Coastal resilience at the nexus of food, energy, and water: an interdisciplinary perspective for resilience planning

COASTAL RESILIENCE AT THE NEXUS OF FOOD, ENERGY, AND WATER: AN INTERDISCIPLINARY PERSPECTIVE FOR RESILIENCE PLANNING

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ABSTRACT

Global climate change poses increased threats to coastal communities. The resilience of coastal communities relies on the protection and continued availability of essential services such as food, energy, and water (FEW) systems. However, the intersection of FEW nexus research and coastal resilience planning has not been well explored. This dissertation seeks to further the goal of operationalizing resilience planning by examining the usefulness of resilience tools and toolkits that have been developed in recent years and exploring how the FEW nexus approach has been applied to coastal resilience planning in both academic and grey literature. The first chapter provides the history of resilience and the FEW nexus as well as the policy and planning challenges associated with combining the two bodies of research. The second chapter explores the utility of tools for on-the-ground resilience planning and implementation needs through interviews with members of state Coastal Zone Management (CZM) Programs and federal and nonprofit partners. Results suggested that local community needs are better addressed when end-users play a role in the tool development process and that CZM Program networks should be leveraged to identify solutions and disseminate information. The third chapter examines how the FEW nexus has been incorporated with coastal resilience planning in peer-reviewed scholarly articles through a systematic literature review. Results reveal three main findings: 1. The FEW nexus approach provides a method to consider systems interdependencies in the context of coastal resilience planning, 2. Coastal resilience planning should consider an energy-centric perspective of the FEW nexus, and 3. The FEW nexus should be expanded to include other systems, namely transportation. Building upon research of academic studies in chapter three, the fourth chapter investigated how the FEW nexus was incorporated into grey resilience literature. Resilience plans from eleven coastal US cities are assessed to understand: 1. How risks to food, energy, water, and transportation (FEWT) systems were addressed within the community resilience plans, and 2. To what extent a nexus approach had been used in resilience plan development. Results reveal that the transportation and energy were the most commonly considered while the food system was least represented within the resilience plans. A FEWT nexus perspective did not appear to be employed during creation of each cities' resilience plan. Chapter five concludes that the findings across these chapters support the idea that employing a food, energy, water, and transportation approach can enhance coastal resilience planning efforts, and is a valuable area ripe for future research.

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DEDICATION

I dedicate this dissertation to my mom, Cheryl A. Raub. I would not be who I am, or where I am now without you. I tribute my love of the ocean to you, which still inspires all aspects of my life – this dissertation included. I never got to tell you about this dedication, but I do not doubt that you always knew exactly how important you were to me. You always saw me more clearly than most everyone. I love you and I miss you.

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TABLE OF CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1: COASTAL RESILIENCE, THE FOOD-ENERGY-WATER NEXUS, AND THE PLANNING AND POLICY CHALLENGES

Climate change is causing extreme events in coastal and inland areas including (but not limited to) sea level rise, drought, flooding, and an increase in the frequency and severity of storms. Coastal and inland areas additionally face urbanization, aging and changing infrastructure, and security risks. In the face of increasing risk, the concept of resilience has become popular in coastal areas. Additionally, coastal communities rely on a number of systems for their health and wellbeing, namely food, energy, and water. These systems are also impacted by the vast number of hazards in coastal areas which can cause disruption of service. The nexus of food, energy, and water systems (FEW nexus or 'nexus') is increasingly advocated as its own unit of analysis as the three systems are heavily interconnected (Cairns & Krzywoszynska, 2016; Endo et al., 2015; Gallagher et al., 2016; Howarth & Monasterolo, 2016). Specifically, there is a growing body of research dedicated to identifying and understanding the implications of the interdependencies of critical infrastructure (Choi et al., 2001; Chtioui et al., 2016; Nan & Sansavini, 2017). Critical infrastructure refers to the systems relied on to support day-to-day life, such as, the energy grid, food distribution, or water treatment plants. As technology and society have advanced, individual critical systems have become increasingly integrated and interconnected (Nan & Sansavini, 2017). System interdependence means that a disruptive event in one critical infrastructure system can induce devastating consequences, or subsequent failure, within each system dependent on it. This dissertation focuses on the resilience of coastal communities and human populations in the context of food, energy and water systems and their interactions. To propose a metaphor, this dissertation acts as a Venn diagram and explores the intersection of coastal resilience planning and the food-energy-water nexus.

