Natural Hazards
https://doi.org/10.1007/s11069-020-04142-1

ORIGINAL PAPER

Examining of the actor collaboration networks around hazard mitigation: a hurricane harvey study

Qingchun Li, et al. ***[full author details at the end of the article]***

Received: 10 May 2019 / Accepted: 25 June 2020

Abstract

The objective of this study is to examine the properties of actor collaboration networks and to analyze how they influence the coordination of hazard mitigation in resilience planning in Harris County, Texas. Effective resilience planning can only be achieved through the collective actions of various actors and the network structures unfold the collaboration among the actors. Understanding the structural properties of actor collaboration networks for hazard mitigation may hold the key to understanding and improving the resilience planning process. To this end, after Hurricane Harvey, we administered a stakeholder survey to actors in various urban sectors involved in hazard mitigation (e.g., flood control, transportation, and emergency response). The survey aimed to capture actor collaboration networks for hazard mitigation in Harris County, Texas prior to Harvey. The collaboration represents that the survey respondents worked with the actors in the survey roster for hazard mitigation. We asked the respondents the frequency of the collaboration in the survey (e.g., yearly, monthly, weekly and daily). We examined three network structural properties to study actor positions in the network: degree centrality, boundary spanners, and core-periphery structure, because degree centrality could indicate what actors had more collaborations; boundary spanners could reveal what actors were in strategic positions to connect otherwise separate actors; and core-periphery structure could identify what actors formed the core of actor collaboration network for hazard mitigation and whether the core was composed of actors from diverse sectors. The results showed: (1) governmental actors from different sectors had high degree centrality and betweenness centrality, which indicated that governmental actors had a more influential role in coordination and information dissemination in hazard mitigation planning and implementation; and (2) fewer flood control and non-governmental actors were at the core of the actor collaboration networks, which reduced the extent of hazard mitigation coordination. The results identify potential influential actors (such as City of Houston, Harris County, and Houston–Galveston Area Council) in coordination of hazard mitigation and yield recommendations for increased actor network cohesion for better coordination of hazard mitigation across diverse sectors in resilience planning.

Keywords Actor collaboration network · Hazard mitigation · Resilience planning · Network properties · Hurricane harvey

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11069-020-04142-1) contains supplementary material, which is available to authorized users.

Published online: 03 July 2020

1 Introduction

Natural hazards and disasters have posed a great threat to the well-being of society (Berz et al. 2001; Matyas and Silva 2013). As National Research Council defined, resilience is the 'ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events' (National Research Council 2012). Hence, resilience planning across the diverse sectors of infrastructure and urban development plays an important role in dealing with the increased risk of disasters (Berke et al. 2015; Malecha et al. 2018). The planning process, however, requires collective actions involving different actors (e.g., organizations, agencies, and groups) with different perspectives and goals. Resilience planning, in particular, involves multi-actor processes that require essential coordination across different infrastructure sectors (e.g., transportation, community development, flood control, emergency response, and environmental conservation) and scales (e.g., local, county, regional and state) (Woodruff and Regan 2019). Woodruff and Regan (2019) found that involving diverse actors from various urban sectors in the planning process will greatly improve the quality of resilience planning.

Lack of essential coordination among different actors cannot only lead to fragmented resilience planning, but also can affect infrastructure systems through faulty decision making, delayed investments, and lengthy response and recovery procedures during and after disasters (Bodin 2017; Godschalk 2003; Opdyke et al. 2017; Sadri et al. 2018). Furthermore, Opdyke et al. (2017) noted that coordination among various actors (e.g., intergovernmental agencies) may face many barriers due to 'poor census, low level of trust, and contested authority among actors'. Hence, the structure of actor networks on which the coordination behavior among various infrastructure sectors unfolds is a key aspect for understanding and assessing of the extent to which resilience planning integrates hazard mitigation across diverse sectors of urban development (Doreian and Conti 2012). Although much research has studied how actor networks affect community resilience to disasters (Abbasi 2014; Fan et al. 2018; Kapucu and Van Wart 2006; Kotani and Yokomatsu 2016; Zhu and Mostafavi 2016), most of the existing works of literature have focused on the role of actor networks in emergency response and recovery processes during and after disasters and did not fully consider structural properties of actor networks unfolding coordination of hazard mitigation for resilience planning. In this paper, we mapped the actor collaboration network for hazard mitigation in Harris County, Texas area and examined three network properties (e.g., degree centrality, boundary spanner, and core-periphery structure) to study the actors' network positions that would affect coordination of hazard mitigation across diverse actors in resilience planning. The study attempts to answer the following research questions based on the network positions of actors: (1) What actors in collaboration networks would have a greater influence on coordination in hazard mitigation (measured based on higher degree centrality)? (2) What actors in collaboration networks played an important role in information dissemination and coordination improvement in terms of hazard mitigation (boundary spanners identified based on betweeness centrality measures)? (3) What actors in collaboration networks are densely connected with each other (based on examining the core of the actor networks)? (4) What is the composition of the sectors (e.g., transportation, community development, flood control, emergency response) in the cores and how would the composition of the sectors affect the coordination of hazard mitigation across diverse sectors?

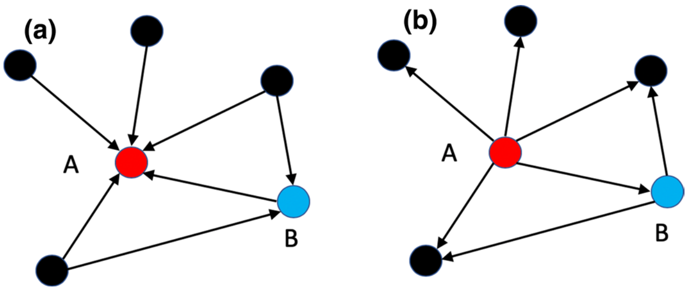

Fig. 1 A graphical depiction of degree centrality. *Note*: **a** indegree of A = 5, indegree of B = 2; **b** outdegree of A = 5, outdegree of B = 2

2 Properties of social networks in hazard mitigation

In this study, we conducted social network analysis (SNA) to examine the actors' network positions (e.g., degree centrality, boundary spanner and core-periphery properties) in the collaboration network. Also, we classified actors into governmental and non-governmental actors across five infrastructure sectors involved in resilience planning (e.g., community development, flood control, emergency response, transportation and environmental conservation), in order to study network positions of actors of different types and from different sectors. Various structural properties of actor networks can provide insights into the roles and importance of actors in hazard mitigation integration aspect of resilience planning. Research regarding social networks suggests that there are empirical benefits to specific structural locations and the underlying structural properties of the network will influence the flow of information (Borgatti 2005; Phelps et al. 2012). For example, a network actor that has a higher degree centrality than other actors may have more resources and be of more prestige, prominence, importance, and power (Borgatti 1995). A network actor that occupies a boundary spanning location may control information flow because of its strategic positions (Lazega and Burt 1995). Actors in the core position of the network may represent specialized information (Bastos et al. 2017), power elites (Larsen and Ellersgaard 2017), more social solidarity (Bourgeois and Friedkin 2001), and stronger connections that allow more complex and thorough information to be transmitted between the network actors (Aral and Van Alstyne 2011). However, there is still a lack of empirical evidence that specific types of actors (e.g., governmental or non-governmental, at different government levels or from different infrastructure sectors) would occupy distinct structural locations according to theorized benefits of the network structure. In particular, in this study, we examine degree centrality (connectivity), boundary spanners, and core-periphery properties in actor coordination networks. These three network properties are explained in the following sections.

