Institutional Connectedness in Resilience Planning and Management of Interdependent Infrastructure Systems

Shangjia Dong, Ph.D.[1]; Qingchun Li[2]; Hamed Farahmand[3]; Ali Mostafavi, M.ASCE[4]; Philip R. Berke[5]; and Arnold Vedlitz[6]

Abstract: The objective of this paper is to propose a framework for characterizing and analyzing institutional connectedness as an emerging property in the human system affecting resilience planning and management in interdependent infrastructure systems (IISs). Three components of institutional connectedness are identified: coordinated actor networks; integrated plans and policies; and congruent values, norms, and cognition. Individual supreme performance alone, however, does not guarantee effective resilience planning and management. This study emphasizes that the three components are mutually connected and influence each other and reveals the significance of institutional connectedness as an underexplored dimension of interdependencies in the coupled sociotechnical systems. The study conceptualizes institutional connectedness as an emerging property of the human system influencing resilience management and planning in IISs and shows it can only be achieved through a coordinated actor network for collaboration and value sharing; integrated plans and policies for collective actions; and congruent values, norms, and cognition schemes for reaching agreed-upon resilience solutions. To illustrate the application of the conceptual framework, the study examined the three components of institutional connectedness through a case study of flood resilience management in Harris County, Texas, and highlights the critical role institutional connectedness plays in resilience planning and management of IISs. The proposed framework provides an integrated and interdisciplinary assessment of institutional connectedness to enable effective resilience management and planning in IISs. **DOI: 10.1061/(ASCE)ME.1943-5479.0000839.** © *2020 American Society of Civil Engineers.*

Introduction

Cities and their surrounding urban and suburban areas rely on a network of interwoven infrastructures where one entity's function and performance affect its connected counterparts. Given the increasing magnitude and frequency of disasters, preparing the bewildering array of interdependent infrastructure systems (IISs) to be resilient against various disturbances and to be able to adapt to changes remains a critical objective across different infrastructure sectors (Naderpajouh et al. 2018; Folke 2006). IISs are complex sociotechnical systems consisting of physical systems as well as human systems (Little 2004). In sociotechnical systems, the behavior of the physical systems is tied to the decisions and actions made by the human systems. Human actors' decisions are also highly dependent on the institutions that form values and preferred norms of human elements. While the existing literature related to resilience in IISs has focused primarily on properties of physical infrastructure (Dong et al. 2019a, b, c, 2020b), little of the existing work has examined the characteristics in human systems and their influence of the resilience of physical infrastructure in IISs (Choi et al. 2019). Therefore, to strengthen physical infrastructure facilities and systems and properly consider their interdependencies, it is essential to examine the characteristics of human systems that influence resilience planning and management.

The human system in resilience planning and management comprises various actors and the institutions that govern their decisions, behaviors, and interactions. Actors can have different values, preferences, priorities, and goals. In fact, actors in different infrastructure systems usually have varying priorities and preferences pertaining to development, hazard mitigation, and resilience improvement. Thus, the absence of harmony and integration among actors and the institutions that govern their decisions would adversely affect the collective actions related to resilience planning and management in IISs (Valentin et al. 2018). Institutions are the "systems of rules, decision-making procedures, and programs that give rise to social practices, assign roles to the actors in these practices, and guide interactions among the actors of the relevant roles" (Young et al. 1999), which include formal (e.g., regulations and policies) and informal (e.g., norms and shared cognition) mechanisms (Brody and Atoba 2018). In the process of planning and managing resilience, implementation of hazard mitigation policies and recovery actions might diverge due to institutional barriers, including fragmented actor networks, conflicting plan and policy preferences, and incongruent values and norms. Failure to address the institutional challenges could diminish the capacity to effectively plan and manage resilience in IISs (Opdyke et al. 2017). Therefore, to characterize the extent of harmony and integration among institutions of IISs that govern their decisions and behaviors, we propose the concept of institutional connectedness in this paper.

[1]Assistant Professor, Dept. of Civil and Environmental Engineering, Univ. of Delaware, Newark, DE 19716 (corresponding author). ORCID: https://orcid.org/0000-0003-4280-0500. Email: sjdong@udel.edu

[2]Graduate Research Assistant, Zachry Dept. of Civil and Environmental Engineering, Texas A&M Univ., College Station, TX 77843. ORCID: https://orcid.org/0000-0003-0769-0238. Email: qingchunlea@tamu.edu

[3]Graduate Research Assistant, Zachry Dept. of Civil and Environmental Engineering, Texas A&M Univ., College Station, TX 77843. Email: hamedfarahmand@tamu.edu

[4]Assistant Professor, Zachry Dept. of Civil and Environmental Engineering, Texas A&M Univ., College Station, TX 77843. Email: amostafavi@civil.tamu.edu

[5]Professor, Dept. of City and Regional Planning, Univ. of North Carolina at Chapel Hill, Chapel Hill, NC 27599. Email: pberke@email.unc.edu

[6]Professor, Bush School of Government and Public Service, Texas A&M Univ., College Station, TX 77843. Email: avedlitz@tamu.edu

Note. This manuscript was submitted on August 17, 2019; approved on May 11, 2020; published online on July 21, 2020. Discussion period open until December 21, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Management in Engineering***, © ASCE, ISSN 0742-597X.

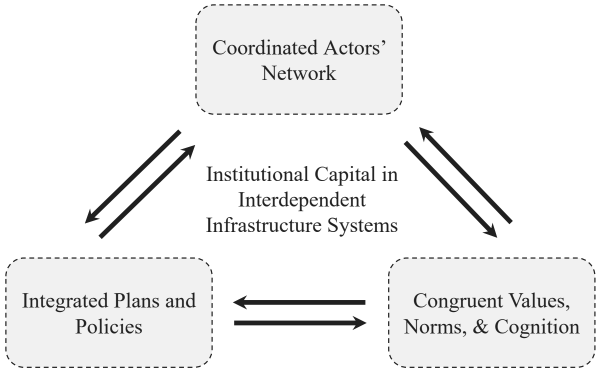

Fig. 1. Institutional connectedness analysis framework.

Institutional connectedness delineates the agreement, similarity, or harmony among institutions in terms of the actors' coordination, plans and policies integration, and values, norms, and cognition congruence (Fig. 1). In particular, actor networks and the level of coordination among actors from different infrastructure sectors (e.g., flood control, transportation, and emergency facilities) influence the extent to which interdependencies among infrastructure are considered in prioritization of projects and investments to reduce physical infrastructure vulnerability (Dong et al. 2020a). Insufficient coordination in actor networks and omission of interdependencies among infrastructure systems would lead to an increase in physical vulnerability (Li et al. 2019a). In fact, the stronger the physical interdependency, the higher the institutional connectedness a community requires to ensure the effective resilience planning and management of IISs. In addition, the level of integration among various plans and policies related to hazard mitigation and infrastructure development plays a vital role in guiding resilience management in IISs for reducing physical and social vulnerability to natural hazards (Berke et al. 2015). Lack of integration among plans and inadequate consideration of infrastructure interdependencies could lead to conflicting plans and policies, which would not only affect the effectiveness and efficiency of the infrastructure planning, design, and operation process, but also make IISs more vulnerable to disturbances (Malecha et al. 2018). Furthermore, congruent values, norms, and cognition are important in forming actors' implementation of resilience practices. Because actors and organizations are inherently reluctant to follow policies conflicting with their values and norms, a robust resilience planning and management process requires aligned values and norms among different actors and stakeholders. The discrepancies regarding the values and knowledge of different actors about various aspects of resilience management (e.g., hazard magnitude, vulnerability sources, and resilience goals) would adversely affect collective actions in resilience planning and management in IISs.

This paper conceptualizes institutional connectedness as an emerging property in human systems influencing resilience management and planning in IISs. Institutional connectedness emerges due to interactions among three important processes in human systems: (1) actor networks coordination; (2) consistency of values, norms, and policy preferences; and (3) integration among plans. Although the importance of consistency of values or actor's coordination in resilience management and planning had been discussed in the literature (Li et al. 2019a, b; Farahmand et al. 2019), these components were examined separately and without consideration of the relationship among them. Institutional connectedness is not only affected by the individual components (e.g., actor network coordination, congruence of values and policy preferences, and integration of plans), but also by the relationships among these three components. To address this gap, the proposed framework intends to examine the three components and their relationships affecting the emergence of institutional connectedness to provide an integrative characterization of resilience management and planning in IISs.

