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RESEARCH ARTICLE

A social network analysis of collaborative governance for the food-energy-water nexus in Phoenix, AZ, USA

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Abstract
Despite the known benefits of integrated policy and planning, traditional governance decisions in the food-energy-water (FEW) nexus are often made without cross-sector collaboration, potentially leading to unintended consequences and decreased resource security. Applying collaborative governance approaches to the FEW nexus provides an opportunity to shift towards integrated policy of food, energy, and water governance; doing so first requires an understanding of the limitations of current governance structures and the opportunities for change. We conduct a social network analysis of stakeholders in Phoenix, AZ using secondary data sources to construct the social network of collaboration and to analyze the ability of the governance landscape to facilitate or hinder collaborative governance. The social network measures indicate potential challenges to collaborative governance of FEW nexus stakeholders, such as limited trust between actors. However, leveraging bridging actors provides opportunities to increase collaborative governance between sectors. This research is important for implementing collaborative FEW nexus governance in practice.

Keywords Collaboration · Integrated resource management · Natural resource management · Resource security · Stakeholder analysis · Food-energy-water nexus

Introduction

Food, energy, and water systems are linked through social, economic, environmental, and technological processes. Policy, planning, and management decisions in one sector thus impact the related sectors (Clarke et al. 2018). The food-energy-water (FEW) nexus is a framework to enhance basic scientific understanding of these interconnected systems, as well as inform cross-sector collaboration and policy coherence (Endo et al. 2017; Saundry and Ruddell 2020). Despite the proposed benefits of a FEW nexus approach (Leck et al. 2015; Rasul and Sharma 2016), policy, planning, and management decisions about one sector are often made without full consideration of the impacts on the related sectors and the potential unintended consequences. Conventional environmental science and policy frameworks, which often focus on narrow disciplinary or management silos, may produce fragmented knowledge and inconsistent policies. This disjointed approach may underestimate cascading risks and lead to policies that ignore unintended consequences and fail to take advantage of possible synergies. To address these concerns, continued scholarship is necessary to refine key constructs and critically evaluate a FEW nexus approach to science, policy, planning, and management and to provide targeted and evidence-based recommendations for collaborative processes between FEW nexus sectors.

A focus on collaborative governance presents one potential avenue to promote coherent policies for the FEW nexus. To understand the potential of collaborative governance for food, energy, and water sectors, we must understand and critique current governance structures and social dynamics to reveal opportunities for and barriers to enhanced coordination. This involves applying principles from collaborative governance theory (Ansell and Gash 2008; Emerson et al. 2012) to the

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specific interconnected policy system of the FEW nexus. For new configurations of governance to move towards greater integration of the FEW nexus perspective, we must understand the limitations of current structures and identify opportunities for transformations. Social network analysis (SNA), a process of measuring interactions between actors (Borgatti et al. 2009), has been used to quantify and visualize the collaborative governance of a system (Baird et al. 2016; Fliervoet et al. 2016). By employing SNA to a system of collaborative governance between FEW nexus actors, we can better understand the system and create policy implications for improved collaborative processes.

This paper analyzes the FEW nexus to examine the collaboration between the sectors as a precursor to understanding the potential of collaborative governance to increase resource security, reduce cross-sector vulnerabilities, and facilitate policy coherence. We define collaboration as actors working together to produce, implement, or support policy, planning, management, or decision-making within the study area. We frame our analysis through the use of bridging structures and an associated set of analytical measures from SNA. Understanding the bridging structures of the network provides opportunity to identify and understand the collaboration between the food, energy, and water sectors and actors. These actors include organizations and stakeholders across food, energy, and water sectors and governance levels, such as electrical utilities, municipal water services departments, farms, irrigation districts, and state and local government agencies. From this analysis, we provide discussion points for facilitating collaborative governance of the FEW nexus in leading towards these desired outcomes. Our research provides several tangible contributions. First, we conduct our FEW nexus governance analysis at the metropolitan scale—a key decision-making level—complementing existing regional (e.g., Rasul and Sharma 2016), national (e.g., Bazilian et al. 2011; Howarth and Monasterolo 2016), and global studies (e.g., D'Odorico et al. 2018). Second, we characterize the stakeholder network through secondary data sources, including meeting minutes, joint policy committees, and operation plans. SNA using secondary data is an efficient approach to reveal the formal policy network, complementing perception-based studies (Daher et al. 2019). These contributions provide a foundation for understanding the complete institutional network and discourse for potential governance reconfigurations, which is a necessary step for future research on metropolitan scale FEW nexus governance. We examine the case of FEW nexus governance in Phoenix, AZ, USA, through SNA to diagnose the specific limitations of the current governance landscape, identify opportunities for change to facilitate collaboration, and provide recommendations for new configurations that will support collaborative FEW governance.

Conceptual background

Collaborative governance

Collaborative governance is an approach to public policy that engages actors across economic sectors and scales to affect the outcomes of planning, management, and decision-making processes (Ansell and Gash 2008; Emerson et al. 2012). As research on collaborative governance proliferated, this approach was applied to a range of policy contexts, from public administration (e.g., Emerson et al. 2012) to economic policy (e.g., Agranoff and McGuire 1998) to natural resource management (e.g., Koontz and Thomas 2006; Sullivan et al. 2019). Proponents of collaborative governance argue that this paradigm supports effective resource governance by addressing challenges of power asymmetries, enhancing accountability of the decision-making body, increasing transparency and reducing the political nature of the decision-making process, including stakeholders directly in knowledge generation and decision-making, and facilitating cross-sector coordination in planning (Ansell and Gash 2008; Emerson et al. 2012).

Collaborative governance has been critiqued, however, for lacking consensus in the definitions of key terms and in operationalization (Emerson et al. 2012), leading to the interchangeable use of the term with related concepts such as co-management and adaptive co-management (Plummer et al. 2013). This presents challenges for evaluation of collaborative governance approaches (Potts et al. 2016). Some scholars have also questioned the effectiveness of collaborative practices to improve environmental outcomes (Koontz and Thomas 2006). Furthermore, critics note that collaborative governance studies often fail to incorporate theories of power (Brisbois and de Loë 2016; Eberhard et al. 2017). Despite these critiques, the theory of collaborative governance provides utility for understanding integrated natural resource management in general and management of the FEW nexus specifically.

