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Integrating resilience and nexus approaches in managing flood risk

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As climate change has worsened, so too has the risk weather-driven natural disasters pose to critical infrastructure, such as vital food, energy, and water systems. While both the concepts of a *food-energy-water (FEW) nexus* and *resilience* emphasize the interdependence of complex systems, academic studies have largely neglected a potential synthesis between the two. When applied in tandem, we believe the FEW nexus and resilience can be mutually reinforcing. Nexus approaches can enhance cross-sectoral evaluation and decision making in resilience planning, and resilience-oriented approaches can better situate the FEW nexus within a broader social, ecological, and governance context. From the small body of existing academic literature considering these concepts in tandem, we have identified a promising foundation for relevant future research that targets three key challenges: *coordination, scale*, and *heterogeneity*. Responding to these challenges, in turn, can lead to actions for constructing more resilient infrastructure systems that meet vital human needs in the midst of increasingly frequent floods and other extreme weather events.

KEYWORDS

community resilience, flood resilience, nexus approach, food-energy-water nexus, planning

1 Introduction

Natural disasters, such as flood events, disregard political jurisdictions, and impact multiple infrastructure sectors simultaneously. The system failures caused by extreme flooding typically cascade far beyond the impacted area, revealing both the sprawling nature and fragile interdependence of the critical infrastructures that have been constructed to meet the needs of modern societies. As climate change has made water-based disasters more frequent and more disruptive, societies have increasingly responded to the need for climate adaptation by making resilience a precondition for infrastructure funding. In the United States, the Infrastructure Investment and Jobs Act (2021) and the Inflation Reduction Act (2023) provide for more than $700 billion in infrastructure and climate funding, and mandate that climate adaptation planning be embedded into the federal grant application processes. Globally, over $30 trillion in Environmental, Social, and Corporate Governance (ESG) assets are increasingly being leveraged to address the causes and consequences of climate change (PwC, 2022).

Research undertaken by the authors points to the value of integrating resilience and nexus approaches to climate adaptation planning generally, and flood resilience planning in particular. Critical infrastructure resilience to climate change is advanced by planning that embraces a nexus approach, which provides a basis for structuring and supporting

the high level of coordination and cross-sectoral decision-making that interdependent systems demand (Belinskij, 2015). We substantiate this finding here by: (1) providing an overview of the food-energy-water (FEW) nexus and resilience as they are applied to infrastructure systems, (2) reviewing how the two approaches have been combined in both peer-reviewed academic and gray (i.e., community resilience plans) literature, and (3) outlining how three planning challenges associated with the FEW nexus and resilience—coordination, scale, and heterogeneity—can be overcome in ways that lead to more successful resilience planning.

1.1 Resilience, complex systems, and panarchy theory

Resilience has roots in social ecological systems, complex systems, and panarchy theory. Each emphasizes the interconnections between elements of different systems. Resilience is a "boundary object" (Baggio et al., 2015), with applications across many different disciplines, including community resilience (Norris et al., 2008; Berkes and Ross, 2016), urban resilience (Meerow et al., 2016), infrastructure resilience (Curt and Tacnet, 2018), ecological resilience (Adger, 2000), and social resilience (Adger, 2000; Davidson, 2010), to name a few. It is the shared focus on system interconnections that make resilience and nexus approaches natural complements.

The linkages between food, water, and energy make them representative of social-ecological systems (SES) that address the complex interactions between humans and the natural environment, captured by the broader concept of system of systems (Rinaldi et al., 2001). As complex systems, SES have characteristics that include uncertainty, emergence, nonlinear behaviors, and self-organization (Matei and Antonie, 2015). Emergent properties are system characteristics that arise through interactions between subsystems (Desouza and Flanery, 2013), meaning an emergent property cannot be understood by studying parts of a system individually (Berkes and Ross, 2016). Nonlinear behaviors result from feedback loops between connected system components (Sturmberg et al., 2017). Self-organization is where local interactions between an initially disordered system lead to a form of overall order.

Resilience is also closely tied to panarchy theory, a "conceptual model that describes the ways in which complex systems of people and nature are dynamically organized and structured across scales of space and time," (Allen et al., 2014). Panarchies include scale nesting and adaptive cycles (Benson and Garmestani, 2011). Each adaptive cycle is connected to, or nested within, other adaptive cycles, thus creating strong cross-scale interactions. A key characteristic of a panarchy, and therefore a key consideration when building resilience, is the presence of cross-scale or bottom-up cascades, in which the lowest adaptive cycles impact higher cycles within the system, creating the uncertainty characteristic of complex systems (Garmestani et al., 2008). An example of this is the disruption that Flynn (2015) caused to the transportation systems in metro-New York, that generated far-reaching disruptions to the regional intermodal transportation system and domestic and international air travel (Flynn, 2015).