The proposed institutional connectedness framework provides an appropriate conceptual explanation to (1) better understand the extent to which complex interactions among various processes in human systems influence a community's resilience, and (2) examine the extent of harmony and integration among actors and their institutions that affect resilience planning and management in IISs. The institutional connectedness required for resilience management and planning in IISs should match the level of interdependencies in the physical system. In other words, as infrastructure systems are becoming more interdependent, the human systems that govern and manage the physical system should become more institutionally connected. In addition, using the institutional connectedness framework for examining the harmony and integration of actors and their decision-making process enables a more integrative and interdisciplinary understanding of resilience planning and management in IISs from a sociotechnical systems perspective. The remainder of this paper will further elaborate on the three components of the institutional connectedness framework and their relationships with each other. Then the application of the institutional connectedness framework is demonstrated in a case study of interdependent flood control, transportation, and emergency facilities infrastructure in Harris County, Texas, in the context of Hurricane Harvey.

Institutional Connectedness Components

IISs are coupled systems composed of multiple interdependent physical infrastructures and various actors who collectively manage and govern resilience in IIS. Fig. 2 shows an overview of the IIS structure depicted as a coupled human–physical system (i.e., a sociotechnical system). Understanding the complex behavior of each system not only requires adopting a domain-specific perspective (Vespignani 2012) but also necessitates a holistic approach for understanding the interdependencies between different systems with different inherent characteristics (i.e., physical, human, and institutional). The resilience performance of physical components

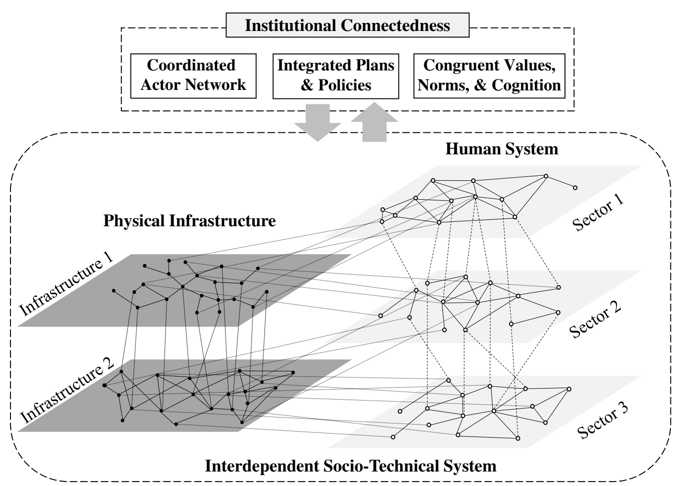

Fig. 2. Institutional connectedness components for resilience management in interdependent infrastructure systems.

in IISs is influenced by their physical attributes and interdependencies as well as the effectiveness of resilience planning and management processes. Resilience management and planning are governed by the institutional connectedness as an important characteristic of human systems in IISs.

Coordinated Actor Networks

Actor networks are structures on which the behaviors of human systems and corresponding interorganizational interactions (e.g., communication, coordination, collaboration, and support) are formed. In the context of this study, actors refer to different stakeholders in IISs such as governmental organizations, agencies, nongovernmental organizations (NGOs), and community groups. The structure and properties of actor networks have a significant impact on the extent of coordination and collaboration required for collective actions (Verschoore and Adami 2019), such as preparing for, responding to, and recovering from disaster-induced disruptions (Aerts et al. 2018), resilience planning (Godschalk 2003; Mills et al. 2014; Woodruff and Regan 2019), and natural resource governance (Bodin and Crona 2009; Olsson et al. 2006).

In addition, actor networks that represent formal or informal, stable or ad hoc social and institutional associations promote collective actions because actors could learn from past experience, communicate, and plan for future uncertainties. The level of coordination among actors from different infrastructure sectors influences the extent to which interdependencies among infrastructures are considered in prioritization of projects and investments to reduce physical infrastructure vulnerability. Therefore, a coordinated actor network is necessary to achieve the essential level of collective actions, coordination, collaboration, and communication among IIS actors, and to promote effective planning and implementation of resilience strategies and actions in IISs. More importantly, involvement of different actors in disaster management is essential for resilience planning and management in IISs because they often have different expertise and can produce a deep comprehension of community resilience for disaster recovery in different dimensions.

Integrated Plans and Policies

Plans are often created within different domains of urban development and sectors of IISs and implemented by actors strategically in pursuit of their goals and priorities (Afroz et al. 2016). They are an amalgam of both technical and scientifical foundation and policy element that reflect values and priorities in the form of visions and goals and cognition of actors involved in the planning process. Plans and policies form the basis of legislative governance (Naderpajouh et al. 2018) and can be considered the formal regulative institutions with pivotal roles in an actor's decision-making. Because plans and policies are guiding the daily decisions and actions aligning with their visions and goals, they can therefore influence the resilience of IISs. For example, community hazard mitigation plans guide future development with respect to the hazard, built and natural environments, and human vulnerability (Berke et al. 2011; Horney et al. 2017); transportation and flood control infrastructure development and environmental conservation plans influence flood risk management.

The network of plans that are created in different domains and implemented by different actors can have different perspectives and goals (Hopkins and Knaap 2018). For example, a transportation improvement program may focus on improving the traffic congestion by road development, while a flood control plan would be concerned with hazard mitigation through restricting growth in hazard-prone areas. In the absence of plan integration, there would be contradictions and inconsistencies among the network plans. In particular, when hazard mitigation elements are not consistently integrated across networks of plans, the likelihood that plans would raise vulnerability of physical infrastructure and cause undesirable interdependencies increases. A good case in point is conflicts between land use and hazard mitigation plans that would increase vulnerability in infrastructure systems in hazard-prone areas (Berke et al. 2015). Therefore, resilience planning of IISs requires integration of hazard mitigation across a network of plans instead of focusing on individual plans.

Congruent Values, Norms, and Cognition

Values generally refer to shared beliefs about desired and preferred behaviors and outcomes (Scott 2008). The value of an object shows its relative worth, utility, or importance. The value of the same object or solution to a shared problem can, however, differ between stakeholders (Abreu et al. 2009). The creation of value in a multiactor system and collective action processes would depend on the presence of shared understanding and agreement among organizations regarding actions to be taken to reach solutions. Congruence of values, which can be defined as the existence of the agreement, alignment, or harmony between distinct value systems of different actors, is therefore essential to maximize collective values to ensure the satisfaction of all actors and to enable a more unified collective action for resilience planning and management in IISs (El-Gohary and Qari 2010).

While values determine what is considered as worth, merit, utility, or importance (El-Gohary and Qari 2010), norms define the traditional manner in which activities should be pursued and by which practices would be formed (Scott 2008). Incorporation of actors' preferable norms into policy making facilitates the implementation of policy options that make practical sense for actors involved in governance and management (Ford et al. 2019). In addition, cognition refers to actors' understanding of different aspects of a problem. The absence of shared cognition among actors can devolve into fragmented procedures in defining and understanding practices and complexities associated with resilience planning and management in IISs. Congruent cognition would enhance collaboration among actors, facilitate the assessment of solutions and policies, and help identify potential challenges in achieving the desired outcomes (Cannon-Bowers and Salas 2001). Hence, congruent cognition among actors can enhance the development and implementation of effective hazard mitigation and resilience plans and facilitate effective coordination in collection action and ultimately improve resilience in IISs.

Relationships among Institutional Connectedness Components

The three components of institutional connectedness influence each other. The interactions between different components of institutional connectedness are shown in Fig. 3. In a human IIS, the structure and characteristics of actor networks could significantly affect the actors' collaboration (Baggio et al. 2015; Li et al. 2019b; Sapat et al. 2019) as well as the integration of plans and policies (Hunsberger et al. 2017; Samuel and Siebeneck 2019). In addition, congruent values and cognition among actors can facilitate effective actor coordination in collective action and enhance the development and implementation of integrated hazard mitigation and resilience plans and policies (Li et al. 2020). In particular, interactions among actors would increase in a coordinated actor network, which consequently leads to a more congruent institutional setting, i.e., aligned values, norms, and cognition (Christensen and Ma 2020).

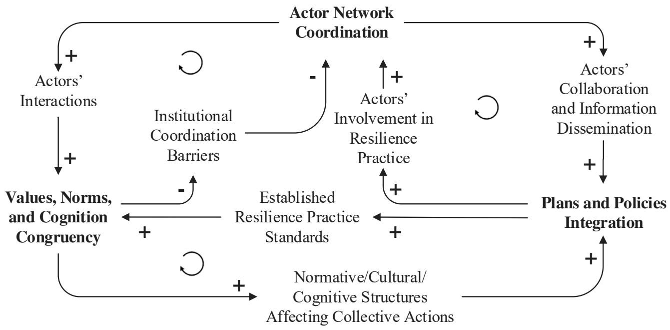

Fig. 3. Institutional connectedness components interdependency. Plus signs indicate positive impact and minus signs indicate negative impact.