Food-energy-water nexus governance

The food-energy-water nexus refers to a systematic understanding of the interactions, trade-offs, co-benefits, and relationships between the three sectors (Bazilian et al. 2011). Taking a systems approach to the sectors may improve understanding of how decisions made in one sector can affect the other two, helping to reduce unintended consequences, increase resource security, and improve sustainability (Leck et al. 2015; Kurian et al. 2019). FEW nexus governance specifically is conceptualized as the communication and coordination among multi-level stakeholders and decision-makers across the sectoral boundaries of food, energy, and water (Lele et al. 2013). Scholars have discussed the importance of incorporating nexus thinking into the decision-making and governance processes of the three resources for comprehensive decision-making and disciplinary collaboration (Lele et al. 2013; Pahl-Wostl 2019). However, studies have shown that, in practice, many FEW nexus systems continue to have fragmented approaches to governance (e.g., Lebel et al. 2020). Several empirical studies have uncovered barriers to these collaborations, including power asymmetries (Weitz et al. 2017a; Pahl-Wostl 2019), lack of trust (Howarth and Monasterolo 2016), rigid sectoral planning approaches and regulations (Liu et al. 2018; Pahl-Wostl 2019), and lack of communication (Howarth and Monasterolo 2016; Weitz et al. 2017b; Liu et al. 2018).

Scholarship on FEW nexus governance has grown in recent years to better understand these barriers and governance challenges (Newell et al. 2019; Pahl-Wostl 2019; Opejin et al. 2020). Collaborative governance provides an opportunity to address these challenges. Using the Collaborative Governance Regime (CGR) defined by Emerson et al. (2012) as a foundational framework, we implement the three components of principled engagement, capacity for joint action, and shared motivation to create opportunity for overcoming existing FEW nexus challenges. Principled engagement includes effective *communication* between actors and sectors. Capacity for joint action includes *procedural and institutional arrangements* that facilitate collaboration, which can address challenges of rigid sectoral planning approaches and regulations. This refers to the protocols and organizational structures needed to manage repeated interactions (Emerson et al. 2012). Shared motivation includes the need for *trust* between actors. Focusing on the concepts of *collaboration*, *institutional arrangements*, and *trust* as proxies for three key components of the CGR framework, then, understanding the structure of these concepts within a specific FEW nexus case is an important first step to understand the limitations of current governance structures and identify opportunities at which collaboration can be implemented. We believe these three components are most important in understanding FEW nexus governance specifically because all three have been identified as key barriers to implementation of integrated FEW nexus governance (e.g., Howarth and Monasterolo 2016; Liu et al. 2018; Pahl-Wostl 2019). Thus, a FEW nexus governance system that is able to overcome these barriers is more likely to successfully engage in cross-sector collaborative governance. Employing the concept of collaborative governance to the FEW nexus provides a pathway to understand the nature of FEW nexus collaboration, and implementing social network analysis provides an approach towards understanding specific FEW nexus barriers to collaboration.

Network structures

Social network analysis is a method to understand the similarities, relationships, interactions, and knowledge flows between individuals and organizations (Borgatti et al. 2009). It has become an important tool for analyzing and understanding natural resource governance systems (Prell et al. 2009), as these systems consist of a variety of actors from different sectors who interact at multiple scales in heterogeneous ways (Salpeteur et al. 2017). Specifically, SNA is useful to understand the communication complexities present within the FEW nexus (Kurian et al. 2018). It can show the structure of the system to understand the functioning of the overall network (Prell et al. 2009); address patterns of actor relationships to identify potential power asymmetries (Bodin and Crona 2009); and highlight the multi-scalar nature of a governance system (Salpeteur et al. 2017).

In a network, actors or nodes refer to the stakeholders or organizations who are present within the network and ties refers to the connections between them; these nodes and ties create the structure of the network. Examining whole network structures can provide insight into the level of collaboration across the system, and node centrality measures can indicate the level of power or communication specific actors hold (Bodin and Crona 2009). Bridging structures, specifically, focus on the connections between different subgroups (Bodin and Crona 2009; Horning et al. 2016). Two network measures to understand the bridging properties of the network include betweenness centrality and the group E-I Index. Betweenness centrality is a node-level measure that identifies the specific actors who most serve as bridges within the network (Freeman 1978; Bodin and Crona 2009; Friemel 2017). These bridging actors can link multiple subgroups together (Horning et al. 2016). The group E-I Index, a measure of external versus internal ties, measures the level to which a group is oriented towards within-group embeddedness (Krackhardt and Stern 1988). External ties, also called bridging ties, are those across multiple subgroups, while internal ties are those within the same subgroup. This provides insight into the level of collaboration within and between multiple subgroups (Wasserman and Fraust 1994). Three additional measures of the whole network structure are also examined to provide insight into the collaborative governance of the whole system. The network E-I Index provides an indicator of whether the network structure is oriented towards distinct subgroups or holistic integration (Krackhardt and Stern 1988). Network centralization, the level to which one actor is most central to the network, can indicate the distribution of communication activity (Bodin et al. 2006; Bodin and Crona 2009). Density, the proportion of existing ties relative to all possible ties, can be an indicator of the level of trust within the network (Bodin et al. 2006). Table 1 provides an overview of the specific network structures used within this study and their indicator for collaborative governance within the FEW nexus.

