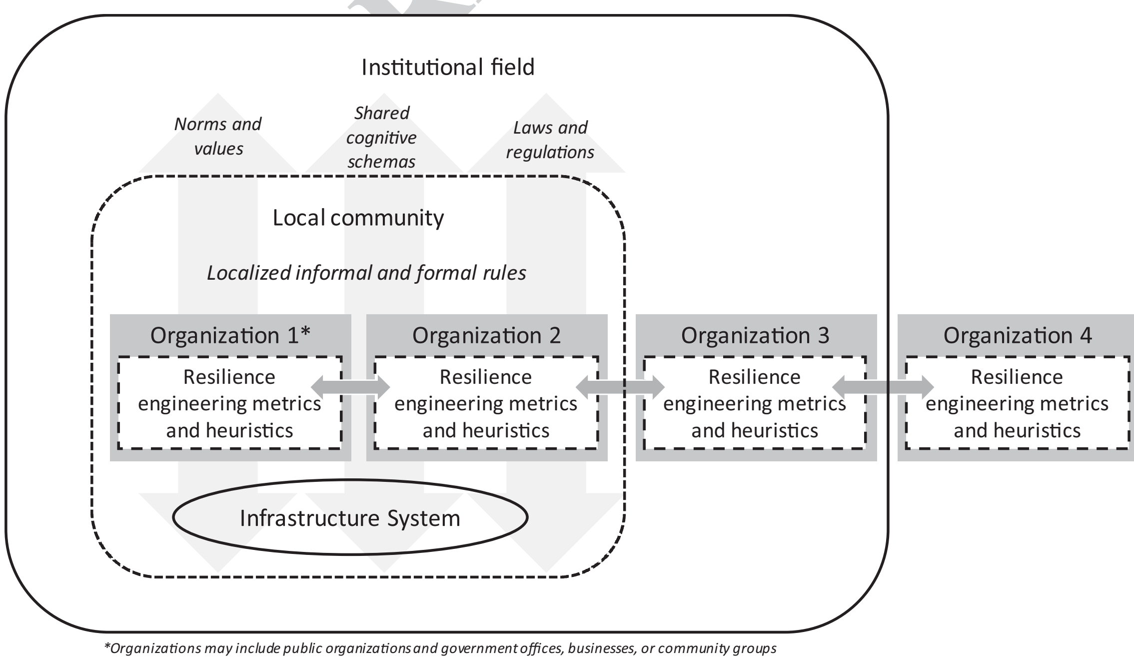

Fig. 1 Depiction of the three proposed perspectives

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different fields in order to avoid potential misinterpretation which can become to comprise resilience of the system.

5 Conclusions

In this paper, we set out a case for interdisciplinary research agenda on resilience management. Ultimately, we see the challenge of managing resilience as a critical problem particularly given changing patterns of natural and man-made hazards. We have reviewed the context of managing resilience through three different theoretical perspectives, to help scholars and practitioners alike to address the managerial and engineering problems to build resilient systems. Furthermore, we have provided three brief empirical illustrations to describe how these three perspectives instantiate themselves in different real-life settings.

We embrace the pluralism of different scientific discourses about resilience (Olsson et al. 2015), which might help us to build up more practically relevant claims about how resilient systems can be planned, built, and managed. The given empirical examples support the formulation of research agenda to provide practical solutions for management of resilience, specially in the context of infrastructure systems. We recommend the institutional theory as a necessary lens to further explore the implications of the theoretical and practical means applied in managing resilience, including definitions, metrics, and principles. Organizational context of the path from theory to policy, and from policy to practice and outcome should be explored considering institutional complexity and the decoupling of policies and practices across multiple domains.

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