2.1 Degree centrality

A network is made up of nodes connected by edges (also called links or ties) (Newman 2018). We use degree centrality to measure an actors' connectivity to other actors in the network. Degree centrality in network theory measures the number of links connected to the studied nodes (Freeman 1978) (Fig. 1). Because nodes with a higher degree centrality connect to more nodes in the network, actors with higher degree centrality have been

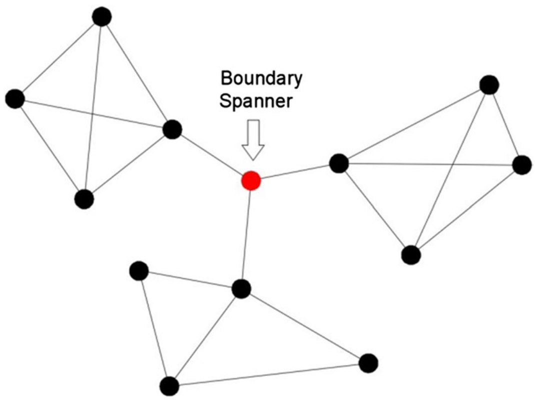

Fig. 2 Example of a boundary spanner

interpreted to have access to more resources, be more popular, or be of more prestige, importance, and power (Borgatti 1995). Gibbons (2004) also found that nodes with a higher degree centrality can increase overall network connectivity and facilitate the flow of information dissemination.

In this study, the mapped collaboration networks are directed because the edges were associated with directions (Newman 2018). The directions of an edge represent that one actor collaborated with the other actor. Based on directed network data, actors with a higher in-degree centrality are those with whom a greater number of other actors coordinate. This means that actors with high in-degree centrality may have increased access to resources that other actors need for hazard mitigation. Actors with higher out-degree centrality are in greater communication with other actors in the network. This can mean that these actors are more active in coordination for hazard mitigation. Considering these points, we defined the actors with a higher degree centrality (either in-degree or out-degree centrality) as influential actors in the collaboration network. The influential actors would potentially have a greater influence on the coordination for hazard mitigation among diverse actors within and across different urban sectors. Identifying the influential actors will increase understanding of the basic structure of the collaboration network and increase the ability to make future recommendation and policies for improving coordination of hazard mitigation among the actors.

One limitation of relying solely on degree centrality to capture the network property is that degree centrality cannot reflect positions of given nodes in the global structure of the network (Opsahl et al. 2010). In other words, the degree centrality measure does not capture information beyond the focal actor's immediate connections. For example, although nodes with higher degree centrality connect many other nodes, they still may not be the shortest path to the information source or be in a critical position to control the information flow (Borgatti 2005). This entails the examination of next two network properties: boundary spanner and core-periphery structure.

2.2 Boundary spanner

The boundary spanner, as illustrated in Fig. 2, bridges or closes the gap between otherwise disconnected actors in the network. Boundary spanners are important in facilitating information dissemination and communication among disparate groups because they are in a unique structural position that allows them access to diverse bodies of information and knowledge (Granovetter 1983; Hannibal and Ono 2017; Long et al. 2013). Therefore, boundary spanners have a potentially great impact on coordination improvement in hazard mitigation integration across diverse sets of actors. As many actors in urban systems come from different infrastructure sectors (e.g., flood control, transportation, emergency response, community development and environmental conservation), boundary spanners may play a critical role in information dissemination and coordination improvement across infrastructure sectors. To illustrate, actors from different urban sectors may have various operation strategies and goals in urban growth, flood control, and environmental preservation (Hughes et al. 2003). Actors in transportation sectors may foucs on improving transportation system to avoide traffic congestion, while actors in flood control sectors and environmental conservation sectors would pay more attention to hazard mitigation and environmental preservation (Li et al. 2020). The problem is that hazard mitigation are multi-actor processes that need the involvement of actors across different infrastructure sectors. If actors representing different infrastructure sectors lack essential coordination, the mitigation strategies developed by actors in different sectors could be conflicted, resulting in a reduction in effectiveness and efficiency of planning, design, and the operation process for hazard mitigation (Malecha et al. 2018). Boundary spanners may offer useful solutions by connecting actors of dissimilar sectors and improving information dissemination and coordination across different sectors. Identifying potential boundary spanners in the actor collaboration network further our understanding about which actors play important roles in information dissemination and improve coordination of hazard mitigation across different infrastructure sectors.

Although boundary spanners provide a unique function for information flow that is crucial for information dissemination and coordination improvement across diverse infrastructure sectors, this function may relate to an overall fragmented network (Feiock 2013; Scholz et al. 2008). On the other side, a densely connected group can allow complex and thorough information to be transmitted between the network actors (Milallos 2013; Uzzi 1997). These findings necessitate the discussion of the next network property: core-periphery structure.

2.3 Core-periphery structure

Nodes in a core location in the overall structure are usually a densely connected group, while nodes are loosely connected with each other in the periphery (Holme 2005). Rombach et al. (2014) also noted that the core nodes need to well connect with the nodes in periphery. Core-periphery structure is ubiquitous in real networks (Rajput et al. 2020; Zhang et al. 2015). Figure 3 illustrates an example of core-periphery structure in the network. Due to the dense structure of core actors, a diverse core composed of actors from different infrastructure sectors would assist in providing essential coordination among core actors in hazard mitigation. Meanwhile, because distances between the core and the periphery are short in the network, a diverse core could also help information disseminate to periphery nodes of various sectors (Schilling and Phelps 2007; Uzzi and Spiro 2005). Woodruff and Regan (2019) found that multi-actor involvement would greatly improve the quality of resilience plans. This suggests that a diverse core is desirable for coordination of hazard mitigation across diverse actors in resilience planning. If the core is composed of actors from a single infrastructure sector, and because the periphery nodes are generally not well connected with each other, the communication and coordination across different

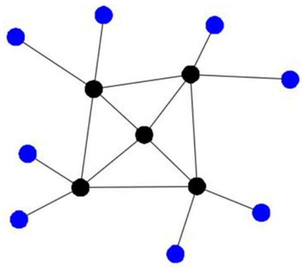

Fig. 3 An example of a core-periphery structure in the network

infrastructure sectors may be inhibited. This inhibition will highly affect the efficiency of coordination among actors in hazard mitigation. Examining the core-periphery structure of the actor collaboration network would inform the characteristics of the core and periphery nodes (e.g., what actors are in the core and what actors are in the periphery), helping planners understand the extent of coordination of hazard mitigation among actors.