1.2 The food-energy-water nexus

The food-energy-water nexus has its origins in the 2011 Bonn Nexus Conference on "The Water Energy and Food Security Nexus—Solutions for a Green Economy" (Endo et al., 2015). Nexus approaches such as FEW, are synergistic with systems of systems, and draw attention to the numerous points of interdependence among the food, energy, and water systems (Xiao et al., 2019). For example, the 2013 flood in Boulder, Colorado demonstrated the negative cascading impacts among critical systems where along with extensive power outages, six of the seven roads next to creeks washed out causing transportation disruptions. The washed-out roads, in turn, disrupted supply chains such as fuel shipments required to replenish backup generators and food supplies. Without electrical power, cell towers were compromised eroding communications and refrigerators could not operate resulting in food spoilage (Romero-Lankao and Norton, 2018). As this flood event in Boulder highlighted, the inherent interdependence of food, energy, and water systems translates into a growing risk of cascading failures across critical infrastructure sectors as the threat of extreme flooding grows with climate change (Howarth and Monasterolo, 2016). Nonetheless, food, energy, and water systems along with other critical infrastructure sectors are usually regulated independently, and are also addressed separately in resilience discussions (Roege et al., 2014; Tendall et al., 2015; Diao et al., 2016).

Nexus approaches are not only applied to food, energy, and water systems. Some researchers have situated ecology within the same nexus (De Roo et al., 2021), while at a more macro level, others have proposed a related water-migration nexus that highlights how environment and climate crises influence global migration (Nagabhatla and Fioret, 2020). While the nexus approach cannot be infinitely extended, as not all systems bear equally on each other, the analysis of overlapping nexuses can help to anticipate the cascading impacts of far-reaching threats. Contextualizing adjacent nexuses may also help inform the necessary level and scale of related resilience discussions. For example, while the overlap between a food-energy-water nexus and a water-migration nexus may not be relevant to resilience planning at a local level, it may be highly relevant to resilience discussions at the national and regional scales.

2 Flood resilience and the FEW nexus: planning and policy challenges

Given the limitations of resilience approaches that address only individual infrastructure systems, we have identified three challenges that must be understood and acted upon in order to capitalize on the advantage a nexus approach can provide for enhancing critical infrastructure resilience in the face of major disruptions to include flooding events:

- **Coordination**: Food, energy, and water systems are largely managed independently when coordination is needed across sectors.
- **Scale**: Food, energy, and water systems (including infrastructure, water bodies, and flood events) are complex and operate across global, national, regional, and local scales.

- **Heterogeneity**: Resilience planning must account for the heterogeneity of individual communities, to include differences in geography, political climate, population density, socio-economic conditions, and exposure to specific natural hazards.

The authors two exploratory studies were conducted to investigate the application of nexus approaches to resilience, broadly, and resilience planning, specifically. These studies deepen an understanding of the coordination, scale, and heterogeneity challenges, and suggest potential strategies for how they can be overcome. In the first study, a systematic literature review of peer-reviewed, academic literature was conducted. This revealed that, as of 2020, only twenty studies had combined the topics of the food-energy-water nexus with resilience (Raub et al., 2021a). In the second exploratory study, a document analysis was conducted to assess how the FEW nexus had been applied in the context of community resilience plans (Raub et al., 2021b). A common finding from the literature review was the recognition of infrastructure interdependencies. For instance, when an electrical substation is damaged as a result of a flooding event, it affects the water, telecommunications, and other systems that are connected to that substation. The literature review also found that while the food-energy-water nexus can usefully provide a starting point, other systems such as transportation should be added to the nexus, as needed (Raub et al., 2021a). Findings from the analysis of publicly available resilience plans suggested that, while reference to the FEW nexus was not explicit, there was evidence that a broader nexus approach was increasingly recognized as being relevant to resilience planning (Raub et al., 2021b).

2.1 Coordination in the face of siloed management

Traditionally, food, energy, and water systems have been managed separately across multiple jurisdictions with differing regulations, policies, and procedures (Arnold, 2009; Tendall et al., 2015; Smith et al., 2016). This siloed management structure impedes collaboration in resilience planning (Folke, 2016; Gonzales and Ajami, 2017; U. S. Energy Information Administration, 2020). The coordination challenge associated with building resilience therefore requires overcoming the constraints associated with individual infrastructure systems being run and managed by institutions within a given political jurisdiction, with each having complex relationships with other infrastructure-managing institutions (Gim and Miller, 2022). A prominent example of how cross-jurisdictional coordination can be facilitated is the interstate compact authorized by the U.S. Congress in 1921 that created the Port Authority of New York and New Jersey.