On the other hand, institutional barriers that hinder the formation of a coordinated actor network can be diminished in an institutional environment where values, norms, and cognition are congruent (Chong 2014). Such congruence can also facilitate the formation of aligned normative and cultural-cognitive structures and eventually yield integrated plans and policies. In fact, aligned values and norms enable prioritizing the actions to eliminate the institutional barriers that limit the implementation of plans and policies (Morrison et al. 2018). In turn, when plans and policies are integrated, they support collective action (March et al. 2017). The more actors involved in such practices, the more interaction would occur between them, and consequently, a more coordinated network of actors emerges (Li et al. 2019b). A coordinated actor network can also impact resilience management and planning because more information could be shared and an agreed-upon solution can be reached (Gupta et al. 2016). On the contrary, conflicting values and norms can inhibit actors from establishing agreed-upon sets of policies and solutions that promote collective value. On the other hand, fragmented actor networks are at risk of creating conflicting plans and ultimately increasing vulnerability in physical infrastructure (Buijs et al. 2018). These barriers may arise from the adherence of actors to their institutional values and preferred activities, which can potentially affect collaboration efforts in hazard mitigation practices and resilience-enhancing activities (Baggio et al. 2015). In the remainder of this section, we explore the relationships among the three components of institutional connectedness framework.

Coordinated Actor Network and Integrated Plans and Policies

A coordinated actor network could increase the level of integration of plans and policies, facilitate collaboration and information dissemination among actors and organizations that govern interdependent infrastructure systems, and improve comprehension of infrastructure interdependencies in the resilience planning and management process. Actors develop plans and policies that govern, maintain, or operate interdependent infrastructure systems. The involvement of diverse actors across sectors is essential for disaster management, in particular for resilience planning and management in IIS. Chan et al. (2019) emphasized the importance of involvement of different actors (e.g., NGOs, universities, private sectors) because they often have different expertise and can produce a deep comprehension of community resilience for hazard mitigation planning and disaster recovery in different dimensions. For example, constructing new infrastructures in a hazard-prone area would encourage urban development activities in the area and make IIS more vulnerable to natural hazards. To avoid situations like this, transportation, land use, and hazard mitigation plans should be integrated and consider the underlying interdependencies. Such integration among plans could only be achieved in a coordinated actor network. In addition, centrality-identified hub actors can influence other actors' perception of hazard risk and consequently affect their preferred solutions for hazard mitigation and resilience improvement. The lack of a diverse core in the actor network may, however, create marginalization of peripheral actors. This limitation could eventually result in conflicts and inconsistencies in resilience planning and management processes (Finn et al. 2007; Bodin 2017). Moreover, the boundary spanners (actors who can link actors in different clusters) can facilitate collaboration and information exchange among different groups of actors. This bridging of collaboration and information exchange across different clusters promotes institutional congruence and collective action.

Coordinated Actor Network and Congruent Values, Norms, and Cognition

The communication, collaboration, and coordination in an actor network are influenced by values, norms, and cognition. Actors who share common values and norms as well as a foundation of agreed-upon solutions to problems tend to establish ties, communicate more frequently, and collaborate more effectively (Matinheikki 2019). The relationship between actors' network structure and actors' values, norms, and cognition promotes the formation of network clusters consisting of actors with similar values, norms, and cognition. In most cases, however, actors may have different or even conflicting values that potentially hinder collaborative and cooperative decision-making and limit creating collective value (El-Gohary and Qari 2010). In actor networks formed by heterogeneous entities with diverse sets of values and interests, identifying actors' values and recognizing common values are imperative to effective collaboration (Abreu et al. 2008). Hence, in the context of resilience planning and management in IIS, it is important to consider ways to manage the relationships in the multiactor organization network with diverse or even conflicting values (Järvensivu and Möller 2009; Bahadorestani et al. 2019).

Investigation of the structure and properties of actor networks can provide valuable insight into ways to eliminate institutional barriers that hinder collective action. Actors with a large number of ties are shown to have more influence in the network and can facilitate collaboration by promoting shared values for IIS resilience planning and management. For example, Li et al. (2020) showed that governmental actors have significantly more ties in resilience management, allowing them to exert more influence in relation to hazards and resilience solutions. Within a network of actors, the value lies in the extent to which a certain outcome satisfies the priorities and preferences of the actors (Martinez-Hernandez 2003). The segregation (e.g., communities) in actor networks is usually due to different goals, priorities, and sectoral boundaries of various infrastructure systems. Considering the fact that planning and management of resilience in IIS involve a diverse group of actors, it is essential that actors agree on common rules and practice and build common cognition and norms. A coordinated actor network structure can help in achieving such goals.

Integrated Plans and Policies and Congruent Values, Norms, and Cognition

The development of plans and policies is influenced by the values of the decision maker and their preferred actions. An integrated network of plans and policies requires collaborative development among actors to define priorities based on actors' values and

J. Manage. Eng., 2020, 36(6): 04020075

preferred policy settings. Actors, however, do not necessarily have congruent values and norms or shared understanding of the effective solutions for dealing with a shared problem (El-Gohary et al. 2006). The existence of disagreement and value contradictions can cause actors' efforts to diverge, and consequently reduce the effectiveness of disaster risk mitigation and resilience planning activities. On the other hand, potential conflicts can be prevented when actors reach an agreement on the valuation of different policies and solutions. Therefore, successful implementation of resilience plans and policies requires consideration of actors' priorities and preferences (Burnside-Lawry and Carvalho 2016; Taeby and Zhang 2018) and investigation of their values, norms, and cognition about problems. In a preferred situation, well-integrated plans and policies motivate cooperation between actors from different backgrounds and IIS sectors. Congruence of values, norms, and cognition not only could lead to fragmented plans and policies, but also affects policy implementation because actors may be less likely to endorse and adhere to plans and policies that are not aligned with their values. To diminish the adverse effects of such incongruity, more actors are encouraged to become involved in planning and policy-making processes to ensure the incorporation of values and norms from diverse actors into different plans and policies (Woodruff and Stults 2016; Woodruff and Regan 2019). For example, the participation of actors in communication forums could encourage knowledge sharing and formation of congruent cognition about related issues (Kaufman 2012). By doing so, potential conflicts among various means of regulative governance can be reduced.

Case Study

In this section, we examine the application of the institutional connectedness framework in resilience planning and management of three IISs (flood control, transportation, emergency response) in Harris County, Texas. In the case study, we employ the institutional connectedness framework to explain challenges arising due to the absence of institutional connectedness in IISs' resilience planning and management. The case study discusses the three aforementioned components of institutional connectedness individually as well as their relationships (Fig. 4).

Study Area and Context

Harris County, where the largest city in Texas—Houston—is located, has witnessed a huge population growth over the past 10 years and has aligned with a laissez-faire development pattern and zoning (Qian 2010). The rapid growth of the county, however, is not in parallel with flood control infrastructure development, which gives Harris County the dubious distinction of being one of the most flood-prone counties in the nation. Hurricane Harvey landed on the Texas Gulf Coast on August 25, 2017, and affected the region with extreme rainfall and a devastating flood, which caused extensive economic and social consequences (NOAA 2017, 2019). Considering that Harris County is also one of the fastest-growing counties in the nation, current land use policies, incentives, and infrastructure investments regarding hazard mitigation are not sufficiently integrated to support a long-term hands-off approach to planning for urban development (Berke et al. 2018). Therefore, we use Harris County as the study area and investigate its resilience management and flood risk governance practices prior to Hurricane Harvey.

Materials and Data

The empirical data used in the case studies were obtained from two sources: (1) hazard mitigation and infrastructure development plans; and (2) a stakeholder survey containing questions regarding actors' coordination networks and their values and preferences regarding infrastructure needs, risks, and vulnerability. In the context of this study, actors' coordination networks are the networks representing hazard mitigation planning coordination and collaboration among actors. Each link between two actors represents coordination and collaboration for hazard mitigation in resilience planning among the actors.