Examining aforementioned three network properties–degree centrality, boundary spanners, and core-periphery structure of the actor network–would improve the understanding of roles and levels of coordination of organizations in the pre-Hurricane Harvey actor collaboration network. Such information could help provide recommendations to strengthen essential coordination between diverse actors, consequently improving hazard mitigation across the diverse sectors of urban development. Overall connectivity and degree centrality would inform the actors in collaboration networks that have a greater influence on coordination in hazard mitigation. Potential boundary spanners would inform the actors in collaboration networks that play an important role in information dissemination and coordination improvement in terms of hazard mitigation. An analysis of the core-periphery structure would inform densely connected actors (e.g., the core) in collaboration networks and the composition of the sectors in cores, thus helping planners understand how the composition of the sectors would affect the hazard mitigation integration across diverse sectors.

To this end, we mapped collaboration actor networks of 109 organizations, with 160 distinctive departments responsible for different infrastructure sectors in Harris County, Texas, based on information collected through a stakeholder survey. We studied and discussed the three network properties of the mapped actor collaboration network in order to understand roles and structural positions of organizations in the actor network and how these roles and positions affected coordination of hazard mitigation across different sectors in resilience planning.

3 Context: Houston and Hurricane Harvey

In 2017, Hurricane Harvey hit Houston, the fourth largest city of United States. Houston suffered an estimated $125 billion loss, mainly from the flooding triggered by the rainfall and the release of the Addicks and Barker reservoirs (NOAA and NHC 2018). Hurricane Harvey and its devastation, however, is only the latest hurricane in the long history of hurricane events in the Houston area. The Houston area has been flooded ten times from 1935 to 2017 (Wiki 2019). Just before Hurricane Harvey, two floods hit Houston in 2015 and 2016, and caused 16 casualties and over $1 billion financial loss (Berke 2019).

The reason why Huston is a flood-prone city may lie in the conflict between urban growth and the negligence of appropriate urban planning on flood control infrastructure systems. As the biggest city in Texas, Houston has witnessed a huge population growth over the past ten years, aligned with a laissez-faire development pattern of Texas. Houston is known for its lack of formal zoning policy, with economic development being the driving force (Masterson et al. 2014). Houston's metropolitan area is one of the fastest growing in the nation and the population is projected to 10 million by 2040 (METRO 1969). Yet, officials in Houston failed to integrate the rapid urban growth with land use regulations, incentives, and infrastructure investments considering hazard mitigation (Berke et al. 2019). This implies that, to some extent, there is a lack of essential coordination in hazard mitigation across infrastructure sectors (e.g., flood control and transportation), which has caused poor integration of hazard mitigation in resilience planning at the county and city.

3.1 Data and methods

We gathered the data to map collaboration among actors in hazard mitigation through a stakeholder survey. After Hurricane Harvey, we administered a stakeholder survey in Harris County, Texas, aimed at collecting, among other things, essential data regarding collaboration for hazard mitigation among actors from different infrastructure sectors. We sought to map a network of actors involved in hazard mitigation planning and implementation across different urban sectors. A research team, including researchers from civil engineering, urban planning, and sociology, complied information from various plans and organizational websites and identified 95 important and influential actors involved in hazard mitigation across different urban sectors (e.g., community development, flood control, transportation, environmental conservation and emergency response). These actors were in the survey roster as the potential actors with whom the survey participants collaborated. The survey question to collect the collaboration data is stated as follows: 'This question focuses on understanding the collaborations and relationships among key organizations and how they work together in dealing with catastrophic events such as Hurricane Harvey. In the months or years prior to Hurricane Harvey, to the best of your knowledge, did you or any other employee from your organization collaborate or work directly with any of the organizations listed below on flood mitigation efforts? If so, how frequent has been such collaboration? Note: You may leave a row blank if you have not had any interaction with an organization.' The survey participants need to select an answer from following options or leave a row blank: '1 Daily, 2 Weekly, 3 Monthly, 4 Several times per year, and 5 Not at all.'

We finished the first draft of survey instruments on January 18, 2018 and tested the online survey system in the following several days. Then we started a pilot test of the stakeholder survey on January 31, 2018, in order to get feedback from participants on the first draft of developed survey instrument. We randomly invited 15 individuals as a group from the existing sample pool of selected organizations. We concluded the pilot test on February 12, 2018 with four individuals completed the pilot test. We refined the survey instruments based on the feedback obtained in the pilot test. The stakeholder survey officially started on February 15, 2018. We sent out total 795 invitations, and we invited survey respondents from both governmental and non-governmental organizations at different scales (e.g., state, regional, county and local) that involved in resilience planning from different urban sectors. We invited respondents who were in positions of management and planning (e.g., CEO, chair and department head) in organizations. Thus, the invited

Table 1 Examples of actors in each category

Category	Examples
Flood control	Harris County Flood Control District, City of Houston Floodplain Management Office, The Texas Floodplain Management Association, City of Pearland Floodplain Administration
Emergency response	City of Houston Fire Department, FEMA Emergency Corps, Texas Department of Public Safety, Harris County Office of Emergency Management
Transportation	HGAC Transportation Policy Council, Houston Transtar, METRO, Port of Houston Authority
Community development	H-GAC Community and Environmental Planning, City of Houston Parks Board, U.S. Army Corps of Engineers (USACE) Research and Development, Bay Area Houston Economic Partnership
Environmental conservation	Texas Water Development Board, Bayou Land Conservancy, Conservation Fund, The Nature Conservancy
Regional governance	City of Houston, Harris County, Houston–Galveston Area Council, American Planning Association

survey respondents had a clear picture about involved work and planning for hazard mitigation. We concluded the survey on April 10, 2018 and received total 198 individual responses representing 160 distinctive departments of 109 organizations (around 30% response rate).