While there were elements of the resilience plans that showed signs of nexus thinking, direct application of a nexus approach to resilience planning and management of interconnected infrastructure systems would help address present coordination challenges. For example, the resilience plans showed an element of nexus thinking through the inclusion of partnerships and co-benefits in many of their resilience-building actions. In California, the City of Oakland's resilience plan initiated the creation of a Civic Design Lab, pulling a range of city departments and community stakeholders to partner in a shared problem-solving process, rather than assigning specific issues to individual entities in a division-of-labor approach (City of Oakland, 2016). Another indication of a nexus approach helping overcome coordination challenges in resilience planning was in the description of co-benefits within several of the plans. For example, Boston's resilience plan indicated that its action on neighborhood water management would prioritize the implementation of green infrastructure, such as tree plantings and green/blue roofs, which would also reduce extreme heat (City of Boston, 2017). By identifying and making co-benefits explicit, plan writers can convey positive impacts that each resilience building action would have on other systems thereby generating wider support for embracing the plans.

While many communities have framed coordination between systems in terms of efficiency, fewer have embraced coordination as essential for managing the risks associated with system interdependencies. For instance, Action 55 from Miami's resilience plan described how "significant efficiencies and cost-savings can be achieved with better planning and coordination of capital projects" (County of Miami-Dade et al., 2019). The plan points out that coordinating physical infrastructure work can mean only digging once, rather than doing the same work multiple times for different projects, sparing excess time, cost, and disruption. Missing, however, is an explicit recognition that coordination in mitigating risk across interconnected sectors can remove unnecessary points of failure and facilitate a more effective post-flood recovery.

2.2 Addressing cross-scale interactions

The difficulty of coordination across sectors and jurisdictions is coupled with the challenge of differing scales and specifying system boundaries, particularly within the context of the FEW nexus. Additionally, cross-scale interactions can arise in the context of how impacts to one infrastructure system can reduce or increase the impacts at other scales (feedback loops) depending on systems interconnections (Helmrich et al., 2023). For example, in the context of the 2013 flood in Boulder, Colorado, it was reported that zoning regulations (broader scale) helped to mitigate the impacts of the flood whereas the disruption to the transportation system (washed out local roads) amplified the impacts of the flood such as by hindering food supply chains, the movement of recovery workers to keep the wastewater treatment plant operational, and the repair of disrupted power lines (Romero-Lankao and Norton, 2018).

From another perspective, "studies on the FEW nexus often adopt a broad-scale top-down approach without considering the nexus' central importance at household, neighborhood or local levels, especially in rural contexts" (Leck et al., 2015, p. 454). One study of sustainable development at the FEW nexus found that policymakers often focused on the macro-scale and failed to adequately consider inevitably varied local perspectives (Biggs et al., 2015). Ultimately, building resilience requires a combination of bottom-up and top-down approaches. This is supported by the two exploratory studies described previously, which revealed

another aspect of the scale challenge—community engagement (Raub et al., 2021a,b). In any application of a nexus approach to resilience, people at the local level (e.g., those impacted by higher-scale decision making) must be included and consulted from the beginning if resilience planning is to be successful (Raub et al., 2021a,b).

Several strategies have been proposed to overcome scale and system boundary issues within food, energy, and water systems. The food system, especially in urban areas, is often heavily dependent on global supply chains (Paci-Green and Berardi, 2015), making it more vulnerable to overseas shocks and disruptions. A way to improve resilience in the face of this risk is to encourage more local sourcing of food (Smith et al., 2016). But tradeoffs must be considered. Should a disaster such as a flood event be experienced locally, a community will need access to food sources removed from the impacted area. For the energy system, resilience can be advanced by building microgrids that are networked to the larger, regional energy grid on normal days, but can continue to operate independently at the neighborhood level should others portions of the grid be knocked down by a disaster (Gilani et al., 2020). When there is a common water source used by multiple jurisdictions, scale challenges can be managed (Hughes and Pincetl, 2014) by developing a more local, decentralized, approach that uses stormwater capture, water reuse and recycling, and demand-side management (Gonzales and Ajami, 2017).

2.3 Heterogeneity and the importance of taking community differences into account

The concept of resilience can be difficult to operationalize since it can encompass approaches to managing all possible threats to many types of communities at differing scales (Pizzo, 2015). Some regions may prioritize building resilience to flood and hurricanes, which others focus on their exposure to earthquakes and forest fires. Some communities are closely intertwined with neighboring communities, while others may be more geographically remote and independent. Some may have ample resources at their disposal, while others have almost none. With respect to the FEW nexus, urban communities are generally net consumers of food, energy, and water, while rural communities often play a role in producing these resources (Sukhwani et al., 2019).