We selected and reviewed three regional plans in Harris County, Texas, to study the plan and policy integration in hazard mitigation and infrastructure development. The three regional plans are the 2040 Regional Transportation Plan (RTP), the Gulf-Houston Regional Conservation Plan (RCP), and the capital improvement program (CIP). The latest RTP developed by the Houston-Galveston Area Council (H-GAC) provides a guide for maintaining and improving the current transportation system. The Gulf-Houston RCP identifies conservation needs, collaborative projects, and initiatives for improvement of the environmental and economic health of the eight-county area. The goal of the CIP is to create a framework to plan, acquire, design, and construct flood control infrastructure annually. The selected plans represent three main areas affecting hazard mitigation in resilience planning (e.g., infrastructure development, flood control, and environmental conservation). The RTP focuses on infrastructure development to improve transportation systems. The CIP focuses on hazard mitigation and flood control. The Gulf-Houston RCP relates to environmental conservation. We used the information gathered

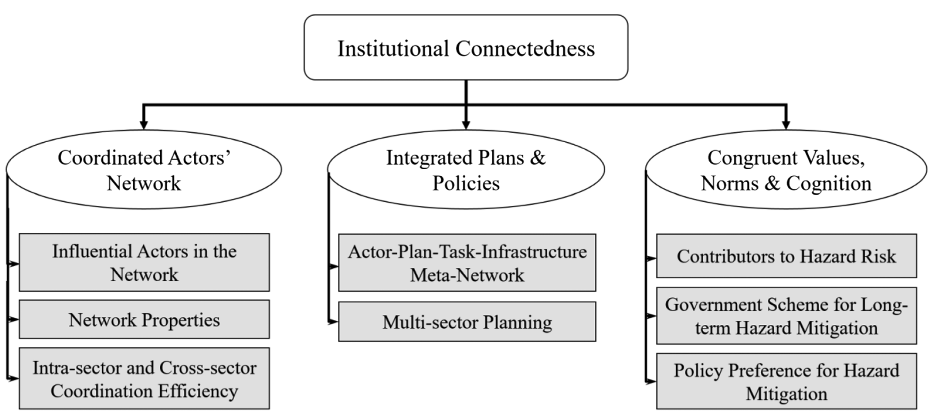

Fig. 4. Overview of linkage among components of institutional connectedness.

from the plans to examine the consistency between tasks and policies across different plans.

In addition, a stakeholder survey was conducted to collect valuable data regarding infrastructure needs, risks, and vulnerabilities resulting from the interconnections between flood control, emergency response, transportation systems, and urban planning. The stakeholder survey consists of four main parts: respondent experience and background with flood mitigation, organizational network, regional hazard mitigation planning, and flood risk assessment and policy planning. Meanwhile, at the end of the survey, respondents were asked to recommend someone believed to be suitable to participate the survey. On January 31, 2017, a pilot test of the stakeholder survey was conducted to get feedback and comments on the survey instrument. The pilot test randomly selected a group of 15 individuals from the existing sample including those who were already interviewed. The pilot test received four respondents and was closed on February 12, 2018. The stakeholder survey instrument was refined based on the received feedback. The stakeholder survey officially started on February 15, 2018, and closed on April 10, 2018. A total of 795 invitations were sent by the survey team in 25 waves. In the end, 198 individual respondents completed the survey, of which 23 participants were recommended by respondents. These 198 individual participants come from 160 distinctive departments of 109 varied organizations. The survey team had a follow-up procedure to maximize the response rate: (1) each respondent received at least three to four reminder emails (unless they completed the survey before receiving all four reminders); and (2) after multiple reminders were sent, survey team members would call the respondent and/or their organization in an attempt to persuade them to complete the survey. There were 2,769 follow-up emails sent during survey period.

Coordinated Actor Network in Resilience Planning

The analysis of actors' coordination networks first examined the degree centrality to assess an actors' connectivity to other actors in the network (Gibbons 2004; Borgatti and Halgin 2011). Centrality measures a node's importance in the network considering its connection to other nodes (degree centrality) and its occurrence on the shortest-path search between every pair of nodes (betweenness centrality). A higher degree of centrality can increase overall network connectivity and facilitate the flow of information dissemination. A boundary spanner bridges the gap between otherwise disconnected actors in the network (Borgatti and Everett 2000; Hannibal and Ono 2017). In a two-mode network, potential boundary spanners are identified by betweenness centrality. Identifying potential boundary spanners in the actor collaboration network can inform the network-building strategy about whom to include to assist information dissemination and to improve coordination in hazard mitigation integration. Besides, because multiactor involvement in the planning process would highly improve the quality of resilience plans, we can examine diversity of actors in the core structure of the network to examine communication and coordination across different infrastructure sectors (Borgatti 2009; Woodruff and Regan 2019). In addition, network efficiency describes the cost (i.e., distance of shortest path) of communication or collaboration in a network. It was examined as a performance measure to assess the efficiency of current actor coordination and also guide the collaboration enhancement. The details related to network analysis methods can be found in Li et al. (2019a).

Analyzing the information obtained from the stakeholder survey, the results show that the actor network structure is composed of 80% governmental actors and 20% nongovernmental actors in the core of the network (Fig. 5). Examples of governmental actors at the core are the City of Houston, Harris County, and Texas

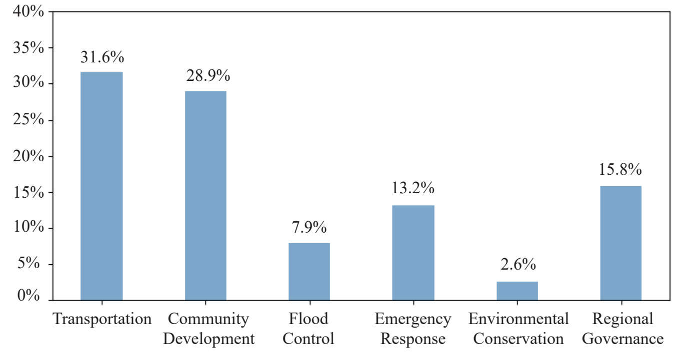

Fig. 5. Composition of IISs in the core of the actor collaboration network.

Department of Transportation (TxDOT), each of which had a great influence on coordination improvement and information dissemination in hazard mitigation for resilience planning. These governmental actors also have a high degree of betweenness centrality and are potential boundary spanners in actor collaboration networks. The actor network analysis reveals that fewer flood control and nongovernment actors were at the core of the actor collaboration networks compared with actors from other infrastructure sectors (e.g., transportation) and government actors. The absence of diversity in the core structure of actor networks inhibits effective collaboration among actors and marginalization of actors on the periphery of the network. Subsequently, this reduced the extent and effectiveness of hazard mitigation coordination in the resilience planning process.

We mapped two-mode (respondent–organization) directed networks based on the information collected in the survey, and the ties in the mapped network represent frequency of collaboration (daily, weekly, monthly, and yearly) [details in Li et al. (2019a)]. The network represents collaboration for hazard mitigation among actors from IISs. We focused on two frequencies of collaboration, monthly and weekly, and examined three network properties (i.e., degree centrality, betweenness centrality, and core–periphery structure) to understand influential actors in the mapped networks.

Degree Centrality

Degree centrality was calculated as $d_i = \sum_j^n x_{ij}$, where i is the focal node, j represents all other nodes, n is the total number of nodes in the network, and x_{ij} is defined as 1 if node i and node j are connected to each other, and 0 otherwise.

Boundary Spanner

Potential boundary spanners in a network were identified by betweenness centrality extended for the two-mode network using $g(v) = \sum_{s \neq v \neq t} [\delta_{st}(v)]/\delta_{st}$, where δ_{st} is the total number of shortest paths from node s to node t and $\delta_{st}(v)$ is the number of those paths that are through node v. Let n be the number of nodes in the node set U and m be the number of nodes in the node set V. Then node betweenness centrality of U is normalized by dividing $U_{\max}$ and node betweenness centrality of V is normalized by dividing $V_{\max}$

$$U_{\max} = 1/2[m^2(s+1)^2 + m(s+1)(2t-s-1) - t(2s-t+3)] \quad (1)$$

$$V_{\max} = 1/2[n^2(p+1)^2 + n(p+1)(2r-p-1) - r(2p-r+3)] \quad (2)$$

where $s = (n-1)/m$; $t = (n-1) mod\, m$; $p = (m-1)/n$; and $r = (m-1) mod\, n$. Because there is no specific threshold of betweenness centrality for identifying a boundary spanner, in this analysis we assumed that greater betweenness centrality implies potential boundary spanners in the actor collaboration network. Tables 1 and 2 list actors with the top 5 and top 10 betweenness centrality in two modes (i.e., actors in the survey roster and survey respondents, respectively) of actor coordination networks.