The following sections detail the histories of resilience and the food-energy-water nexus, respectively, and then define the challenges that arise when attempting to combine the two bodies of research in the context of planning and policy.

1.1. The History of Resilience

The concept of resilience has its roots in ecology and was proposed by Holling (1973) in the article entitled "Resilience and Stability of Ecological Systems." Resilience has evolved into a way of thinking about how to manage systems, "the resilience perspective shifts policies from those that aspire to control change in systems assumed to be stable, to managing the capacity of social-ecological systems to cope with, adapt to, and shape change" (Folke, 2006, p. 254). Social-ecological systems (SES) refer to the complex interactions between humans and the natural environment. SESs are complex systems/complex adaptive systems whose common characteristics include, emergence, uncertainty, nonlinear behaviors, and self-organization (Matei & Antonie, 2015). Emergent properties refer to system characteristics that arise as a product of the interactions between its subsystems (Desouza & Flanery, 2013), meaning the emergent property cannot be understood by studying individual parts of the system (Berkes & Ross, 2016). Nonlinear behaviors arise due to feedback loops between connected system components (Sturmberg et al., 2017). SESs, particularly in the context of natural systems, are characterized by having multiple stability regimes or equilibria (Folke, 2006). These system characteristics are key to understanding "resilience thinking." Resilience thinking was developed as “a theoretical framework for understanding what drives SESs, centered around the idea of resilience” (Folke et al., 2010, p. 1).

Resilience is also strongly tied with panarchy theory. Panarchy has been defined as 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). Panarchy diverges from a complex system through its inclusion of scale nesting (i.e. cross-scale interactions are important) and adaptive cycles (e.g. levels are not static, each evolves and functions across discrete ranges of scales) (Benson & Garmestani, 2011). Each adaptive cycle is connected to, or nested within, other adaptive cycles, thus creating strong interactions across scales.

A key characteristic of a panarchy, and, subsequently, system characteristics to consider when building resilience, is the presence of cross-scale, or bottom-up cascades (Garmestani et al., 2008). This means that the lowest adaptive cycles can impact interconnected adaptive cycles to produce change from the bottom to higher/larger cycles within the system. Bottom-up cascades often lead to the uncertainty and ‘surprises’ common to complex systems (Garmestani et al., 2008). Top-down control often fails in SESs as it assumes complete knowledge of the system (Zia et al., 2014). The importance of a bottom-up focus is echoed by Desouza and Flanery (2013).

The concept of resilience has been applied and defined in many different contexts. In the opening line of the first chapter of Resilience, Development, and Global Change, Brown (2016) begins “resilience has recently been described as a theory of change, a new development paradigm, a defining metaphor for our era, and a buzzword” (p. 5). Resilience has been used in a number of different fields, including, ecology, psychology, engineering, economics, social sciences and social-ecological systems (Baggio et al., 2015). The term resilience has been applied to community resilience (Berkes & Ross, 2013; Norris et al., 2008), urban resilience (Meerow et al., 2016), infrastructure resilience (Curt & Tacnet, 2018), ecological resilience (Adger, 2000), and social resilience (Adger, 2000; Davidson, 2010), to name a few. As such, resilience has many different definitions depending on the field it is being used in (Table 1.1).

Table 1.1. Examples of resilience definitions as applied to different fields and contexts.

Field	Definition
Social resilience	"The ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change" (Adger, 2000, p. 347).
Ecological resilience	"A characteristic of ecosystems to maintain themselves in the face of disturbance" (Adger, 2000, p. 347).
Community resilience	"The existence, development, and engagement of community resources by community members to thrive in an environment characterized by change, uncertainty, unpredictability, and surprise" (Magis, 2010, p. 401).
Urban resilience	"Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity" (Meerow et al., 2016, p. 39).
Engineered Resilience	"The ability of a system [the system can be a single system, an infrastructure, or even a System-of-Systems] to resist to resist the effects of a disruptive force and to reduce performance deviations" (Nan & Sansavini, 2017, p. 36).

While resilience has been defined as either bouncing back or bouncing back and transforming, and as a descriptive, neutral concept, or as a normative, good concept, three distinct, but not discrete, types of change within resilience have been described: resistance, incremental change, and transformation (Matyas & Pelling, 2015).