In understanding the relationships between FEW nexus actors and sectors, social network analysis has been proposed as an approach to measure and visualize the collaboration of

Table 1 The overview of key SNA measures to understand collaborative governance components and bridging structures of the FEW nexus

Collaborative governance component	SNA measure	Type of network structure	Definition
Communication	Network centralization	Whole network	Indicates the level to which communication is controlled by one actor or distributed evenly across all actors (Wasserman and Fraust 1994)
Procedural and institutional arrangements	Network E-I Index	Whole network	Proportion of the difference between external and internal ties and the total number of ties across the whole network (Krackhardt and Stern 1988)
Trust	Density	Whole network	Measure of the number of ties divided by the total number of ties possible (Friemel 2017)
Bridging measurements	**SNA measure**	**Type of network structure**	**Definition**
Bridging actors	Betweenness centrality	Node-level	Sum of the shortest paths between all possible pairs of nodes that lead through that node (Freeman 1978; Friemel 2017)
Between-group interaction	Group E-I Index	Subgroup	Proportion of the difference between external and internal ties and the total number of ties within the subgroup (Krackhardt and Stern 1988)

the system (Kurian et al. 2018). SNA has been used in previous studies to examine the communication within each FEW nexus sector (Stein et al. 2014), for stakeholder identification and analysis (Hauck et al. 2016), to select the key powerful actors of the system (Kharanagh et al. 2020), and to quantify the level of communication between water actors and other FEW nexus stakeholders (Daher et al. 2019, 2020). These studies highlight the diversity of applications of SNA to understand the collaboration of FEW nexus actors. While these studies present strong analysis of the collaboration between FEW nexus governance actors, additional interpretation is needed for identifying barriers to and opportunities for collaborative governance of the FEW nexus.

Research approach

Study case: Phoenix, AZ

To analyze the limitations and opportunities for collaborative governance for the food-energy-water nexus, we examine the Phoenix metropolitan area in central Arizona, USA. Specifically, we focus on the Phoenix Active Management Area (AMA) as the FEW system in our study (Fig. 1). The Phoenix AMA is a hybrid hydrogeological and political water resource management district, specifically designated to regulate groundwater management. Organizations located within this boundary must adhere to certain FEW nexus policies,

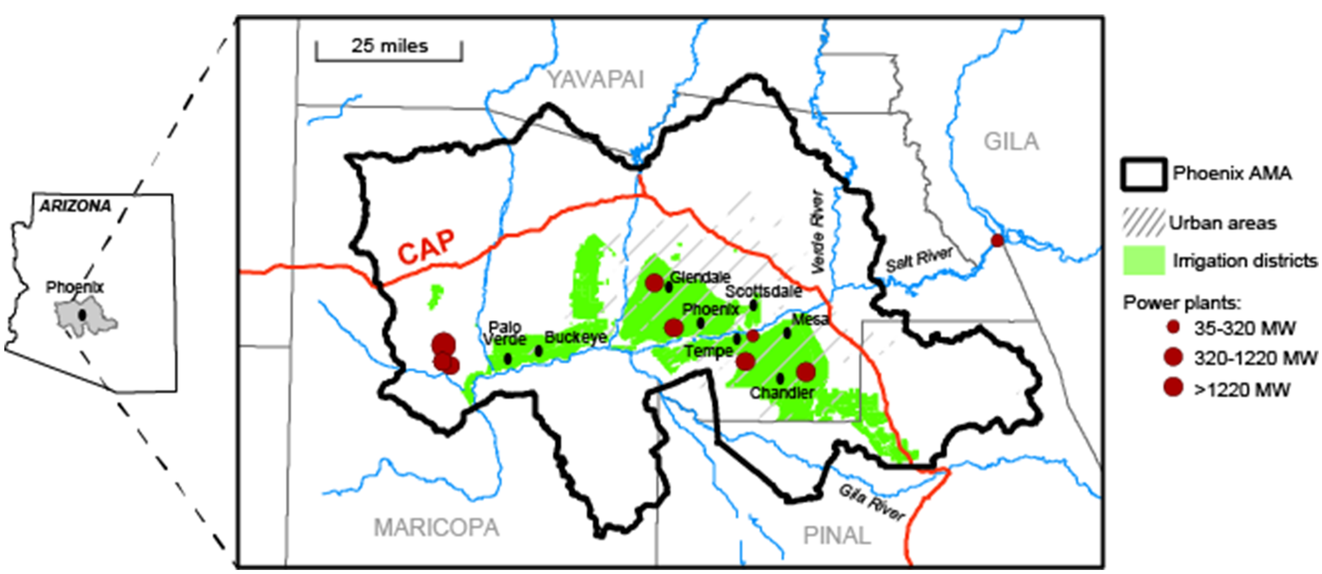

Fig. 1 The map of the Phoenix Active Management Area, including the cities and counties, rivers, power plants, and Central Arizona Project canal (source: White et al. 2017)

such as the inability to establish new agriculture within the boundary, limits on agricultural use of groundwater, and requirements for new developments to secure water resources before urban expansion can occur. Thus, the boundary sets parameters that can influence food, energy, and water governance. The Phoenix AMA covers an area of about 14,500 km^2 and encompasses the Phoenix metropolitan area, a rapidly growing region home to approximately 4.5 million residents. As described in White et al. (2017), the Phoenix area contains complex and interconnected water, food, and energy systems. For example, much of the water used within the Phoenix AMA is transferred via the Central Arizona Project (CAP) canal, which brings water 336 miles over 3000 ft of elevation gain from the Colorado River to central and southern Arizona; CAP is the single largest user of electricity in the state (Bartos and Chester 2014). Additionally, with a strong history and culture of agriculture throughout Arizona, about 32% of water within the AMA was used for irrigation as of 2017, despite the growing urban population (Arizona Department of Water Resources 2020).

The Phoenix metropolitan area includes a diversity of actors within the FEW nexus. The food sector is defined as actors involved in the production, processing, and distribution of food and agricultural products. These include governmental actors such as the AZ Department of Agriculture, small-scale actors such as family farm and irrigation districts, and commodity lobbying organizations such as the AZ Farm Bureau and the Arizona Cottongrowers Association. The water sector includes actors involved in the supply, delivery, reuse, and outflow of water resources (Wiek and Larson 2012), such as the Arizona Department of Water Resources, the Salt River Project (SRP, a joint electrical utility and water utility cooperative), the Central Arizona Project (a water supply, transport, and management agency), and municipal water services departments and regional associations. The energy sector includes utilities and regulators of electricity and energy such as the AZ Corporation Commission (which sets electrical utility rates for the state), Arizona Public Service (an electrical utility), and SRP. All actors included in the study are physically located within the Phoenix AMA. With the current linkages between resources in the semi-arid region of Arizona centered around water resources, using a designated area from the water sector provides a bounded system to explore the FEW nexus at the metropolitan scale.