The results show that governmental actors, especially those who have multiple departments involved in different infrastructure sectors (e.g., City of Houston, Harris County), play a critical role in collaboration for hazard mitigation. Those involved with multiple infrastructure sectors can serve as potential boundary spanners to connect otherwise separated actors. Similarly, regional actors (e.g., Houston-Galveston Area Council) also have huge impacts on hazard mitigation collaboration effort because they possess a high in-degree centrality, which suggests that they can potentially improve collaboration efficiency and information dissemination on hazard mitigation tasks. The Harris County Flood Control District (HCFCD) exhibited a high degree of centrality, both as the actor in the survey and the survey respondent, indicating that HCFCD not only has resources for collaboration but also is active in seeking collaboration with other actors.

We also extracted the 35 actors that are both in the survey roster and are respondents. We then mapped a multilayer network in which each layer represents one infrastructure system and links represent the reported collaboration among these overlapped actors [details in Li et al. (2019a)]. We examined the level of coordination within and across the IISs based on a simulation process. The simulation process removed links within and across layers in the network based on the reported collaboration frequency and evaluated the network efficiency after the removal to assess the level of coordination within and across IISs. Network efficiency can be calculated based on $E = 1/[N(N-1)]\sum_{i,j} 1/d_{ij}$, where N represents the total number of nodes in the network and d_{ij} is the distance of the shortest path between node i and j. Table 3 provides the network efficiency under intra- and interlink perturbation.

The multilayer collaboration network analysis showed that coordination performance within individual sectors was better than cross-sector coordination performance. Achieving a greater coordination performance among actors across infrastructure systems is more difficult and would require a higher collaboration frequency compared to within-sector coordination. The analysis results also showed problematic fragmentation among certain sectors. For example, actors from the community development sector had insufficient coordination for hazard mitigation with actors in flood control and transportation systems. This fragmentation resulted in conflicting and inconsistent plans and policies that increased vulnerability in physical infrastructure systems (as discussed in the following sections). Overall, the analysis showed insufficient collaboration across

Table 1. Potential boundary spanners at weekly collaboration

Betweenness	Actors in the survey roster	Infrastructure sector
0.1350	Harris County	Regional governance
0.1300	City of Houston	Regional governance
0.0640	Texas Department of Transportation	Transportation
0.0531	City of Houston Department of Public Work and Engineering	Regional governance
0.0461	Federal Emergency Management Agency	Emergency response
	Survey respondents	
0.1873	Harris County Office of Homeland Security and Emergency Management	Emergency response
0.1564	Harris County Flood Control District	Flood control
0.0822	H-GAC Community and Environmental Planning	Community development
0.0747	H-GAC Public Services Department	Community development
0.0734	Harris County Engineering Department	Community development
0.0518	Blueprint Houston	Community development
0.0460	Center of Houston's Future	Community development
0.0404	Harris County Judge's Office	Regional governance
0.0352	City of Houston Parks and Recreation Department	Community development
0.0305	Private company	Community development

Table 2. Potential boundary spanners at monthly collaboration

Betweenness	Actors in the survey roster	Infrastructure sector
0.1278	Harris County	Regional governance
0.0869	City of Houston	Regional governance
0.0640	Harris County Office of Emergency Management	Emergency response
0.0441	United Way of Greater Houston	Community development
0.0403	Houston-Galveston Area Council	Regional governance
	Survey respondents	
0.0833	H-GAC Public Services Department	Community development
0.0776	Harris County Office of Homeland Security and Emergency Management	Emergency response
0.0740	Harris County Engineering Department	Community development
0.0689	H-GAC Community and Environmental Planning	Community development
0.0646	Harris County Flood Control District	Flood control
0.0424	Houston Wilderness	Environmental conservation
0.0363	Blueprint Houston	Community development
0.0328	City of Clear Lake Department of Engineering	Community development
0.0256	Bayou Preservation Association	Environmental conservation
0.0219	Harris County Judge's Office	Regional governance

J. Manage. Eng., 2020, 36(6): 04020075

Table 3. Network efficiency under intra- and interlayer link perturbation

Infrastructure system	Mean of network efficiency
Flood control	0.37
Transportation	0.46
Emergency response	0.37
Community development	0.25
Environmental conservation	0.26
Flood control and community development	0.05
Transportation and flood control	0.17
Transportation and community development	0.01
Environmental conservation and flood control	0.03
Emergency response and flood control	0.16
Emergency response and transportation	0.28

sectors in the actor network of the case study region before Hurricane Harvey.

Plan and Policy Integration in Hazard Mitigation and Preparedness

The extent to which plans and policies accounted for physical infrastructure interdependencies can partially explain the plan and policy integration in hazard mitigation and preparedness. To quantitatively measure the plans and policies integration, we employed a metanetwork method [details in Li et al. (2020)] to measure the consistency rate of plans and stakeholders. The metanetwork analysis compares the potential network (i.e., the ideal relationships) and the actual network (i.e., the actual relationships) to examine the consistency among tasks and policies across different networks.

We mapped the actor-plan-task-infrastructure metanetwork based on a manual review of the selected three regional plans. We reviewed the plans to abstract relevant node entities (e.g., actors, plans, tasks, and infrastructure) and their interdependencies to map the metanetwork model. Nodes in the metanetwork were abstracted based on plan statements. For example, a task to expand the roadway network, the extension of IH-10W, was identified in RTP. Then the node IH-10W was abstracted as infrastructure, and the node expand the roadway network was abstracted as a task (Li et al. 2020). After mapping the actor-plan-task-infrastructure metanetwork, we determined the potential metanetwork based on the infrastructure dependencies. If tasks and projects relates to the dependent infrastructure, tasks and projects should be consistent with each other. Therefore, links between these tasks and projects should exist in the potential metanetwork. Likewise, the tasks and projects related plans and policies should be consistent with each other, and links between these plans and policies should exist in the potential metanetwork. Then we assessed the plan and policy integration based on the comparison of the links in the potential network and the mapped actual metanetwork (Tables 4 and 5).

Analysis results revealed considerable fragmentation among the plans. Most of the policies in the plans did not consider dependencies between flood control and transportation infrastructure systems. This led to contradictory and inconsistent hazard mitigation and land use plans, such as constructing a new highway segment in a hazard-prone area. For example, the newly constructed State Highway 99 (SH-99) segment was located upstream of two aging flood control reservoirs: Barker and Addicks, both built in the 1940s in West Houston. While the SH-99 project was planned to improve the traffic and road network in Houston, the lack of integration between transportation plans with flood control and hazard mitigation plans (in the absence of land use planning in the city) encouraged further infrastructure development upstream of flood

Table 4. Consistency rates of actors, plans, and tasks

Network	Number of links between actors	Number of links between plans	Number of links between tasks	Total
Potential metanetwork	147	62	200	409
Actual metanetwork	54	19	8	81
Consistency rate, C	0.367	0.306	0.04	0.198

Table 5. Rates of tasks that do not consider infrastructure dependencies and affected infrastructure

Indicator	Value
Total tasks	55
Number of tasks that do not consider infrastructure dependencies	52
Ratio of tasks that do not consider infrastructure dependencies	0.95
Total infrastructure	70
Number of affected infrastructures	61
Affected infrastructure ratio	0.87

control reservoirs. Increased pavements in the area and the elimination of green land that could absorb and store stormwater in the reservoirs' watershed resulted in the elimination of permeable green land, which increased the water level of two flood control reservoirs, exacerbated by unprecedented rainfall of Hurricane Harvey. To protect the reservoirs from breaching and preventing further catastrophic losses (both reservoirs had been identified as high risk and the water levels had reached the maximum level), the operator made the difficult decision to release floodwater to downstream neighborhoods. The release inundated more than 9,000 houses (almost all of which lacked flood insurance) for more than 2 weeks. From this example, it can be seen that the transportation plan is not integrated with the flood control plan, which increased physical vulnerability during natural disasters.