As there are many competing definitions of resilience, this dissertation conceptualizes resilience as bouncing back and transforming, meaning a community that seeks to become resilient should strive to be transformative instead of returning to a prior state. Resilience is also conceptualized as having a descriptive meaning- due to the uncertainty that accompanies resilience, there is no guarantee that a resilience-building action will result in an improved system or a less desirable system. This dissertation follows the definition of resilience presented by the Stockholm Resilience Center (n.d.):

> Resilience is the capacity of a system, be it an individual, a forest, a city or an economy, to deal with change and continue to develop. It is about how humans and nature can use shocks and disturbances like a financial crisis or climate change to spur renewal and innovative thinking.

1.2. The History of the Food-Energy-Water Nexus

Food, energy, and water systems are each pillars of human social development and wellbeing. Currently, food, energy, and water systems are all independently regulated and are often incorporated into broader resilience discussions separately (e.g., resilience of the food (Tendall et al., 2015) system, the energy system (Roege et al., 2014), and the water system (Diao et al., 2016)). These systems currently face a myriad of threats ranging from increased consumer demand to climate change (Howarth & Monasterolo, 2016). The challenge lies in how to adapt food, energy, and water systems to withstand these threats.

The concept of the food-energy-water nexus, or what was then called the water-energy-food nexus, began during the Bonn 2011 Nexus Conference on “The Water Energy and Food Security Nexus - Solutions for a Green Economy” (Endo et al., 2015). Nexus approaches refer to incorporating the interconnections and tradeoffs between target systems into the methodology of any research. These approaches identify that relationships and feedback between sectors are inextricably linked and encourage decision-making in coordination with other sectors rather than working in silos (Belinskij, 2015). More recently, the United Nations Sustainable Development Goals

(SDGs) include the provision of food, energy, and water (United Nations, 2020) and it has been argued that nexus approaches will be necessary to ensure that these SDGs are met (Liu et al., 2018).

There are multiple benefits to employing a nexus approach or a specific FEW nexus approach. For one, sectors can become more efficient if multiple are considered together (Minne et al., 2011). Nexus approaches can lead to identifying co-benefits, tradeoffs, consequences, and they can "enhance integrated planning, decision-making, governance and management" (Liu et al., 2018, p. 469). While the FEW nexus has historically been water centric, considering each of the sectors equally can reveal the connections between systems that may have been overlooked when considering them individually (Smajgl et al., 2016).

1.3. Coastal Resilience at the FEW Nexus: Planning and Policy Challenges

While various efforts to study resilience are underway, there is also no nationwide strategic plan to prepare for or implement disaster resilience and currently most federal hazard mitigation funding is only available after a disaster has occurred (Government Accountability Office, 2015). In the context of planning and policy, it is important to note that no US policy currently exists that incorporates FEW nexus considerations into resilience planning or policy. Even without FEW nexus considerations, there is no national resilience policy to either incentivize or mandate resilience planning in the US.

The only formal resilience planning incentivization in the US was via the 100 Resilient Cities program (*100 Resilient Cities*, n.d.). 100 Resilient Cities (100RC) was a program from the Rockefeller Foundation that funded 100 cities around the world to hire a Chief Resilience Officer and to write a city resilience plan. This program began in 2013 but has since ended and has been replaced by the Resilient Cities Network (*Resilient Cities Network*, n.d.). The Resilient Cities Network is comprised of approximately 200 cities around the world, but the Network does not provide funding to any of the cities. This means that resilience planning in the US is currently a voluntary endeavor with no formal guidance.

Resilience has been primarily studied within ecological, engineering, and social science, but the concepts are being applied to communities and cities (Folke, 2006; Pizzo, 2015). Since its appearance in urban planning in the 1990's, studies have not addressed the complex, multidisciplinary nature of resilience (Lu & Stead, 2013). Many studies describe the interdependence of the many physical and social systems involved in resilience and call for more integrative approaches to adaptation and mitigation planning against extreme weather events (Cheong, 2008; Hatzikyriakou & Lin, 2017; Lloyd et al., 2013). There is a need for "greater integration of research and policy analysis across sectors and regions," (Wichelns, 2017, p. 1), however, many challenges exist to doing so. The intersection of coastal resilience and the FEW nexus is a relatively unexplored area of research. Future research is needed to connect the FEW nexus of urban systems with resilience (Heard et al., 2017).