Methods

We used secondary data to reconstruct the social network between food, energy, and water actors in the Phoenix AMA, following the methodology outlined by Williams and Shepherd (2017). Secondary data has been used to provide insight into FEW nexus governance in previous studies (Lebel et al. 2020). Our goal was to diagnose the potential limitations of the current governance structure to answer the following questions:

1. What does the structure of the network indicate about collaboration between food, energy, and water sectors? What are the implications for collaborative governance?
2. Who are the bridging actors between the three sectors? How can they facilitate greater collaboration within the network?

We employed social network analysis to investigate these two research questions. To address our first research question, we use the network measures of network centralization, the network E-I Index, and density to understand the structure of collaborative governance within the network. To address our second research question, we use betweenness centrality and the subgroup E-I Index to identify and understand the bridging actors.

Data collection and analysis

We began by collecting secondary data about the connections between FEW actors in the Phoenix AMA. Our sampling approach used purposive sampling of secondary data sources through deductive understanding of the study context as based on previous literature (Williams and Shepherd 2017). That is, we used our understanding of the study context to identify the initial sources for data collection, noted instances of and organizations involved in collaboration from those initial sources, and then searched for those organizations to find additional data sources that provided new instances of collaboration. We analyzed initial sources to direct us towards additional ones and continued to collect new data sources until further collection revealed no new collaborations between stakeholders (Williams and Shepherd 2017). We defined these data sources as any documents containing collaboration between food, energy, and water organizations or decisions made to manage these resources. We included organizations, not individuals, in the sources, and these data sources were bounded by a one-year timeframe (between April 2018 and April 2019). The secondary data used in the study included organization membership lists, meeting minutes, research projects, operation plans, board and committee member lists, contracts, legislative documents, and peer-reviewed publications. We used a total of 27 data sources and identified 93 actors. A complete list of the sources used for the secondary data and all of the identified stakeholders can be found in the data repository.

From these sources, we extracted stakeholder organizations. Each organization was classified as a water, energy, food, or cross-cutting actor based on its primary mission and functions. Cross-cutting actors refer to those whose mission did not lie singularly within any one sector (e.g., Arizona

Department of Environmental Quality). The organizations were then triangulated with peer-reviewed publications on the FEW nexus actors within Phoenix (e.g., Larson et al. 2013; White et al. 2017) to ensure the validity of the stakeholders identified. We created a symmetrical matrix with all the actors extracted from the data; we used a "1" to indicate collaboration between them and a "0" where no evidence of collaboration was found. We defined "collaboration" as membership in the same collaborative organization; involvement in the creation of joint legislation or policy; or contractual linkages. We assumed reciprocal relationships between all actors.

We employed UCINET 6.0 (Borgatti et al. 2002) to analyze the relationships within the FEW nexus. We evaluated measures of network density, network E-I Index, network centralization, node betweenness centrality, and subgroup E-I Index. Table 1 provides and overview of these measures and their significance within the FEW nexus. NetDraw software was then used to visualize the network to view the overall network structure.

Results

Examining the geodesic distribution of the network, the overall network structure includes a centralized core and a larger periphery. The core consists mostly of water organizations who are connected to one another, to centralized cross-cutting organizations, and to some centralized food organizations. The periphery consists mostly of food organizations and energy organizations. A geodesic visualization of the network can be seen in Fig. 2a. The quantitative measures of the findings are presented in two sections to address the research questions: (1) the collaborative governance components of communication, procedural and institutional arrangements, and trust, and (2) the bridging structures between the subgroups.

Collaborative governance components

Table 2 provides the results of the three network measures used to analyze the communication, procedural and institutional arrangements, and trust within the FEW nexus governance network. First, network centralization can be used as a proxy measure of the *communication* level in the network. Our analysis indicates a network centralization of 0.38, where 1 indicates a completely centralized network with all connections through a single actor and 0 indicates a perfectly distributed network (Wasserman and Fraust 1994). Thus, our value suggests a more distributed network structure, which may allow for increased communication as more actors are connected to others directly (Bodin et al. 2006; Bodin and Crona 2009). Second, the *procedural and institutional arrangements* of the network can be inferred from the network E-I Index. This provides an indication of the structure of the network overall and its orientation towards either within-sector or cross-sector collaboration, suggesting whether organizational structures of the sectors are suitable for engagement across them (Krackhardt and Stern 1988). It is measured on a scale between −1, full closure where all actors only collaborate with those outside their own subgroup, and 1, full bondedness where actors only collaborate with those within their own subgroup. With a value of 0.042, the network has a very slight tendency towards bondedness over closure of the subgroups. Finally, the density of the network can be an indicator for the level of *trust* within the complete FEW nexus system. From our analysis, the network density shows that 10.6% of the possible relationships exhibited collaboration between the organizations. This provides an indication of the level of trust within the network, relative to the potential level of trust (Bodin et al. 2006).

Bridging structures

To understand the bridging structures between the FEW nexus subgroups, node-level betweenness centrality and subgroup values of the E-I Index were measured. Table 2 provides an overview of these measures. First, the stakeholder with the highest value for betweenness centrality is Salt River Project, which may indicate that SRP has the greatest control over communication within the network and that the stakeholder can serve as a bridge between others. This may be because SRP is an umbrella of two entities, one is an agency of the state that serves as an electrical utility and the other is a water utility cooperative that manages the majority of water rights within the Phoenix metropolitan area, including significant rights to agricultural users. Its positionality within the network allows SRP to collaborate with many others on joint engagements regarding FEW nexus resources. The City of Phoenix and the Arizona Department of Agriculture also serve as network bridges. The high level of betweenness centrality for the City of Phoenix may be because it is the largest city in the Phoenix metropolitan area and is thus connected to many other groups to distribute services. For the state Department of Agriculture, the high betweenness centrality may come from the organization's multifaceted role as a regulator, state policy agency, and support system between the disaggregated agriculture actors and the state legislative bodies. Second, the values for group E-I Index show the level to which each sector is oriented towards internal-group collaboration or external-network collaboration. The food sector has about the same level of within-group and cross-sector collaboration. The water sector has more ties within the sector than with energy and food stakeholders. The energy sector, however, has more ties with non-energy FEW nexus stakeholders than within its own sector. However, the energy