To understand the collaboration between different infrastructure sectors, we categorized actors into five sectors, including flood control, emergency response, transportation, community development, and environmental conservation (Farahmand et al. 2020; Li et al. 2019). Some actors (e.g., Harris County, City of Houston, Houston–Galveston Area Council) were regarded as regional governance, because they or their departments may have been involved in different infrastructure sectors. Table 1 lists examples of actors in each category. Meanwhile, we wanted to see whether the governmental and non-governmental attributes affected the network property. These two attributes (i.e., governmental and non-governmental) were also included as node attributes.

The network components of the survey provide information to create a two-mode (respondent-organization) directed networks, where the tie represents the frequency of collaboration (weekly, monthly, and yearly) were mapped. The network represents collaboration among actors (e.g., organizations, agencies and groups) from different infrastructure sectors in terms of hazard mitigation. Here, we focused on two frequencies of collaboration, monthly and weekly. The monthly collaboration actor network includes all the ties in the weekly network, with additional ties at only monthly collaboration level.

3.2 Degree centrality

In this paper, degree centrality was calculated according to Freeman's (1978) definition (Eq. 1).

$$d_i = \sum_{j}^{n} x_{ij} \tag{1}$$

In Eq. 1, i is the studied node, j are other nodes in the network, n represent all the nodes in the network, and x_{ij} is defined as 1 if node i and j are linked, and 0 otherwise.

3.3 Boundary spanner

In this paper, potential boundary spanners in a network were identified by betweenness centrality extended for the two-mode network (Scott et al. 2015) (Eq. 2).

$$g(v) = \sum_{s \neq v \neq t} \frac{\delta_{st}(v)}{\delta_{st}} \tag{2}$$

where δ_{st} represents all the shortest paths in the pair of nodes s and t and $\delta_{st}(v)$ represents number of paths including node v. In bipartite networks, betweenness centrality would be normalized by dividing the denominator in Eqs. 3 and 4 corresponding to its node set. In Eqs. 3 and 4, n is the node number in node set U and m represents the node number in another 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} (Scott et al. 2015).

$$U_{max} = \frac{1}{2}\left[m^2(s+1)^2 + m(s+1)(2t-s-1) - t(2s-t+3)\right] \tag{3}$$

$$V_{max} = \frac{1}{2}\left[n^2(p+1)^2 + n(p+1)(2r-p-1) - r(2p-r+3)\right] \tag{4}$$

where $s = \frac{n-1}{m}, \quad t = (n-1) \mod m, p = \frac{m-1}{n}, \ r = (m-1) \mod n$

Node betweenness centrality could indicate the importance of a node connecting other nodes in the network, because betweenness centrality calculates how many times the node is included in the shortest paths of other node pairs (Zambrano Leal 2012). Boundary spanners usually have a higher betweenness centrality in a network as they are in a strategic position that connects to potentially dissimilar actors or groups from various walks of life or backgrounds. Creswick and Westbrook (2010), Di (2012), and Hawe and Ghali (2008) adopted betweenness centrality to identify potential boundary spanners in their research.

Although different studies adopted betweenness centrality to identify boundary spanners, there is no specific threshold for betweenness centrality with which to judge a boundary spanner (i.e., for what value of betweenness centrality indicator we can judge the node is a boundary spanner). Therefore, in this analysis, we assumed that greater betweenness centrality implies potential boundary spanners in the actor collaboration network.

3.4 Core-periphery structure

There are several methods available to identify core-periphery structure, including block model (Borgatti and Everett 2000), k-core decomposition (Holme 2005), spectral methods and geodesic paths (Cucuringu et al. 2016), modularity identification (Da Silva et al. 2008), random walker (Rossa et al. 2013) and structural equivalence (Doreian 1985). In this paper, we adopted k-core decomposition to examine the core-periphery structure in the collaboration actor networks. Because the mapped networks are bipartite networks, other methods for identifying core-periphery structure cannot be directly applied without the network projection. K-core decomposition, however,

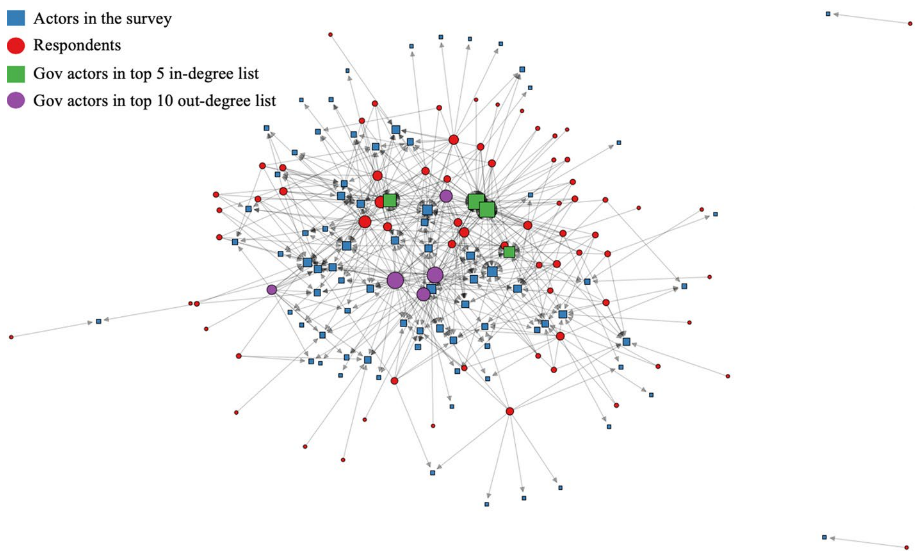

Fig. 4 Weekly collaboration actor network: 160 nodes; 478 ties; 95 isolates were removed; four Gov actors in top 5 in-degree list; five Gov actors in top out-degree list

only relies on the node degree centrality and can be directly applied to the bipartite network, as k-core is 'the maximal sub-graph with the minimal degree k' (Holme 2005).

We also calculated the density of the core. For the bipartite network, because there are only edges between two node sets, the maximum possible undirected ordinary density should be calculated according to Eq. 6 (Borgatti 2009). We normalized the results by dividing this maximum possible density to avoid misleadingly low results.

$$\frac{m \times n}{(m+n)(m+n-1)}$$

where n and m have the same definitions for Eqs. 3 and 4.

4 Results and discussion

Collaboration actor networks at the departmental level were mapped based on the data collected from the stakeholder survey. Figures 4 and 5 show the monthly and weekly collaboration actor networks respectively. The mapped networks are directed networks, meaning that the direction of a tie (or edge) is from survey respondents dictating the level of collaboration with actors listed in the survey. The blue nodes represent actors listed in the survey, while the red nodes represent survey respondents representing actor departments who took part in the survey. Isolates are not presented in the figures below. Sizes of nodes are proportional to their degree centrality in Figs. 4 and 5. The following analyses focus on weekly and monthly frequency levels.