To begin the investigation into combining these two bodies of research in the context of policy and planning, this dissertation first defines the following four challenges that coastal communities will likely face when creating plans or designing policy interventions to build resilience at the nexus of food, energy, and water systems.

Defining these challenges provides the landscape in which this dissertation enters and the intersection of fields it hopes to advance:

- **Collaboration**: Food, energy, and water systems are currently managed independently.
- **Scale**: Food, energy, and water systems are complex and operate across national, regional, and local scales.
- **Heterogeneity**: Resilience building is unique per community.
- **Solutions**: There is a lack of established resilience-building techniques.

1.3.1. Collaboration Challenges

The FEW nexus approach requires that the intersection of multiple systems be considered, therefore, combining the nexus approach with coastal resilience planning will require the multiple systems in consideration to collaborate. However, a key challenge to collaboration is that each of the FEW systems are independently regulated. At the national level, food, water, and energy systems are currently managed by federal and tribal agencies and as a result, are managed under a diverse set of policies. Nationally, the US Army Corps of Engineers, the Bureau of Reclamation, and the Environmental Protection Agency (EPA) primarily manage the U.S. water system. The water system is regulated by a variety of policies including the Clean Water Act, Safe Drinking Water Act, National Environmental Policy Act, Endangered Species Act, and the Water Resources Development Act. Food systems are federally managed by the U.S. Department of Agriculture (USDA) and the Food and Drug Administration (FDA). The energy system is largely managed by the Department of Energy and, offshore, energy is managed by the Bureau of Ocean Energy Management and the Bureau of Safety and

Environmental Enforcement. These independent agencies and policies act to silo the systems and discourage collaboration.

As with the national level, food, energy, and water systems tend to be siloed at the local level as well, which does not entice collaboration. At the regional, state, and local levels, FEW systems are managed by the regional offices of federal and tribal agencies, municipalities, NGOs, and the private sector. At the state and local level, water services are provided both privately and publicly, with the majority of water services being provided publicly (Arnold, 2009). At this level, water and wastewater treatment facilities must still abide by the Clean Water Act as regulated by EPA. Local and regional electric utilities provide energy, but the energy grid is regulated by the US Department of Energy and interstate energy sales are regulated by the Federal Energy Regulatory Commission (FERC). One way in which states regulate retail electricity suppliers is through adopting Renewable Portfolio Standards, which require energy retailers to supply a certain amount of electricity from renewable sources (Saundry, 2019). Food provisioning at the local level is typically defined as either being via a “long” or “short” food chain (Smith et al., 2016). Long food chains encompass supermarkets in urban areas, which are driven by retailers and heavily regulated by industry and government, whereas short food chains are often characterized as the opposite of long food chains and include Community Supported Agriculture and farmers markets (Smith et al., 2016).

The FEW nexus and other nexus approaches could provide the context for otherwise siloed systems to collaborate. For example, a study of a flood event in Boulder, Colorado applied a nexus approach to target interviews with stakeholders from FEW sectors and then they intentionally included representation from each sector in the focus groups they used to create fuzzy cognitive maps of how the flood event impacted each key sector and residents of the community (Romero-Lankao & Norton, 2018). Results from a FEW nexus optimization model (i.e., economically optimized water use under political constraints) applied to countries in the Amu Darya Basin in Central Asia identified a "framework to provide economic motivation for all riparians to cooperate through the development of water storage infrastructure" (Jalilov et al., 2018, p. 407). Additionally, applying a nexus framework could incentivize collaboration through its demonstrated advantages. For example, a balanced Nexus framework was applied to the Mekong basin in which food, energy, and water systems were equally weighted (opposed to favoring one system) and found that it could better identify changes in cross-sector connections due to changes in single-sectors (Smajgl et al., 2016).