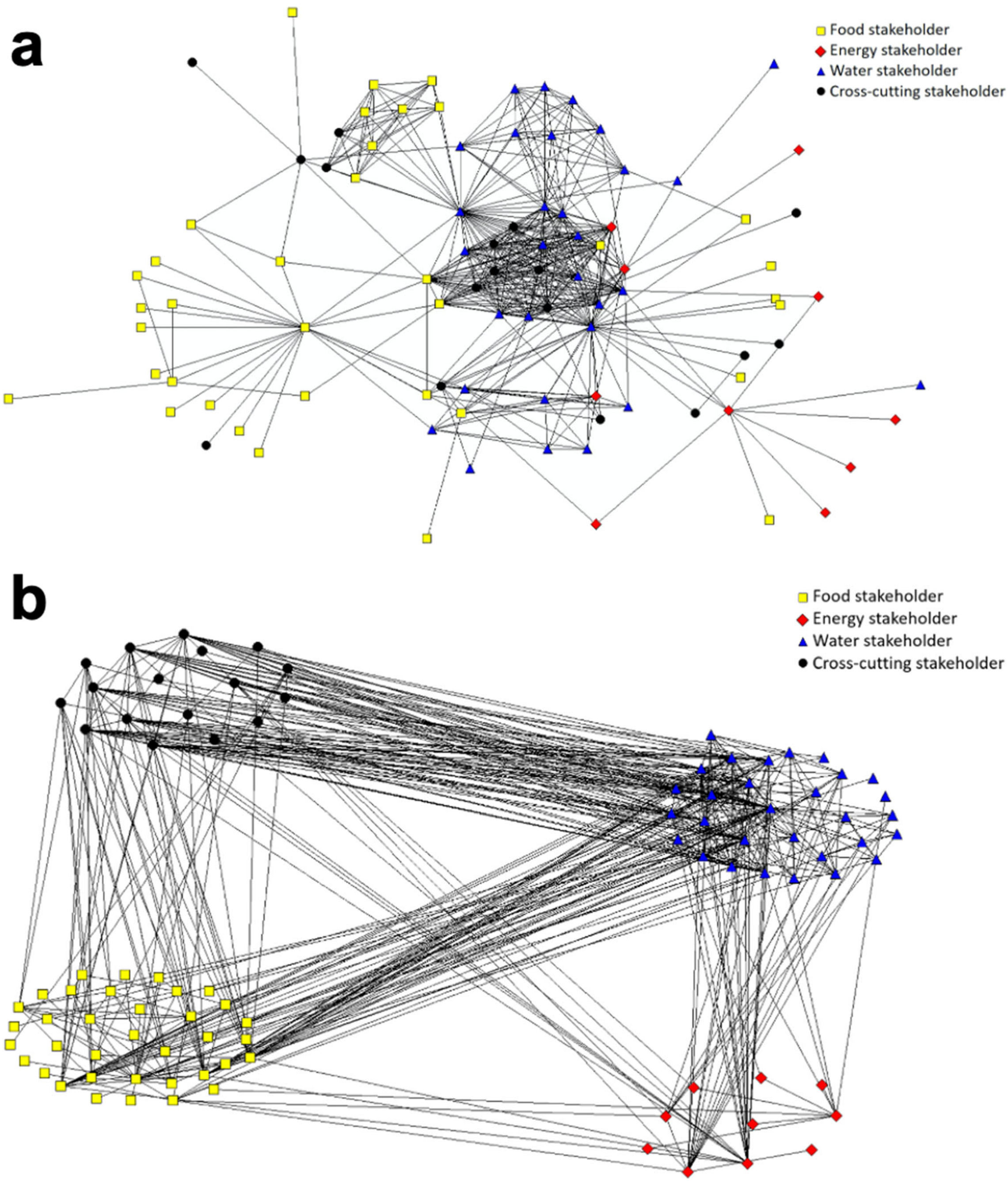

Fig. 2 The network of the actors in the FEW nexus of Phoenix **a** based on geodesic distances and **b** grouped by FEW nexus sector attribute

sector has a notably smaller number of actors than the other two and has many fewer ties overall. These subgroup values for the E-I Index may suggest that the water sector has greater within-group collaboration than the other two, while the energy sector has the greatest collaboration outside of its sector. A symmetrical density matrix between the three sectors provides greater detail regarding the two-way collaborative ties. As seen in Table 3, there is the greatest density of ties in the water-energy nexus, followed by the food-water nexus. The energy-food nexus has the lowest density, suggesting the lowest relative level of communication between these two sectors. A visualization of these relationships can be seen in the network visualization grouped by FEW nexus sector in Fig. 2b.

Discussion

Scholars have recommended increased collaboration across food, energy, and water sectors for integrated governance to manage risks, increase resource security, and achieve sustainability (Pahl-Wostl 2019). Integrated governance of the FEW nexus, then, would benefit from the implementation of

Table 2 Values and actors of key SNA measures at the whole network level and at the node level

SNA measure	Value	Actor or sector
Collaborative governance components		
Network centralization	0.381	--
Network E-I Index	0.042	--
Density	0.106	--
Bridging measurements		
Betweenness centrality	1334.02	SRP
	1283.95	City of Phoenix
	1187.77	Arizona Department of Agriculture
Group E-I Index	− 0.221	Water
	0.020	Food
	0.563	Energy

collaborative governance approaches. The results of our social network analysis provide insight into the opportunities for collaborative governance, limitations to collaboration, and implications for overcoming existing barriers. First, in understanding the network structure of the FEW nexus in the Phoenix AMA, we can identify opportunities for collaborative governance through successful components already in practice between the three sectors. The network centralization, as an indicator for the level of *communication* between FEW nexus stakeholders, shows a more distributed over centralized communication structure. This suggests that collaboration is not controlled by one or a few specific actors within the network, but instead is distributed throughout the network and allows for more complex and independent communication channels between actors (Bodin et al. 2006; Bodin and Crona 2009). Additionally, the E-I Index for the whole network, as an indicator of the level of compatibility between sectoral *procedural and institutional arrangements*, suggests that the network does not have a tendency towards either within-group or outside-group collaboration (Krackhardt and Stern 1988). This suggests that there may be a balanced level of collaboration between within-sector and cross-sector engagement.