Such inconsistency among plans and policies can be explained in the multisector planning context in Harris County before Hurricane Harvey. Houston, the county seat of Harris County, is the only major city in North America without zoning policies and its modest land use regulations are well known (Qian 2010). Compared to other cities in the country, government-initiated urban development policies regarding land use regulations are limited in Houston, a large part of which is made up of superneighborhoods and homeowner associations (Qian 2010). These private land use regulations at the neighborhood level without essential governmental intervention usually focus on economic growth rather than hazard mitigation and flood risk reduction on IISs. In addition, land use planning in Harris County has been highly influenced by transportation infrastructure development and other megaprojects (Qian 2010). Rapid urbanization such as creating more dense development patterns in the Houston downtown area together with incompatible low investment on hazard mitigation projects have made the region vulnerable to hazards. The lack of integration of county development and planning policies with hazard mitigation led to unbalanced developments and amplified social and physical vulnerabilities of the county (Berke et al. 2015, 2018). The three components of the proposed institutional connectedness framework are connected and influence each other, which can be used to identify opportunities for enhancing the effectiveness of resilience management and planning. For example, the lack of integration between hazard mitigation and urban development plans can be alleviated by increasing the

J. Manage. Eng., 2020, 36(6): 04020075

coordination efficiency across the responsible sectors. In particular, we observed that the coordination performance for actors in the community development and transportation sectors is low. Therefore, one possible solution for increasing the integration of urban development and hazard mitigation plans would be improving the coordination between sectors (e.g., flood control and transportation) that are mainly involved in development of these plans.

Presence and Absence of Congruence in Values, Norms, and Cognition

The data obtained from the stakeholder survey were analyzed to assess the congruence among actors' values, norms, and policy preferences [see details in Farahmand et al. (2019)]. For example, to examine the extent of congruence among different sectors or organizations involved in flood risk reduction and hazard mitigation, a list of alternative policies was prepared, and actors were asked to score policies based on their preferences on implementing the best policies. The policy choices by different actors were then analyzed to better identify the presence or absence of congruence across different IIS sectors. Table 6 summarizes the extent of congruence regarding contributors to flooding, responsible government for long-term hazard mitigation, and policy preference for mitigating flood risk.

First, the actors' attitude regarding the contributors to flooding in the region was assessed. Respondents were provided a list of potential contributors to flooding and asked to rank them based on their attitude. A score was assigned to each rank (no effect = 1, very strong = 5) and the means were calculated in each urban sector. The results show that actors from different IIS sectors did not have a congruent cognition about the main contributor to flooding in the region. For example, insufficient protection of wetlands and open space had a high score (among the top flooding contributor selected by actors in the environmental conservation sector), while others did not include it in their top three choices. However, all sectors reached an agreement regarding the significant contribution of building in areas prone to flooding.

Second, respondents were asked to express their attitude about the level of government including city, county, state, and federal that they believe has the greatest responsibility for long-term hazard mitigation in the region. They could choose among different levels of government (city, county, state, or federal) or choose all shared responsibility. The results show that at least 60% of respondents in each sector selected all shared responsibility, which indicates the presence of congruent institution regarding the responsible government for hazard mitigation. This suggests all levels of government should take part in the hazard mitigation practices, which requires coordination between different levels of governments and between actors and governments. In doing so, the practices are better aligned with actors' norms. Common norms among different actors across various IIS sectors can facilitate an effective establishment of a decentralized and multilayer governance scheme, which has been suggested to be the most proper approach for hazard risk mitigation governance (Boyer-Villemaire et al. 2014). In terms of the relationship between components of institutional connectedness, we can see that the congruence regarding responsibility sharing for hazard mitigation is aligned with the significant role of governmental actors in the coordination network.

Third, actors' preferred policies for mitigation of flood risk in the region were examined. Respondents were asked to rank a list of policies that could reduce the risk of future flooding. A score was assigned to each answer choice (strongly oppose = −2, strongly support = 2) and the mean of each sector was calculated. We can see from Table 6 that actors had varying preferences regarding flood risk mitigation policy prioritization. For example, actors from environmental conservation sectors support protective wetland and open space as an effective solution for coping with the risk of future floods. This policy, however, is not among the top choices for other sectors. Similarly, elevate buildings was the most preferred policy by flood control actors but was not supported by actors in other sectors. These actors accept flooding as an inevitable consequence and seek solutions to minimize the loss associated with the inundation of assets, such as elevating structures, to protect assets from the flood. Building elevation policy is, however, strongly opposed by transportation actors. These results provide examples that actors from different sectors have different policy preferences due to different values and norms. These variations can be viewed as barriers for collective action in resilience planning and management. The existence of agreed solutions such as limit new development in flood-prone areas shows opportunities to devise policies that can enhance collective action for hazard mitigation. The presence of institutional congruence on this policy also gives a direction for plans and policy integration by incorporating it into different plans. This case properly shows how the institutional connectedness framework can identify the room for resilience management and planning improvements by considering the interaction of different components of institutional connectedness.

In summary, the case study reveals low levels of institutional connectedness in flood resilience management in Harris County, Texas, prior to Hurricane Harvey. The fragmentation in the actor

Table 6. Presence (Y) and absence (N) of congruence in resilience management

Resilience management aspect	Transportation	Flood control	Emergency response	Environmental conservation	Community development	Presence or absence of congruence
Contributor to flooding						
Building in areas prone to flooding	4.08	3.33	3.80	4.00	4.03	Y
Development that covers too much land in concrete and/or other impervious materials	3.60	2.73	3.59	4.00	3.40	Y
Insufficient protection of wetlands and open space	3.00	2.40	2.80	4.08	2.92	N
Insufficient dam capacity	3.50	2.00	2.52	3.07	2.85	N
Responsible government for long-term hazard mitigation						
Sharing responsibility for long-term hazard mitigation among different levels of government	84.6	61.1	75.0	87.5	70.0	Y
Policy for mitigation of flood risk						
Limit new development in flood-prone areas	1.09	1.06	1.08	1.40	1.24	Y
Build additional protective levees	0.50	0.00	0.55	0.73	0.54	Y
Protective wetland and open spaces	0.70	0.94	1.02	1.47	0.91	N
Elevate buildings	0.10	1.35	0.63	0.80	0.80	N

coordination network, inadequate integration among different plans and policies, and incongruity in values, norms, and cognition of actors negatively influenced institutional connectedness in flood resilience planning and management before Harvey. The extensive impacts that Harvey had in the region could be partly attributed to the physical vulnerability arising from low institutional connectedness in the IIS.

Conclusion

The proposed institutional connectedness framework provides an integrative conceptual explanation to better understand the collective effects of different human system processes on resilience management and planning in IIS. Institutional connectedness is a collective property that emerges due to complex interactions among various processes in human systems. The extent of institutional connectedness required for resilience management and planning in IISs is proportional to the extent of interdependencies among the physical infrastructure. In other words, the proposed institutional connectedness concept characterizes a collective property in human systems that should match the extent of interdependencies in physical systems in order to have effective resilience management and planning in IIS. Understanding this collective property, its underlying processes and relationships, and its relationship with physical infrastructure interdependencies is the core contribution offered by the proposed framework and its demonstration in the case study. Accordingly, this study contributes to a more integrative and interdisciplinary characterization of resilience management and planning in interdependent infrastructure systems from a sociotechnical systems perspective.

The institutional connectedness framework links physical infrastructure plans, design, and operations with processes and relationships in human systems. Future studies could adopt the proposed framework to examine the factors that reinforce or exacerbate institutional connectedness in human systems of IIS. For example, future studies could examine factors that hinder collaboration and consistency among sectors, or the lack of regulations that mandates collaborations among sectors. In addition, the application of the proposed framework is shown in a case study related to flood resilience management and planning in Harris County, Texas, to elaborate the three components and their relationships. Future studies could adopt this framework in more case studies to examine the determinants of institutional connectedness in different IISs across various geographic and disaster contexts to examine cause-and-effect relationships between the extent of institutional congruence and the community resilience performance. Besides, actor networks in human systems evolve and adapt in response to hazard events and risks. Monitoring the changes of the network and its corresponding institutional connectedness is of great importance in understanding their coevolution over time and quantifying their relationship. Hence, future studies could examine the underlying mechanisms that reinforce institutional connectedness over time. Moreover, future research could explore interventions that enhance institutional connectedness in fragmented and incongruent human systems.

Data Availability Statement

The three plans used in this paper are available from the corresponding author by request. The stakeholder survey data used in the case study are confidential in nature. The research team obtained an institutional review board (IRB) certificate to use such data. To provide such data, restrictions may apply. For example, information that can be used to identify the responders will be removed from the data.

Acknowledgments

The authors would like to acknowledge funding support from the National Science Foundation RAPID project No. 1760258, "RAPID: Assessment of Risks and Vulnerability in Coupled Human-Physical Networks of Houston's Flood Protection, Emergency Response, and Transportation Infrastructure in Harvey," and CRISP 2.0 Type 2 No. 1832662, "Anatomy of Coupled Human-Infrastructure Systems Resilience to Urban Flooding: Integrated Assessment of Social, Institutional, and Physical Networks." Any opinions, findings, and conclusions or recommendations expressed in this research are those of the authors and do not necessarily reflect the views of the funding agencies.