1.3.2. Scale Challenges

Food, energy and water systems have several scales of management considerations as there are many interconnected components of each system that operate across national, regional, state, and local levels. These varied scales result in challenges for operation across them within each of the sectors individually. The challenges are more complex when compounded across the sectors. Folke (2016, p. 7) summarizes "that studies and action of the local [scale] should not only focus on endogenous relations, but also account for and prepare for living and collaborating with influences from other levels [...] It is a truly intertwined social-ecological planet we are living on." Shared water resources often cross jurisdictional boundaries, yet local communities set independent usage priorities (Gonzales & Ajami, 2017). Food systems involve all aspects of "production, processing and packaging, distribution and retail, and consumption," each falling within, and connecting, multiple scales (Tendall et al., 2015). Energy systems also do not obey political boundaries, for example, in the United States, electrical systems are all interconnected (U.S. Energy Information Administration, 2020).

The challenge of operationalizing resilience at different scales is coupled with the challenge of specifying system boundaries, particularly within the context of the FEW nexus. If we take the energy system and the city of Boston, MA as an example, the system boundaries do not typically follow geographic/political boundaries and there are interconnections across scales. At the local scale, Boston as its own Local Control Center (LCC), one of six LCCs in New England, which operates transmission facilities rated 69 kV and below (ISO New England, n.d.). At the regional level, Boston is part of ISO New England, which is the Regional Transmission Organization (RTO) that operates the regional grid (ISO New England, n.d.). Finally, New England's power system is part of the Eastern Interconnection, an independent power grid that is one of four large grids in North America (ISO New England, n.d.). Even defining the boundaries of the city of Boston can be challenging as there are many neighboring regions with little transition between the two. Boston also does not produce all of its own food, it is connected to a broader food system. These systems do not operate in isolation-smaller scale systems connect to larger scale systems and each of these systems are interdependent with a multitude of other systems.

Several strategies have been proposed to overcome scale, or system boundary, issues within food, energy, and water systems. The food system, especially in urban areas, if often heavily dependent on global supply chains (Paci-Green & Berardi, 2015). Therefore, a more localized food system, such as one that incorporates more locally grown food, has been advocated to increase the resilience of the food system as it makes a community less vulnerable to global supply chain disruptions (Smith et al., 2016), although more vulnerable to local disruptions. With the energy system, building microgrids is a way to increase community resilience by disconnecting from the larger, regional energy grid in the event that it is disrupted due to a disaster (Gilani et al., 2020). Scale challenges with the water system can involve sharing a common water source with multiple jurisdictions (Hughes & Pincetl, 2014). A more local, decentralized, approach has also been advocated as a strategy to increase the resilience of the water system, such as turning towards solutions like stormwater capture, water reuse and recycling, and demand-side management (Gonzales & Ajami, 2017).

1.3.3. Heterogeneity Challenges

One of the key challenges with resilience, even without attempting to combine the FEW nexus, is that resilience is unique for every situation. Certain regions must build resilience in anticipation of earthquakes and forest fires, while others must consider the cascading impacts of flooding or hurricanes. The concept of resilience is broad as it encompasses a variety of scales and all possible events at those scales (Pizzo, 2015). The definition is broad in that it applies to a diverse set of potential threats, jurisdictional scales, and types of communities. Building resilience at the FEW nexus involves consideration of a complex set of tradeoffs. These tradeoffs are also unique to each region and scale that resilience is considered (Pittock et al., 2015). Additionally, resilience planning becomes extremely difficult due to this heterogeneity both within and across jurisdictional scales. National, regional, state, and local policies must be taken into consideration, meaning each community has different regulatory authority and limitations.

Heterogeneity also poses challenges when bringing the FEW nexus back into the discussion. Communities can be rural, urban, closely intertwined with neighboring communities, or be highly independent. For example, urban communities tend to be net consumers of food, energy, and water, whereas rural communities tend to be responsible for producing the resources, such as food via agriculture, for urban areas (Sukhwani et al., 2019). The heterogeneity between communities is important to consider as “studies on the FEW nexus often adopt a broad-scale top-down approach without considering the nexus’ central importance at household or village levels, especially in rural contexts” (Leck et al., 2015). Similarly, in a study of sustainable development at the FEW nexus, it was argued that policy makers have often focused on the macro-scale while inadequately considering the diverse perspectives at local scales (Biggs et al., 2015). Therefore, it is important to approach any policy or planning endeavor from more than just a top-down approach due to the heterogeneity between communities in which resilience-building actions occur.