When applying a FEW or other nexus approach to resilience and planning, the heterogeneity of communities and local contexts means that these frameworks should only be used as starting points and then tailored to each scenario. For example, the two exploratory studies described previously (Raub et al., 2021a,b) provided insight into the need for flood mitigation and recovery efforts that account for infrastructure sectors beyond the food-energy-water nexus. For instance, since transportation, like energy, impacts every other system to which it was connected, it is essential to include it in resilience planning (Raub et al., 2021b). Additionally, while focusing on the resilience of infrastructure systems may naturally lead to technological solutions or increasing the robustness of a system, it is important to also understand and leverage the specific social and environmental contexts and connections of interconnected infrastructure systems (Markolf et al., 2018).

One strategy to consider that accounts for heterogeneity when promoting resilience is the use of high-level guidance or regulations that leave room for local tailoring to address individual contexts. There are examples of policy and planning efforts that have accommodated heterogeneity by establishing policies at the national level while directing that planning be done at the subnational or local levels. For instance, the Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act) requires the development of Hazard Mitigation Plans at the local level as a condition of gaining access to federal disaster funding. Similarly, the Coastal Zone Management Act assigns the lead to states and territories on developing Coastal Zone Management Plans so that they can be tailored to local challenges and aligned with state and local laws and regulations. Municipalities can create a Hazard Mitigation Plan for addressing their local needs, and coastal states are allowed to adopt management guidelines appropriate to their coastal zones.

While resilience plans should take into account distinct geographies, political jurisdictions, and hazards, many commonalities transcend particular locations. This important reality is eloquently highlighted in the County of Honolulu's resilience plan:

> No matter where we live on the globe, we all wrestle with similar challenges to our communities. Participation in this worldwide resilience 'ohana reminds us that sometimes difficult actions we take locally are not only being mirrored in other communities, but also adding up to global impact on a broad scale (City and County of Honolulu, 2019, p. 13).

Peer-reviewed literature and resilience plans typically address a variety of different shocks and stresses (Raub et al., 2021a,b). These ranged from flooding, drought, hurricanes, and earthquakes, to aging infrastructure, housing affordability, and systemic racism. Any given location has a distinct history, geography, and demographics, highlighting the need for tailored resilience building actions. However, when undertaking resilience planning, many communities find inspiration and take guidance from one another as reflected by the number of times community resilience plans reference actions from other communities' resilience plans. This has been advanced by the Resilient Cities Network (R-Cities), which has been formed out of the Rockefeller Foundation's 100 Resilient Cities Program. This initiative provides a model for building co-learning networks where expertise and pioneering approaches can be shared to accelerate their use throughout the world (Resilient Cities Network, 2023).

Overall, approaches such as the FEW nexus advance resilience by encouraging the convening of diverse perspectives for assessing benefits, tradeoffs and the cascading impacts of major disruptive efforts such as flooding. In short, while heterogeneity poses challenges, it can also be a strength when it leads cities and towns to experiment with new actions that can be shared within a broader network to facilitate learning that advances progress on a larger scale.

3 Discussion

The starting point for successful flood resilience planning is recognizing that the challenges of coordination, scale, and heterogeneity must be understood and overcome. Applying a nexus approach to resilience planning has promising potential for advancing that understanding and guiding actions for constructing more resilient critical infrastructure. Specifically, combining the FEW nexus with resilience concepts can motivate key stakeholders to embrace coordination among previously siloed sectors, encourage resilience planners to develop needed frameworks and approaches to work across scales, and help to drive the development of innovative strategies for building flood resilience that embraces the heterogeneity of communities. The diversity of scales and contexts means that resilience planners will need to tailor their approach to incorporating the FEW and other nexus approaches into their plans. While no two plans will be exactly alike, future research that examines resilience planning efforts underway at multiple levels are certain to find generalizable lessons that can be made available to all. Such an effort will help to respond to the urgent need for comprehensive resilience plans at the local, state, regional and national levels that can match the mounting risk of extreme weather events associated with climate change.

This article provides a call to action for scientists and planners to further this exploration of applying nexus approaches to advance community flood resilience. There are two important areas of for future research:

- Applications of nexus approaches to other resilience-related planning efforts that augment those captured as a part of the 100 Resilient Cities program. These should include how resilience is being incorporated into a number of other planning efforts, such as Hazard Mitigation Plans and Climate Action Plans (Raub et al., n.d.).
- Efforts that are being taken to overcome longstanding planning and operational silos in order to account for the connections and interdependencies among critical infrastructure systems and between communities and their environment.

Floods and other disasters associated with climate change will always impact the built and natural systems that human communities rely upon. Successful planning and research efforts for building resilience against flood events must consider complex interdependencies across multiple infrastructure sectors, at difference scales and jurisdictions, while being tailored to unique local circumstances.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Raub et al. (2021a,b).

Author contributions

KR: Conceptualization, Data curation, Formal analysis, Writing—original draft, Methodology, Project administration. SF: Conceptualization, Writing—review & editing, Supervision. KS: Conceptualization, Writing—original draft. CH: Writing—review & editing.

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Conflict of interest

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