References

Abreu, A., P. Macedo, and L. M. Camarinha. 2009. "Elements of a methodology to assess the alignment of core-values in collaborative networks." *Int. J. Prod. Res.* 47 (17): 4907–4934. https://doi.org/10.1080/00207540902847447.

Abreu, A., P. Macedo, and L. M. Camarinha-Matos. 2008. "Towards a methodology to measure the alignment of value systems in collaborative networks." In *Proc., Int. Conf. on Information Technology for Balanced Automation Systems*, 37–46. Berlin: Springer.

Aerts, J., W. Botzen, K. Clarke, S. Cutter, J. W. Hall, B. Merz, E. Michel-Kerjan, J. Mysiak, S. Surminski, and H. Kunreuther. 2018. "Integrating human behavior dynamics into flood disaster risk assessment." *Nat. Clim. Change* 8 (3): 193. https://doi.org/10.1038/s41558-018-0085-1.

Afroz, S., R. Cramb, and C. Grunbuhel. 2016. "Collective management of water resources in coastal Bangladesh: Formal and substantive approaches." *Human Ecol.* 44 (1): 17–31. https://doi.org/10.1007/s10745-016-9809-x.

Baggio, J., K. Brown, and D. Hellebrandt. 2015. "Boundary object or bridging concept? A citation network analysis of resilience." *Ecol. Soc.* 20 (2): 1–11. https://doi.org/10.5751/ES-07484-200202.

Bahadorestani, A., J. T. Karlsen, and N. M. Farimani. 2019. "Novel approach to satisfying stakeholders in megaprojects: Balancing mutual values." *J. Manage. Eng.* 36 (2): 04019047. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000734.

Berke, P., J. Cooper, D. Salvesen, D. Spurlock, and C. Rausch. 2011. "Building capacity for disaster resiliency in six disadvantaged communities." *Sustainability* 3 (1): 1–20.

Berke, P., G. Newman, J. Lee, T. Combs, C. Kolosna, and D. Salvesen. 2015. "Evaluation of networks of plans and vulnerability to hazards and climate change: A resilience scorecard." *J. Am. Plann. Assoc.* 81 (4): 287–302. https://doi.org/10.1080/01944363.2015.1093954.

Berke, P. R., M. L. Malecha, S. Yu, J. Lee, and J. H. Masterson. 2018. "Plan integration for resilience scorecard: Evaluating networks of plans in six US coastal cities." *J. Environ. Plann. Manage.* 62 (5): 901–920. https://doi.org/10.1080/09640568.2018.1453354.

Bodin, Ö. 2017. "Collaborative environmental governance: Achieving collective action in social-ecological systems." *Science* 357 (6352): eaan1114. https://doi.org/10.1126/science.aan1114.

Bodin, Ö., and B. I. Crona. 2009. "The role of social networks in natural resource governance: What relational patterns make a difference?" *Global Environ. Change* 19 (3): 366–374. https://doi.org/10.1016/j.gloenvcha.2009.05.002.

Borgatti, S. P. 2009. *Social network analysis*. Vol. 6 of *Encyclopedia of complexity and systems science*, 8279–8291. New York: Springer-Verlag.

Borgatti, S. P., and M. G. Everett. 2000. "Models of core/periphery structures." *Soc. Networks* 21 (4): 375–395. https://doi.org/10.1016/S0378-8733(99)00019-2.

Borgatti, S. P., and D. S. Halgin. 2011. "Analyzing affiliation networks." Chap. 28 in *The SAGE handbook of social network analysis*, 417–433. London: SAGE Publications.

Boyer-Villemaire, U., J. Benavente, J. A. G. Cooper, and P. Bernatchez. 2014. "Analysis of power distribution and participation in sustainable natural hazard risk governance: A call for active participation." *Environ. Hazards* 13 (1): 38–57. https://doi.org/10.1080/17477891.2013.864592.

Brody, S., and K. Atoba. 2018. "Institutional resilience." In *Vulnerability and resilience to natural hazards*, edited by S. Fuchs and T. Thaler, 237–256. Cambridge, UK: Cambridge University Press.

Buijs, J., L. Boelens, H. Bormann, B. Restemeyer, T. Terpstra, and T. Van Der Voorn. 2018. "Adaptive planning for flood resilient areas: Dealing with complexity in decision-making about multilayered flood risk management." In *Proc., 16th Meeting: Adaptive Planning for Spatial Transformation*, 23–25. Amsterdam, Netherlands: Univ. of Groningen.

Burnside-Lawry, J., and L. Carvalho. 2016. "A stakeholder approach to building community resilience: Awareness to implementation." *Int. J. Disaster Resilience Built Environ.* 7 (1): 4–25. https://doi.org/10.1108/IJDRBE-07-2013-0028.

Cannon-Bowers, J. A., and E. Salas. 2001. "Reflections on shared cognition." *J. Organizational Behav.* 22 (2): 195–202. https://doi.org/10.1002/job.82.

Chan, N. W., R. Roy, C. H. Lai, and M. L. Tan. 2019. "Social capital as a vital resource in flood disaster recovery in Malaysia." *Int. J. Water Resour. Dev.* 35 (4): 619–637. https://doi.org/10.1080/07900627.2018.1467312.

Choi, J., N. Naderpajouh, D. J. Yu, and M. Hastak. 2019. "Capacity building for an infrastructure system in case of disaster using the system's associated social and technical components." *J. Manage. Eng.* 35 (4): 04019013. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000697.

Chong, J. 2014. "Ecosystem-based approaches to climate change adaptation: Progress and challenges." *Int. Environ. Agreements: Politics Law Econ.* 14 (4): 391–405. https://doi.org/10.1007/s10784-014-9242-9.

Christensen, T., and L. Ma. 2020. "Coordination structures and mechanisms for crisis management in China: Challenges of complexity." *Public Organization Rev.* 20 (1): 19–36. https://doi.org/10.1007/s11115-018-0423-9.

Dong, S., A. Esmalian, H. Farahmand, and A. Mostafavi. 2020a. "An integrated physical-social analysis of disrupted access to critical facilities and community service-loss tolerance in urban flooding." *Comput. Environ. Urban Syst.* 80 (Mar): 101443. https://doi.org/10.1016/j.compenvurbsys.2019.101443.

Dong, S., A. Mostafizi, H. Wang, J. Gao, and X. Li. 2019a. "Measuring the topological robustness of transportation networks to disaster-induced failures: A percolation approach." *J. Infrastruct. Syst.* 26 (2): 04020009. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000533.

Dong, S., H. Wang, J. Gao, and A. Mostafavi. 2019b. "Robust component: A robustness measure that incorporates access to critical facilities under disruptions." *J. R. Soc. Interface* 16 (157): 20190149. https://doi.org/10.1098/rsif.2019.0149.

Dong, S., H. Wang, A. Mostafizi, and X. Song. 2020b. "A network-of-networks percolation analysis of cascading failures in spatially co-located road-sewer infrastructure networks." *Physica A* 538 (Jan): 122971. https://doi.org/10.1016/j.physa.2019.122971.

Dong, S., T. Yu, H. Farahmand, and A. Mostafavi. 2019c. "Bayesian modeling of flood control networks for failure cascade characterization and vulnerability assessment." *Comput.-Aided Civ. Infrastruct. Eng.* 35 (7): 668–684. https://doi.org/10.1111/mice.12527.

El-Gohary, N., and A. Qari. 2010. "Towards a formal axiology for sustainable infrastructure development." In *Proc., ASCE Int. Conf. on Computing in Civil and Building Engineering*, 357–362. Reston, VA: ASCE.

El-Gohary, N. M., H. Osman, and T. E. El-Diraby. 2006. "Stakeholder management for public private partnerships." *Int. J. Project Manage.* 24 (7): 595–604. https://doi.org/10.1016/j.ijproman.2006.07.009.

Farahmand, H., S. Dong, A. Mostafavia, P. R. Berkeb, S. C. Woodruffb, B. Hannibalc, and A. Vedlitzc. 2019. "Institutional congruence for resilience management in interdependent infrastructure systems." *Int. J. Disaster Risk Reduct.* 4 (Jun): 101515. https://doi.org/10.1016/j.ijdrr.2020.101515.

Finn, D., L. D. Hopkins, and M. Wempe. 2007. "The information system of plans approach: Using and making plans for landscape protection." *Landscape Urban Plann.* 81 (1–2): 132–145. https://doi.org/10.1016/j.landurbplan.2006.11.006.