One way that other policy and planning efforts have dealt with heterogeneity challenges is to have a national policy that authorizes planning at the state or local level. For example, this has been done with Hazard Mitigation Plans through the Stafford Act and Coastal Zone Management Plans through the Coastal Zone Management Act. The Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act) is the policy that guides the disaster assistance purview of FEMA. FEMA, under the Department of Homeland Security, manages the National Flood Insurance Program

(NFIP) and requires a Hazard Mitigation Plan for states and local communities to access federal funding. The Coastal Zone Management Act provides funding and the authority to manage coastal zones to coastal and Great Lakes states. These states are required to have approved Coastal Zone Management Plans. This method of implementation provides general guidance at the national scale but allows heterogeneity at the local scale. Municipalities can create a Hazard Mitigation Plan that targets the hazards and challenges most relevant to each location and coastal states can target the aspects of management that are most relevant to their coastal zones.

1.3.4. Solution Challenges

As noted earlier, resilience has not been well explored at the FEW nexus (de Grenade et al., 2016), meaning there are no well-established techniques for how to operationalize resilience. The concept of resilience needs to be translated into actions, but the outcomes of these actions are uncertain (Pizzo, 2015). It is difficult to mandate actions to build resilience when the appropriate actions are unknown or highly uncertain. To compound the solution challenge further, the actions needed to operationalize resilience will likely be unique per scale and context (Leck et al., 2015). Research is needed to identify potential resilience building actions and then further research is needed to learn how these actions fare per scale and context.

While a comprehensive set of prescribed resilience building actions is lacking, there have been several strategies developed for individual systems that seem promising. However, the challenge still lies in that these strategies will only be appropriate in specific circumstances and many do not take system interconnections into account. For example, managed retreat is a resilience strategy that involves removing property and systems from risky coastal areas (Abel et al., 2011). However, this strategy remains highly controversial and support is difficult to garner (Siders, 2019). Other flood resilience strategies include elevating buildings and purchasing previously flooded properties and returning them to open space (Mobley et al., 2020), installing living shorelines or other “green infrastructure” (Borsje et al., 2011), and increasing the use of permeable surfaces to improve drainage (Harvey, 2020). For the energy system, SmartGrid technologies can increase the systems resilience through strategies such as battery storage, microgriding, distributed generation, and an increased use of renewable energy sources (Hossain et al., 2016). When connecting the energy system to other systems, resilience strategies can take the form of ensuring that the other systems have emergency generators on site in the event of a power outage (e.g., Romero-Lankao & Norton, 2018).

1.4. Research Focus

Defining these challenges sets the stage for the following studies developed to explore the intersection of coastal resilience and the food-energy-water nexus. In this dissertation I study coastal resilience challenges from an interdisciplinary perspective to provide a first step in answering, “when you tell coastal communities to build resilience, what are you telling them to go do?” My dissertation will provide the following three research contributions: (1) I characterize the challenges that coastal communities face when trying to find coastal tools to aid in resilience planning and suggest ways in which these challenges can be addressed; (2) I synthesize the current state of academic coastal resilience planning that incorporates the FEW nexus; and (3) I assess how the FEW nexus has been incorporated into the resilience plans of 12 coastal U.S. cities. Finally, I assess how the three research contributions advance our understanding of how to overcome the four challenges that arise when combining the food-energy-water nexus with coastal resilience planning and policy.

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CHAPTER 2: HELPING COMMUNITIES ADAPT AND PLAN FOR COASTAL HAZARDS: COASTAL ZONE MANAGEMENT PROGRAM RECOMMENDATIONS FOR NATIONAL TOOL DEVELOPERS[1]

Abstract

Adapting to changing coastlines is an unprecedented planning challenge as coastal hazards, including those associated with climate change, influence all areas of resource management. Tools have been developed to aid in understanding coastal hazards and to facilitate the planning and implementation of adaptation strategies. Through interviews with members of eight geographically distributed state Coastal Zone Management (CZM) Programs and several federal and nonprofit partners, we explored the utility of current tools for on-the-ground adaptation planning and implementation needs. State CZM Programs operate as trusted information brokers at the nexus between national resources and local needs. Here we provide seven recommendations for how to overcome the challenges identified with tool discovery, lack of trust, and the coarse spatial resolution of national tools. Our findings suggest local community needs are better addressed when end-users play a role in the tool development process. We also recommend leveraging CZM Program connections because they have the knowledge and expertise to identify solutions and disseminate information. While the recommendations presented here were taken from the perspective of state CZM Programs regarding coastal tools, the lessons learned may provide valuable insight into the tool development process for other resource management fields.