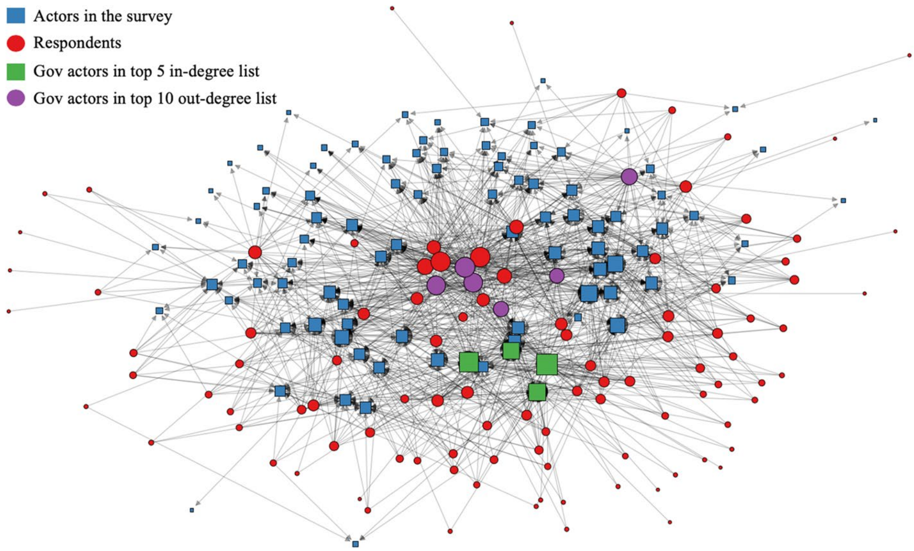

Fig. 5 Monthly collaboration actor network: 200 nodes; 1171 ties; 55 isolates were removed; four Gov actors in top 5 in-degree list; six Gov actors in top out-degree list

4.1 Degree centrality

We calculated degree centrality of each node according to Eq. 1. Tables S1 and S2 in the supplemental documents list actors in the survey with top 5 in-degree centrality and survey respondents with top 10 out-degree centrality at weekly and monthly collaboration respectively.

The degree centrality of actors at weekly and monthly collaboration are quite similar. Among five infrastructure sectors, actors of regional governance have higher degree centrality, particularly for actors with multiple departments involved in different infrastructure sectors, such as Harris County, City of Houston and Houston–Galveston Area Council. Actors from the community development infrastructure sector also have higher degree centrality, especially among respondents. This suggests that actors from the community development sector are more active in the network. Transportation actors (e.g., Texas Department of Transportation) have a higher degree centrality at the weekly level than monthly level. This suggests that transportation actors have more weekly coordination than other actors. However, when other actors include more coordination at the monthly collaboration level, transportation actors do not have more coordination. These results clearly indicate that transportation actors have more programs that need daily and weekly coordination with other actors.

On the other hand, we can see that governmental actors such as Harris County, City of Houston. and their departments (e.g., City of Houston Department of Public Work and Engineering and Harris County Engineering Department) have a relatively high degree centrality. Houston–Galveston Area Council, although not a governmental actor per se, is a regional organization with multiple departments that have close collaborations with local governments to solve problems and issues in Houston–Galveston area. This indicates that governmental actors, especially actors with multiple departments involving different infrastructures, may have increased access to resources and have more influence on collaboration of hazard mitigation in resilience planning.

Furthermore, Harris County Flood Control District (HCFCD) had a relatively high degree centrality, both as the actor in the survey and the survey respondent. This indicates that HCFCD not only has resources for collaboration but also is active in seeking collaboration with other actors. Actors in the survey roster with high in-degree centrality do not necessarily also have high out-degree centrality as a survey respondent. For example, the City of Houston has high in-degree centrality as the actor in the survey roster. However, departments of the City of Houston do not have high out-degree centrality compared to departments of Harris County and the Houston–Galveston Area Council. This may reveal that although the City of Houston has enough resources that other actors need to collaborate with, itself is not active in collaboration with other agencies.

The analysis of degree centrality could answer the first research question. The results indicate that governmental actors, especially actors with multiple departments involved in different infrastructure sectors (e.g., Harris County, City of Houston) play an important role in collaboration for hazard mitigation. Likewise, regional actors, through which local government consider and solve issues (e.g., Houston–Galveston Area Council) also have huge impacts on collaboration in terms of hazard mitigation. These actors have high in-degree centrality, which may imply that they have a more potential influence on improving collaboration and information dissemination in hazard mitigation.

4.2 Potential boundary spanners

To identify the potential boundary spanners in the collaboration actor network, we calculated betweenness centrality of each node. Table S3 and Table S4 in the supplemental documents show the results of betweenness centrality at different collaboration frequency levels.

The potential boundary spanners in the actor networks at weekly and monthly collaboration are similar. Although betweenness centrality does not necessarily have a high correlation with degree centrality, in this case, actors with higher betweenness centrality have higher degree centrality. Similar to degree centrality, actors of regional governance with multiple departments involving various infrastructure sectors, such as Harris County, the City of Houston, and the Houston–Galveston Area Council, have higher betweenness centrality and are more likely to be boundary spanners. Actors from community development sectors also have higher betweenness centrality and transportation actors have higher betweenness centrality at the weekly collaboration level rather than the monthly level. Governmental actors, likewise, have a relatively high betweenness centrality and are potential boundary spanners.

However, there are some actors with relatively low degree centrality that we identified as potential boundary spanners because of their relatively high betweenness centrality. These actors including Federal Emergency Management Agency (FEMA) and Center for Houston's Future at weekly collaboration, and United Way of Greater Houston, Houston Wilderness and Bayou Preservation Association at monthly collaboration. FEMA is reasonable to be the potential boundary spanner as they have a high likelihood of collaborating with actors from various infrastructure sectors in terms of hazard mitigation. Center for Houston's Future, Houston Wilderness, United Way of Greater Houston and Bayou Preservation, on the other hand, are in the strategic positions to connect actors that do not have coordination with other actors (Figs. 6 and 7). These actors, except for