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

Ford, R. M., A. Rawluk, and K. J. Williams. 2019. "Managing values in disaster planning: Current strategies, challenges and opportunities for incorporating values of the public." *Land Use Policy* 81 (Feb): 131–142. https://doi.org/10.1016/j.landusepol.2018.10.029.

Gibbons, D. E. 2004. "Network structure and innovation ambiguity effects on diffusion in dynamic organizational fields." *Acad. Manage. J.* 47 (6): 938–951. https://doi.org/10.5465/20159633.

Godschalk, D. R. 2003. "Urban hazard mitigation: Creating resilient cities." *Nat. Hazards Rev.* 4 (3): 136–143. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136).

Gupta, S., B. Sahay, and P. Charan. 2016. "Relief network model for efficient disaster management and disaster recovery." In *Managing humanitarian logistics*, 85–104. Berlin: Springer.

Hannibal, B., and H. Ono. 2017. "Relationships of collapse: Network brokerage, opportunism and fraud in financial markets." *Int. J. Soc. Econ.* 44 (12): 2097–2111. https://doi.org/10.1108/IJSE-02-2016-0058.

Hopkins, L. D., and G. J. Knaap. 2018. "Autonomous planning: Using plans as signals." *Plann. Theory* 17 (2): 274–295. https://doi.org/10.1177/1473095216669868.

Horney, J., M. Nguyen, D. Salvesen, C. Dwyer, J. Cooper, and P. Berke. 2017. "Assessing the quality of rural hazard mitigation plans in the Southeastern United States." *J. Plann. Educ. Res.* 37 (1): 56–65. https://doi.org/10.1177/0739456X16628605.

Hunsberger, C., et al. 2017. "Climate change mitigation, land grabbing and conflict: Towards a landscape-based and collaborative action research agenda." *Can. J. Dev. Stud. Rev.* 38 (3): 305–324. https://doi.org/10.1080/02255189.2016.1250617.

Järvensivu, T., and K. Möller. 2009. "Meta theory of network management: A contingency perspective." *Ind. Marketing Manage.* 38 (6): 654–661. https://doi.org/10.1016/j.indmarman.2009.04.005.

Kaufman, S. 2012. "Complex systems, anticipation, and collaborative planning for resilience." In *Collaborative resilience: Moving through crisis to opportunity*, 61–98. Cambridge, MA: MIT Press.

Li, Q., S. Dong, and A. Mostafavi. 2019a. "Modeling of inter-organizational coordination dynamics in resilience planning of infrastructure systems: A multilayer network simulation framework." *PLoS One* 14 (11): e0224522. https://doi.org/10.1371/journal.pone.0224522.

Li, Q., S. Dong, and A. Mostafavi. 2019b. "Modeling of inter-organizational coordination dynamics in resilience planning: A multilayer network simulation framework." In *Proc., Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience*, edited by Y. K. Cho, F. Leite, A. Behzadan, and C. Wang. 515–522. Reston, VA: ASCE. https://doi.org/10.1061/9780784482445.066.

Li, Q., S. Dong, and A. Mostafavia. 2020. "Metanetwork framework for analysis of actor-plan-task-infrastructure networks in resilience planning and management." *Nat. Hazards Rev.* 21 (2): 04020016. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000376.

Little, R. 2004. "A socio-technical systems approach to understanding and enhancing the reliability of interdependent infrastructure systems." *Int. J. Emergency Manage.* 2 (1–2): 98–110. https://doi.org/10.1504/IJEM.2004.005232.

Malecha, M. L., A. Brand, and P. R. Berke. 2018. "Spatially evaluating a network of plans and flood vulnerability using a plan integration for resilience scorecard: A case study in Feijenoord District, Rotterdam, the Netherlands." *Land Use Policy* 78 (Nov): 147–157. https://doi.org/10.1016/j.landusepol.2018.06.029.

March, A., M. Kornakova, and J. Leon. 2017. "Integration and collective action: Studies of urban planning and recovery after disasters." In *Urban planning for disaster recovery*, 1–12. Berlin: Elsevier.

Martinez-Hernandez, V. 2003. "Understanding value creation: The value matrix and the value cube." Ph.D. thesis, Dept. of Design, Manufacture and Engineering Management, Univ. of Strathclyde.

Matinheikki, J. 2019. *Creating value through inter-organizational collaboration: A collective action perspective*. Espoo, Finland: Aalto Univ.

Mills, M., J. G. Álvarez-Romero, K. Vance-Borland, P. Cohen, R. L. Pressey, A. M. Guerrero, and H. Ernstson. 2014. "Linking regional planning and local action: Towards using social network analysis in systematic conservation planning." *Biol. Conserv.* 169 (Jan): 6–13. https://doi.org/10.1016/j.biocon.2013.10.015.

Morrison, A., C. J. Westbrook, and B. F. Noble. 2018. "A review of the flood risk management governance and resilience literature." *J. Flood Risk Manage.* 11 (3): 291–304. https://doi.org/10.1111/jfr3.12315.

Naderpajouh, N., J. Y. David, D. P. Aldrich, I. Linkov, and J. Matinheikki. 2018. "Engineering meets institutions: An interdisciplinary approach to the management of resilience." *Environ. Syst. Decis.* 38 (3): 306–317. https://doi.org/10.1007/s10669-018-9704-7.

NOAA (National Oceanic and Atmospheric Administration). 2017. *Fast facts: Hurricane costs*. Silver Spring, MD: NOAA.

NOAA (National Oceanic and Atmospheric Administration). 2019. *National centers for environmental information (NCEI) US billion-dollar weather and climate disasters*. Silver Spring, MD: NOAA.

Olsson, P., L. Gunderson, S. Carpenter, P. Ryan, L. Lebel, C. Folke, and C. S. Holling. 2006. "Shooting the rapids: Navigating transitions to adaptive governance of social-ecological systems." *Ecol. Soc.* 11 (1): 1–21. https://doi.org/10.5751/ES-01595-110118.

Opdyke, A., A. Javernick-Will, and M. Koschmann. 2017. "Infrastructure hazard resilience trends: An analysis of 25 years of research." *Nat. Hazards* 87 (2): 773–789. https://doi.org/10.1007/s11069-017-2792-8.

Qian, Z. 2010. "Without zoning: Urban development and land use controls in Houston." *Cities* 27 (1): 31–41. https://doi.org/10.1016/j.cities.2009.11.006.

Samuel, C., and L. K. Siebeneck. 2019. "Roles revealed: An examination of the adopted roles of emergency managers in hazard mitigation planning and strategy implementation." *Int. J. Disaster Risk Reduct.* 39 (Oct): 101145. https://doi.org/10.1016/j.ijdrr.2019.101145.

Sapat, A., A. M. Esnard, and A. Kolpakov. 2019. "Understanding collaboration in disaster assistance networks: Organizational homophily or resource dependency?" *Am. Rev. Public Administration* 49 (8): 957–972. https://doi.org/10.1177/0275074019861347.

Scott, W. R. 2008. *Institutions and organizations: Ideas and interests*. New York: Sage.

Taeby, M., and L. Zhang. 2018. "Exploring stakeholder views on disaster resilience practices of residential communities in South Florida." *Nat. Hazards Rev.* 20 (1): 04018028. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000319.

Valentin, V., N. Naderpajouh, and D. M. Abraham. 2018. "Integrating the input of stakeholders in infrastructure risk assessment." *J. Manage. Eng.* 34 (6): 04018042. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000638.

Verschoore, J. R., and V. S. Adami. 2019. "Interplay of competition and cooperation in wind farm interorganizational projects: Relational approach." *J. Manage. Eng.* 36 (1): 04019034. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000723.

Vespignani, A. 2012. "Modelling dynamical processes in complex socio-technical systems." *Nat. Phys.* 8 (1): 32. https://doi.org/10.1038/nphys2160.

Woodruff, S. C., and P. Regan. 2019. "Quality of national adaptation plans and opportunities for improvement." *Mitigation Adapt. Strategies Global Change* 24 (1): 53–71. https://doi.org/10.1007/s11027-018-9794-z.

Woodruff, S. C., and M. Stults. 2016. "Numerous strategies but limited implementation guidance in us local adaptation plans." *Nat. Clim. Change* 6 (8): 796. https://doi.org/10.1038/nclimate3012.

Young, O. R., A. Agrawal, L. A. King, P. H. Sand, A. Underdal, and M. Wasson. 1999. "Institutional dimensions of global environmental change." *Public Administration and Public Policy* 2 (1999): 100.