Second, despite the opportunities that the network structure provides, the network also presents challenges for collaborative governance. As an indicator of the level of *trust* within the FEW nexus governance network, the density of the network may be low. This may suggest low levels of trust, cohesion, and reciprocity within the network (Bodin et al. 2006; Bodin and Crona 2009). Additionally, the cross-sector density matrix shows lower levels of density in cross-sector ties than in within-sector ties, suggesting that there may be less trust across the sectors than within them. With limited trust between actors and sectors, there may also be limited social infrastructure to facilitate collaborative governance arrangements for the FEW nexus (Kurian et al. 2018). The limited trust within the FEW nexus governance system would be consistent with previous literature on the FEW nexus that has cited a lack of trust as a key challenge to implementation of integrated approaches to FEW nexus governance (Howarth and Monasterolo 2016) and with literature on FEW nexus governance in Phoenix that uncovered a lack of trust as a reason behind limited FEW nexus decision-making (White et al. 2017). Additionally, the values for the group E-I Index show that the water sector has a greater level of collaboration within its subgroup than with cross-sector stakeholders, while the energy sector has greater collaboration with non-energy stakeholders, though energy collaborations overall are limited. This may be because water resources are the most limited, and thus the most central, resource in the Phoenix area, leading water stakeholders in the system to often collaborate with one another to manage the limited resource. The energy sector, on the other hand, consists of only a few actors with the major electrical utility, Arizona Public Service, operating independently from other energy stakeholders. As it is important to find within-group consensus for successful cross-sector collaboration (Mouraviev and Koulouri 2019), there may be a need for increased within-sector collaboration in the energy sector to facilitate future collaborative governance across the FEW nexus. These results may suggest that there is a need for greater trust and for greater within-group collaboration before cross-sector collaborative governance can improve.

Third, leveraging bridging actors can facilitate greater collaborative governance across the FEW nexus, which may allow stakeholders in the network to overcome existing barriers. Bridging actors can help to build trust among and coordinate increased communication channels between previously unconnected subgroups (Bodin and Crona 2009; Childs et al. 2013). This helps to overcome major challenge to collaborative governance of the FEW nexus in the Phoenix area and is a key component for successful collaborative governance (Ansell and Gash 2008). Of the three most prominent bridging actors, Salt River Project and the City of Phoenix are both situated at the center of water governance and decision-making (Larson et al. 2013) and are seen as having great influence over the governance of the integrated FEW nexus (White et al. 2017). As water is seen as the central resource within the Phoenix FEW nexus (White et al. 2017; Mounir et al. 2019), leveraging these water actors and their networks could provide an opportunity to bring together disconnected

Table 3 A symmetrical density matrix for the food, energy, and water sectors

	Water	Food	Energy
Water	0.324	--	--
Food	0.053	0.079	--
Energy	0.117	0.017	0.156

stakeholders and facilitate greater collaborative governance throughout the integrated FEW nexus in the Phoenix area. Engagement of centralized water actors can have great influence on governance of the food and energy sectors (Pahl-Wostl 2019). Likewise, the Department of Agriculture can serve as a bridge to specifically connect previously disconnected food and agriculture stakeholders to more central water and energy actors, thus facilitating collaborative governance by increasing collaborative connection with the food sector.

The results of the study are limited by the use of secondary data. Though secondary data provides examples of documented, as opposed to perceived, collaboration, this approach is unable to capture the depth or type of collaboration between the organizations. The study may also be limited by the use of descriptive network measures over more advanced analytical techniques. Despite these limitations, our study adequately addresses our research questions to provide an initial understanding of the collaboration between FEW nexus sectors. Additionally, the results show face validity with regional experts and with peer-reviewed publication, which note the challenges to collaboration across different sectors and the centralization of the water sector to local FEW governance (Larson et al. 2013; Bausch et al. 2015). Finally, the results are also consistent with those from previous studies of SNA of the FEW nexus in other locales, which noted high levels of communication between water actors but lower communication of water stakeholder with food and energy actors (Stein et al. 2014; Daher et al. 2019; Kharanagh et al. 2020). Future research could include the use of more sophisticated approaches, such as exponential random graph models, to further investigate the nuances of collaboration within the FEW nexus system.

Conclusion

Increased collaboration within food-energy-water nexus governance may increase sustainability and resilience across all three sectors (Clarke et al. 2018). Most resource managers, however, tend to operate in organizational verticals with limited communication across sectoral boundaries, based in part on bureaucratic design, efficiencies, and professional specialization. Using social network analysis to diagnose limitations and opportunities for collaboration of FEW nexus actors, the case of Phoenix, AZ, presents potential weaknesses in the governance landscape for supporting an integrated FEW nexus approach. The results of our network analysis, based admittedly on a limited snapshot in time, show some challenges for the implementation of collaborative governance, such as limited trust between stakeholders and sectors, which is consistent with prior literature that finds limited collaboration between FEW nexus sectors (e.g., Daher et al. 2019; Lebel et al. 2020). However, our analysis also provides opportunities for collaborative success, such as through a distributed structure to communication and through organizational structures that may align across sectors. To overcome existing challenges and implement collaborative governance in the FEW nexus, future policies and engagements should move towards an integrated over isolated approach by leveraging bridging stakeholders to strengthen governance and collaboration across the entire FEW nexus system. While these limitations and opportunities are specific to the Phoenix case, these findings may have implications for the FEW nexus in similar urban areas. Through these identified limitations and opportunities, we recommend governance shifts that directly engage bridging actors to increase trust between stakeholders and that foster collaboration both within and across sectors.