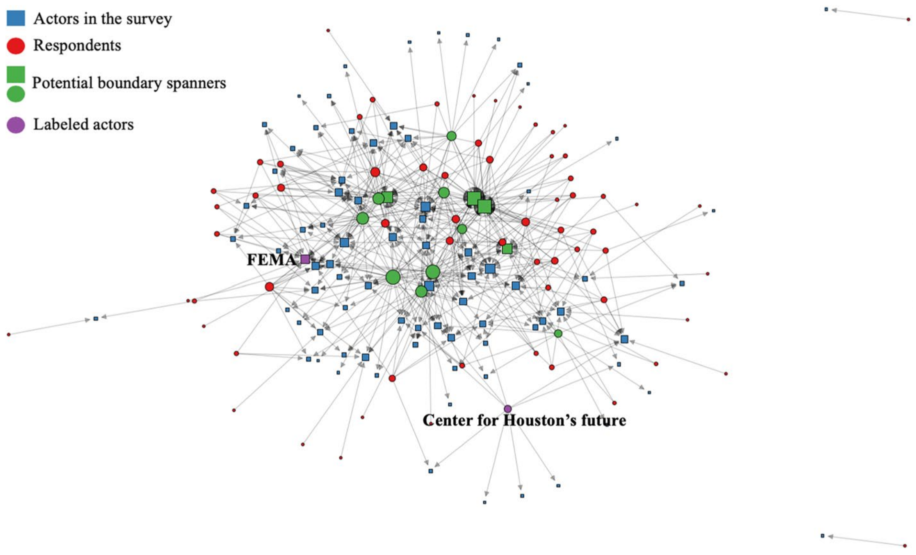

Fig. 6 Potential boundary spanners at weekly collaboration; labeled actors are potential spanners with relatively low degree centrality

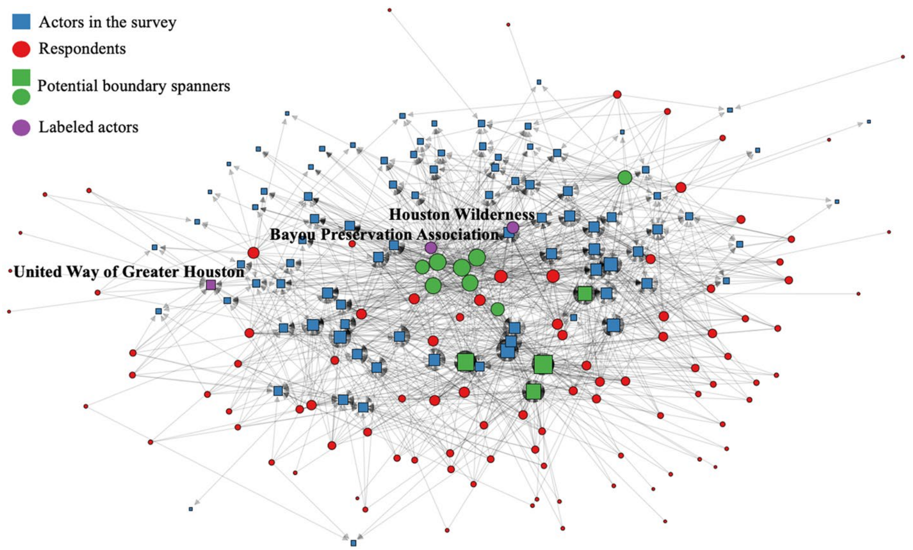

Fig. 7 Potential boundary spanners at monthly collaboration; labeled actors are potential spanners with relatively low degree centrality

FEMA, are non-governmental actors. This result suggests that non-governmental actors also play an important role in information dissemination and coordination improvement in hazard mitigation in resilience planning. Woodruff and Regan (2019) finds that non-governmental actors may offer unique and important insight into hazard mitigation and resilience planning efforts.

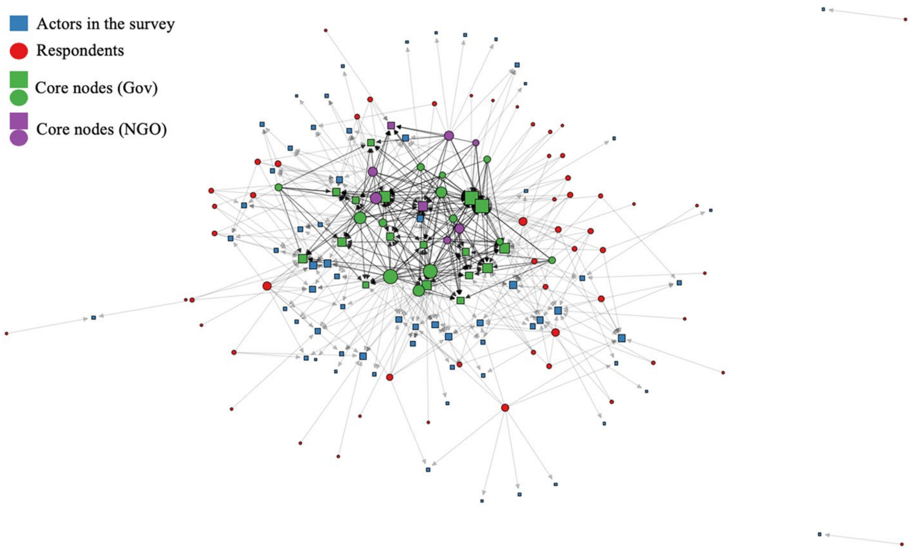

Fig. 8 Core and periphery at weekly collaboration; core density: 0.47; darker edges are edges in the core

Harris County Flood Control District (HCFCD) is the only potential boundary spanner from the flood control infrastructure sector, while most of the potential boundary spanners come from the community development infrastructure sector or governmental actors with multiple divisions. This implies that HCFCD plays an important role in disseminating potentially important information about hazard mitigation. Figures 6 and 7 show the potential boundary spanners (green and purple dots) at weekly and monthly collaboration.

The results of potential boundary spanners could answer the second research question by indicating that the governmental actors involved in multiple infrastructure sectors are the potential boundary spanners to connect otherwise separated actors. The result is highly correlated to their high in-degree centrality. This means many other actors would rely on the collaboration with these high in-degree centrality actors in disseminating and exchanging information. Actors with high in-degree centrality in the survey roster have more influence on improving coordination and information dissemination across different infrastructure sectors, as well as for hazard mitigation integration across diverse sectors.

4.3 Core and periphery

The K-core decomposition method was adopted to identify the core and periphery of the actor collaboration network. The method outputs the densest and smallest core (number of actors in the core) by default. Figures 8 and 9 show the results of core and periphery nodes in actor networks at weekly and monthly collaboration, designated by the blue and red nodes in the core, representing actors in the survey and survey respondents respectively. The darker edges show the links within the cores. Furthermore, to identify the makeup of infrastructure sectors in the core, the number of actors from each infrastructure sector are shown in Table S5 and Table S6 in supplemental documents. Table 2 illustrates the number of governmental and non-governmental actors in the cores.

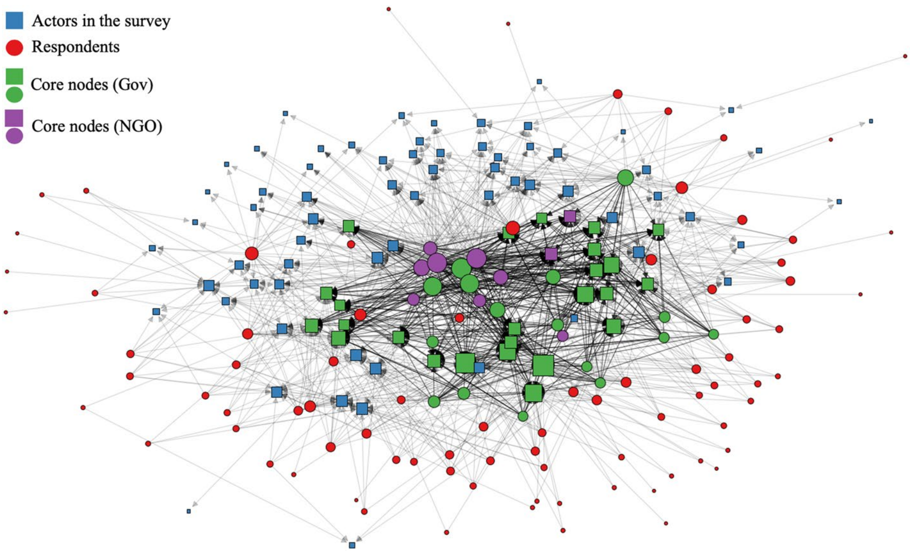

Fig. 9 Core and periphery at monthly collaboration; core density: 0.57; darker edges are edges in the core

Table 2 Number of governmental and non-governmental actors in the cores

Governmental and non-governmental actors	Weekly collaboration level	Monthly collaboration level
Governmental actors	29 (76%)	40 (78%)
Non-governmental actors	9 (24%)	11 (22%)

As illustrated in Figs. 8 and 9, the core nodes at the weekly and monthly collaboration level are densely connected, as the core densities[1] are relatively high: 0.47 and 0.57 respectively. The transportation sector and community development sector make up the largest proportions in the cores, while the transportation sector has the highest proportion in the core of actor network at weekly collaboration, and community development sector has the highest proportion at monthly collaboration. On the other hand, the flood control sector and environmental conservation sector have the lowest two proportion in the cores. Actors of regional governance who could be involved in multiple infrastructure sectors may also play an important role in keeping the cores diverse, as these actors occupy 15.8% and 19.61% respectively in the cores at weekly and monthly collaboration levels. By these actors reasonably distributing their resources to different infrastructure sectors, the procedure would help to keep the core function diverse and improve coordination of hazard mitigation across different sectors.

[1] We translated the cores to undirected networks when we calculated core densities. Due to the nature of the survey instrument, another direction would not be possible to identify. It would highly undervalue the core densities (half), if the cores were kept as directed networks when calculated the core density.

Furthermore, Table 2 shows that governmental actors comprise 76% and 78% of the core nodes at weekly and monthly collaboration levels respectively. Non-governmental actors have a low proportion in the core, with 24% and 22% at weekly and monthly collaboration respectively. However, Woodruff (2019) finds that non-governmental actors play an important role in the resilience planning process. This means that including more non-governmental actors in the cores would help resilience plans maintain high quality.

The results of core-periphery structure analysis could answer the third and fourth research questions by showing that governmental actors occupy nearly 80% of the cores and most of the non-governmental actors are in the periphery. On one hand, this means that governmental actors have greater influence in the collaboration network in terms of hazard mitigation, as demonstrated by the reactions to Hurricane Harvey. On the other hand, this also means that there is not enough non-governmental actors in the planning process. Including non-governmental actors in the planning process would impove the diversity of the cores and improve communication and coordination among actors from different urban sectors.

Furthermore, the cores of the collaboration network are not essentially diverse. Actors from the transportation and community development sectors comprise more than 50% of the cores, while flood control and environmental conservation sectors comprise less than 8% and 4% respectively. However, because governmental actors occupy a considerable proportion in the cores (15.80% and 19.61% respectively) and are involved in multiple infrastructure sectors, they are important in keeping the cores diverse by distributing their resources reasonably to different infrastructure sectors. This means that governmental actors with multiple departments involved different infrastructure sectors will help information dissemination and improve coordination in hazard mitigation across various infrastructure sectors if they distribute their resources reasonably.

5 Discussion

The results of SNA highlight that governmental actors had central positions in actor collaboration networks for hazard mitigation in resilience planning. Governmental actors had high degree centrality (both in-degree and out-degree centrality) and high betweenness centrality, and more than 75% actors (76% and 78% for weekly and monthly collaboration respectively) in the cores were governmental actors. The results imply that non-governmental actors were less involved in the resilience planning process. Also, based on results of core composition, we found that the resilience planning process prior to Harvey did not include diverse stakeholders across different urban sectors. The results are consistent with existing works of plan evaluation. Lyles et al. (2014) found that local planners were less involved in the government-oriented planning process to develop land use approaches, and involving local planner will greatly improve the quality of land use approaches (Burby 2003; Dyckman 2018). Woodruff and Regan (2019) found that non-governmental stakeholders, compared with governmental stakeholders, were less involved in the planning process for climate adaption plan development. They also argued that involving diverse stakeholders will greatly improve the quality of climate adaption plans. Furthermore, Kapucu (2005) and Opdyke et al. (2017) also found governmental actors had central positions in the coordination network of disaster emergency response and disaster recovery, which may cause barrier to effective emergency response and disaster recovery (Gajewski et al. 2011). The SNA of the actor collaboration also facilitated the understanding of the network positions of some important actors involved in hazard mitigation in resilience planning. In the following parts, we will discuss the network position of these actors in the collaboration network for hazard mitigation and we provide some practical recommendations to improve the coordination between governmental and non-governmental actors and actors across diverse urban sectors.

5.1 Important actors and their network positions

The HCFCD, as one of the most important actors of the flood control infrastructure sector, can be identified as occupying an important network location for information dissemination and coordination improvement in hazard mitigation. Results suggest that HCFCD had a relatively high degree centrality (both in-degree and out-degree centrality) and was also identified as the only potential boundary spanner in the flood control infrastructure sector. More importantly, in the cores of the actor networks, HCFCD, as both the actor in the survey and the respondent participated in the survey, contributed the major proportion of flood control sectors at weekly and monthly collaboration levels. This means that HCFCD is in a structurally efficient location to transmit information about hazard mitigation to other actors of different infrastructure sectors in the region. This would improve the coordination of hazard mitigation across diverse sectors in resilience planning. HCFCD has extensive collaboration with other actors (e.g., FEMA, USACE, Harris County Engineering, and City of Houston) regarding hazard mitigation accroding to its official website. For example, since Hurricane Harvey, HCFCD has completed and is working ongoing flood control programs in collaboration with USACE and FEMA.