Code availability Not applicable

Author contribution DDW received grant funding for the study; JLJ and DW designed the study; JLJ conducted the analysis; JLJ drafted the manuscript; and DDW revised the manuscript.

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Data Availability Social network analysis matrix is available at: https://github.com/VADERASU/Social-Network-Analysis.

Declarations

Conflict of interest The authors declare no competing interests.

References

Agranoff R, McGuire M (1998) Multinetwork management: collaboration and the hollow state in local economic policy. J Public Adm Res Theory 8:67–91. https://doi.org/10.1093/oxfordjournals.jpart.a024374

Ansell C, Gash A (2008) Collaborative governance in theory and practice. J Public Adm Res Theory 18:543–571. https://doi.org/10.1093/jopart/mum032

Arizona Department of Water Resources (2020) Fourth management plan: Phoenix Active Management Area. Arizona Department of Water Resources, Phoenix

Baird J, Plummer R, Bodin Ö (2016) Collaborative governance for climate change adaptation in Canada: experimenting with adaptive co-management. Reg Environ Chang 16:747–758. https://doi.org/10.1007/s10113-015-0790-5

Bartos MD, Chester MV (2014) The conservation nexus: valuing interdependent water and energy savings in Arizona. Environ Sci Technol 48:2139–2149. https://doi.org/10.1021/es4033343

Bausch JC, Eakin H, Smith-Heisters S, York AM, White DD, Rubiños C, Aggarwal RM (2015) Development pathways at the agriculture–urban interface: the case of Central Arizona. Agric Hum Values 32:743–759. https://doi.org/10.1007/s10460-015-9589-8

Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, Steduto P, Mueller A, Komor P, Tol RSJ, Yumkella KK (2011) Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39:7896–7906. https://doi.org/10.1016/j.enpol.2011.09.039

Bodin Ö, Crona BI (2009) The role of social networks in natural resource governance: what relational patterns make a difference? Glob Environ Chang 19:366–374. https://doi.org/10.1016/j.gloenvcha.2009.05.002

Bodin Ö, Crona BI, Ernstson H (2006) Social networks in natural resource management: what is there to learn from a structural perspective? Ecol Soc 11:r2 http://www.ecologyandsociety.org/vol11/iss2/resp2/

Borgatti SP, Everett MG, Freeman LC (2002) Ucinet for Windows: software for social network analysis, Version 6. Harvard Analytic Technologies, Lexington

Borgatti SP, Mehra A, Brass DJ, Labianca G (2009) Network analysis in the social sciences. Science 323:892–896. https://doi.org/10.1126/science.1165821

Brisbois MC, de Loë RC (2016) Power in collaborative approaches to governance for water: a systematic review. Soc Nat Resour 29:775–790. https://doi.org/10.1080/08941920.2015.1080339

Childs C, York AM, White D, Schoon ML, Bodner GS (2013) Navigating a murky adaptive comanagement governance network: Agua Fria Watershed, Arizona, USA. Ecol Soc 18. https://doi.org/10.5751/ES-05636-180411

Clarke L, Nichols L, Vallario R et al (2018) Sector interactions, multiple stressors, and complex systems. In: Reidmiller DR, Avery CW, Easterling ER et al (eds) Impacts, risks, and adaptation in the United States: fourth national climate assessment, vol II. U.S. Global Change Research Program, Washington, DC, pp 638–668

D'Odorico P, Davis KF, Rosa L et al (2018) The global food-energy-water nexus. Rev Geophys 56:456–531. https://doi.org/10.1029/2017RG000591

Daher B, Hannibal B, Portney KE, Mohtar RH (2019) Toward creating an environment of cooperation between water, energy, and food stakeholders in San Antonio. Sci Total Environ 651:2913–2926. https://doi.org/10.1016/j.scitotenv.2018.09.395

Daher B, Hannibal B, Mohtar RH, Portney K (2020) Toward understanding the convergence of researcher and stakeholder perspectives related to water-energy-food (WEF) challenges: the case of San. Environ Sci Pol 104:20–35. https://doi.org/10.1016/j.envsci.2019.10.020

Eberhard R, Margerum R, Vella K, Mayere S, Taylor B (2017) The practice of water policy governance networks: an international comparative case study analysis. Soc Nat Resour 30:453–470. https://doi.org/10.1080/08941920.2016.1272728

Emerson K, Nabatchi T, Balogh S (2012) An integrative framework for collaborative governance. J Public Adm Res Theory 22:1–29. https://doi.org/10.1093/jopart/mur011

Endo A, Tsurita I, Burnett K, Orencio PM (2017) A review of the current state of research on the water, energy, and food nexus. J Hydrol Reg Stud 11:20–30. https://doi.org/10.1016/j.ejrh.2015.11.010

Fliervoet JM, Geerling GW, Mostert E, Smits AJM (2016) Analyzing collaborative governance through social network analysis: a case study of river management along the Waal River in The Netherlands. Environ Manag 57:355–367. https://doi.org/10.1007/s00267-015-0606-x

Freeman LC (1978) Centrality in social networks conceptual clarification. Soc Networks 1:215–239

Friemel TN (2017) Social network analysis. Int Encycl Commun Res Methods:1–14. https://doi.org/10.1002/9781118901731.iecrm0235

Hauck J, Schmidt J, Werner A (2016) Using social network analysis to identify key stakeholders in agricultural biodiversity governance and related land-use decisions at regional and local level. Ecol Soc 21. https://doi.org/10.5751/ES-08596-210249

Horning D, Bauer BO, Cohen SJ (2016) Missing bridges: social network (dis) connectivity in water governance. Util Policy 43:59–70. https://doi.org/10.1016/j.jup.2016.06.006

Howarth C, Monasterolo I (2016) Understanding barriers to decision making in the UK energy-food-water nexus: the added value of interdisciplinary approaches. Environ Sci Pol 61:53–60. https://doi.org/10.1016/j.envsci.2016.03.014

Kharanagh SG, Banihabib ME, Javadi S (2020) An MCDM-based social network analysis of water governance to determine actors' power in water-food-energy nexus. J Hydrol 581:124382. https://doi.org/10.1016/j.jhydrol.2019.124382