The City of Houston has a higher in-degree centrality in the survey; however multiple departments within the City of Houston who responded to the survey have lower out-degree centrality in the stakeholder survey. This can imply that the City of Houston may have many other actors available for hazard mitigation purposes, but the individual city departments may not have essential collaboration with other actors. However, individual departments lacking coordination will still affect hazard mitigation integration in resilience planning and will prove to be a vulnerability to disasters. For example, if the City of Houston Fire Department does not have collaboration with USACE, they cannot get the information regarding how USACE maintains the reservoirs and how they prepare for the disturbances. Lack of this information would make that fire department unprepared for the potential dysfunction of the reservoirs, which would impede the mitigation efforts of their emergency response to the flooding triggered by the release. When federal agencies make hazard mitigation for disasters, the coordination and communication with local actors about their strategies and efforts are extremely important so that the information of hazard mitigation can be disseminated effectively.

USACE had relatively low degree centrality (both in-degree and out-degree centrality), low betweenness centrality and was not in the cores of collaboration networks for hazard mitigation. Based on the results of network properties, USACE had minimal coordination with other actors for hazard mitigation. However, USACE had a large impact on Hurricane Harvey. The release of the Addicks and Barker reservoirs led to flooding in the west Houston, where had never come across flooding in the history and was not flooded before the release. Most of the residents in this area did not purchase insurance for flooding (Shilcutt and Asgarian 2017), which increased their financial loss in the flooding and difficulty in recovery from disruptions. The position of USACE in the actor collaboration network may have increased the likelihood that USACE acted without thorough information of other hazard mitigation efforts going on in the area.

5.2 Recommendations

Based on the results of the network property analysis, there are some considerations that might increase the collaboration between actors to improve coordination of hazard mitigation across diverse sectors in resilience planning. First, the actors with multiple departments involved in different infrastructure sectors should take full advantage of their ability to influence the dissemination of information and improve coordination between various sectors. The departments of these actors should actively seek coordination with other actors and the resources between departments should be distributed reasonably to keep the coordination diverse. The actors of flood control sectors, such as the flood plain management departments of each city, should increase their collaboration with other sectors. Federal actors such as USACE should increase their further coordination and engagement with the local actors in hazard mitigation. More non-governmental actors should be involved in the resilience planning process so as to improve the coordination of hazard mitigation and quality of resilience plans. Furthermore, Dong et al. (2020) proposed that besides the examination of actor coordination networks, the integration of plans and policies that actors involved in, and the congruency of actors' norm could also be examined and improved to improve the institutional connectedness for better resilience planning and management of interdependent infrastructure systems.

6 Concluding remarks

The study reported in this paper examined network properties of actor collaboration networks in the Harris County, Texas area. We mapped the actor collaboration networks based on the data collected from a Hurricane Harvey stakeholder survey. Then we examined three network properties in this paper: degree centrality, boundary spanners, and core-periphery structure. Based on the results of examination, we discussed how these network properties affect information dissemination and coordination between actors of different infrastructure sectors, in terms of hazard mitigation across diverse sectors of urban development in resilience planning. The results show that actors, especially governmental actors with multiple departments involved different infrastructure sectors, are strategically located within the network to influence information dissemination and coordination of hazard mitigation. Also found was the fact that the cores of the actor collaboration networks are not sufficiently diverse, which may inhibit broad dissemination of information from a variety of sectors. Maintaining a diverse core would help improve coordination between actors from different infrastructure sectors.

The study provides insights into how the specific types of actors occupied structural locations, which carries important implications for coordination of hazard mitigation in resilience planning. Understanding the structural properties of actor collaboration networks for hazard mitigation and resilience planning may hold the key to understanding and improving the planning and implementation process for disasters such as Hurricane Harvey. Network analysis helps researchers to understand what actors have a potentially significant influence in coordination among network actors. It also highlights which actors play an important role in information dissemination, and how actors in the cores of the networks can improve coordination of hazard mitigation. Based on the results of analyses, recommendations can be made to increase the cohesion of the actor collaboration network, in areas such as Harris County, regarding coordination of hazard mitigation in resilience planning, thus improving the planning process and the quality of resilience plans.

This paper has some limitations and evolving future directions can be pursued. For now, there is not a clear threshold for identifying boundary spanners and in this paper, only potential boundary spanners were discussed. Developing a new method to identify boundary spanners could be a potential direction to better understand this network characteristic. Furthermore, only three network properties were discussed in this paper. More network properties could be studied and discussed in the future to better understand different roles of actors in the actor collaboration network. We present these limitations and possibilities for extending this line of research. To understand the structural properties of communication, coordination, and collaboration in hazard mitigation among actors is important so that the urban system would have better chances to improve collaboration and preparation for future disturbances.

Acknowledgements The authors would like to acknowledge funding support from the National Science Foundation RAPID project # (1760258): 'RAPID: Assessment of Risks and Vulnerability in Coupled Human-Physical Networks of Houston's Flood Protection, Emergency Response, and Transportation Infrastructure in Harvey.' CRISP project # (1832662): 'Anatomy of Coupled Human-Infrastructure Systems Resilience to Urban Flooding: Integrated Assessment of Social, Institutional, and Physical Networks.' Publication supported in part by an Institutional Grant (NA18OAR4170088) to the Texas Sea Grant College Program from the National Sea Grant Office, National Oceanic and Atmospheric Administration, US Department of Commerce. Any opinions, findings, and conclusion or recommendations expressed in this research are those of the authors and do not necessarily reflect the view of the funding agencies. Also, the authors would like to acknowledge Nandita Chaudhuri, Carol Goldsmith, Lisa A Halperin, Kirby Goidel, Steven Vanoye, Anthony S Jackson, Matthew Malecha, and Baiherula Abula for their help with data collection.

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Affiliations

Qingchun Li[1] · Bryce Hannibal[2] · Ali Mostafavi[1] · Philip Berke[3] · Sierra Woodruff[3] · Arnold Vedlitz[4]

✉ Qingchun Li
qingchunlea@tamu.edu

Bryce Hannibal
bryce.hannibal@tamu.edu

Ali Mostafavi
amostafavi@civil.tamu.edu

Philip Berke
pberke@email.unc.edu

Sierra Woodruff
swoodruff@tamu.edu

Arnold Vedlitz
avedlitz@tamu.edu

[1] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77840, USA

[2] the Bush School of Government and Public Service, Texas A&M University, College Station, TX 77843, USA

[3] Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX 77840, USA

[4] The Bush School of Government and Public Service, Texas A&M University, College Station, TX 77840, USA