Koontz TM, Thomas CW (2006) What do we know and need to know about the environmental outcomes of collaborative management? Public Adm Rev 66:111–121. https://doi.org/10.1111/j.1540-6210.2006.00671.x

Krackhardt D, Stern RT (1988) Informal networks and organizational crises: an experimental simulation Author (s): David Krackhardt and Robert N . Stern Source: Social Psychology Quarterly , Vol . 51 , No . 2 (Jun ., 1988), pp . 123-140 Published by : American Sociological Associ. Soc Psychol Q 51:123–140

Kurian M, Portney KE, Rappaold G et al (2018) Governance of water-energy-food Nexus: a social network analysis approach to understanding agency behaviour. In: In: Managing water, soil and waste resources to achieve sustainable development goals, pp 125–147

Kurian M, Scott C, Reddy VR, Alabaster G, Nardocci A, Portney K, Boer R, Hannibal B (2019) One swallow does not make a summer: siloes, trade-offs and synergies in the water-energy-food nexus. Front Environ Sci 7:1–17. https://doi.org/10.3389/fenvs.2019.00032

Larson KL, Wiek A, Withycombe Keeler L (2013) A comprehensive sustainability appraisal of water governance in Phoenix, AZ. J Environ Manag 116:58–71. https://doi.org/10.1016/j.jenvman.2012.11.016

Lebel L, Haefner A, Pahl-Wostl C, Baduri A (2020) Governance of the water-energy-food nexus: insights from four infrastructure projects in the Lower Mekong Basin. Sustain Sci 15:885–900. https://doi.org/10.1007/s11625-019-00779-5

Leck H, Conway D, Bradshaw M, Rees J (2015) Tracing the water–energy–food nexus: description, theory and practice. Geogr Compass 9:445–460

Lele U, Klousia-Marquis M, Goswami S (2013) Good governance for food, water and energy security. Aquat Procedia 1:44–63. https://doi.org/10.1016/j.aqpro.2013.07.005

Liu J, Hull V, Godfray HCJ et al (2018) Nexus approaches to global sustainable development. Nat Sustain 1:455–476

Mounir A, Mascaro G, White DD (2019) A metropolitan scale analysis of the impacts of future electricity mix alternatives on the water-energy nexus. Appl Energy 256:113870. https://doi.org/10.1016/j.apenergy.2019.113870

Mouraviev N, Koulouri A (2019) The water-energy-food nexus lessons for governance. In: Policy and governance in the water-energy-food nexus: a relational equity approach, pp 161–165

Newell JP, Goldstein B, Foster A (2019) A 40-year review of food-energy-water nexus literature and its application to the urban scale. Environ Res Lett 14. https://doi.org/10.1088/1748-9326/ab0767

Opejin AK, Aggarwal RM, White DD, Jones JL, Maciejewski R, Mascaro G, Sarjoughian HS (2020) A bibliometric analysis of food-energy-water nexus literature. Sustain 12:1–18. https://doi.org/10.3390/su12031112

Pahl-Wostl C (2019) Governance of the water-energy-food security nexus: a multi-level coordination challenge. Environ Sci Pol 92:356–367. https://doi.org/10.1016/j.envsci.2017.07.017

Plummer R, Armitage DR, de Loë RC (2013) Adaptive comanagement and its relationship to environmental Governance. Ecol Soc 18. https://doi.org/10.5751/ES-05383-180121

Potts R, Vella K, Dale A, Sipe N (2016) Evaluating governance arrangements and decision making for natural resource management planning: an empirical application of the governance systems analysis framework. Soc Nat Resour 29:1325–1341. https://doi.org/10.1080/08941920.2016.1185557

Prell C, Hubacek K, Reed M (2009) Stakeholder analysis and social network analysis in natural resource management. Soc Nat Resour 22:501–518. https://doi.org/10.1080/08941920802199202

Rasul G, Sharma B (2016) The nexus approach to water–energy–food security: an option for adaptation to climate change. Clim Pol 16: 682–702. https://doi.org/10.1080/14693062.2015.1029865

Salpeteur M, Calvet-Mir L, Diaz-Reviriego I, Reyes-García V (2017) Networking the environment: social network analysis in environmental management and local ecological knowledge studies. Ecol Soc 22. https://doi.org/10.5751/ES-08790-220141

Saundry P, Ruddell BL (2020) The Food- Water Nexus. Springer, Washington, DC

Stein C, Barron J, Nigussie L, et al (2014) Advancing the water-energy-food nexus: social networks and institutional interplay in the Blue Nile. 1–14. https://doi.org/10.5337/2014.223

Sullivan A, White DD, Hanemann M (2019) Designing collaborative governance: insights from the drought contingency planning process for the lower Colorado River basin. Environ Sci Pol 91:39–49. https://doi.org/10.1016/j.envsci.2018.10.011

Wasserman S, Fraust K (1994) Social network analysis: methods and applications, vol 8. Cambridge University Press, Cambridge

Weitz N, Strambo C, Kemp-benedict E, Nilsson M (2017a) Closing the governance gaps in the water-energy-food nexus: insights from integrative governance. Glob Environ Chang 45:165–173

Weitz N, Strambo C, Kemp-benedict E, Nilsson M (2017b) Governance in the water-energy-food nexus: gaps and future research needs. Stockholm, Sweden

White DD, Jones JL, Maciejewski R, Aggarwal R, Mascaro G (2017) Stakeholder analysis for the food-energy-water nexus in Phoenix, Arizona: implications for nexus governance. Sustain 9. https://doi.org/10.3390/su9122204

Wiek A, Larson KL (2012) Water, people, and sustainability-a systems framework for analyzing and assessing water governance regimes. Water Resour Manag 26:3153–3171. https://doi.org/10.1007/s11269-012-0065-6

Williams TA, Shepherd DA (2017) Mixed method social network analysis: combining inductive concept development, content analysis, and secondary data for quantitative analysis. Organ Res Methods 20:268–298. https://doi.org/10.1177/1094428115610807