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2.1. Introduction

Coastal hazards are complex issues, as are the efforts needed to adapt and build resilient communities (Curtice et al., 2012; Dyckman et al., 2014; Few et al., 2007; Spaulding et al., 2016). Key challenges in planning for coastal hazards include understanding and predicting the probability of the timing and severity of future events and evaluating risk tolerance (Spaulding et al., 2016). All coastal communities must engage in adaptation planning[2] and implementation to continue to thrive on our nation's dynamic and changing coastlines. We define coastal communities as all stakeholders living and working in the coastal zone of the ocean and Great Lakes states and territories, including local governments, businesses, and other organizations. To plan for the future, these communities must have access to risk information and knowledge at appropriate scales and levels of reliability.

Ensuring community access to reliable and usable information is a function of the Coastal Zone Management Program (CZM Program). The Coastal Zone Management Act (1972) is a voluntary state-federal partnership that provides assistance to states with federally-approved CZM plans. Currently, 34 of the 35 eligible states and territories participate in the program. Each state plan is designed to implement CZMA in accordance with specific state needs, in partnership with NOAA's Office for Coastal Management (OCM). State and territory CZM Programs work with federal agencies and collaborate with regional and local partners such as universities, regional planning commissions, and local businesses. Through these partnerships, state CZM Programs

[2] Adaptation planning can be defined as visioning for long-range planning horizons that incorporate uncertain scenarios that guide smart development practices and investments to achieve a community's vision for the future.

provide planning, financial, and technical assistance to local communities and take the lead in managing coastal resources using their expertise and on-the-ground knowledge of issues. Between 2012 and 2017, state and territory CZM Programs worked with 1,165 coastal communities nationwide to undertake coastal hazard mitigation efforts (Coastal States Organization, 2018). Recent CZM Program-led efforts included implementation of the Coast Smart program in Maryland that helps communities prepare for short and long-term coastal hazards, the Coastal Hazards Planning Guidance developed for Indiana's local governments, and the Texas Coastal Resiliency Master Plan that significantly helped the state recover after Hurricane Harvey (Coastal States Organization, 2018).

State and territory CZM Programs characterize and prioritize the different coastal hazards impacting their coastlines that include discrete, single events such as hurricanes and tsunamis and chronic issues such as flooding, lake level changes, and shoreline erosion all of which are exacerbated by the impacts associated with climate change. In 2017, the hurricane season alone included three of the five most expensive natural disasters in U.S. history, and the impacts of these storm events were compounded by climate-driven sea level rise (NOAA National Centers for Environmental Information, 2018). Ultimately, the complexity of the issue has resulted in the proliferation of tools[3] intended to support local decision-making. The U.S. Climate Resilience Toolkit alone hosts approximately 500 tools from a variety of organizations and agencies (U.S. Federal Government, 2015). Many of these resources are national in scope and developed by federal agencies and national non-governmental organizations (NGOs). Online resources have been developed to curate these resources and to help users determine which tools

[3]The term "tool" encompasses resources ranging from decision support documents to GIS analyses.

are appropriate for a given purpose. The Climate Adaptation Knowledge Exchange (CAKE) helps users manage their time and navigate the unwieldy number of resources by identifying and explaining relevant data tools and other information (EcoAdapt, 2017).

As the coastal zone combines dense development and critical infrastructure in areas prone to flooding and severe weather, many adaptation tools focus on the coast. The link between large-scale efforts and local communities is important because climate adaptation is a national priority (Lysák & Bugge-Henriksen, 2016) yet adaptation and mitigation planning often occur at the local level (Fu et al., 2017; Measham et al., 2011). National resources include the Sea Level Rise and Coastal Flood Web Tools Comparison Matrix that compares the functions and methods of sea level rise and coastal flood web tools (The Nature Conservancy et al., 2017), and NatureServe's guide for adaptation planners to assist in ecosystem-based climate planning (Rozum & Carr, 2013). Coastal communities may lack the capacity to gather information and develop tailored solutions to meet the needs of their local economic, political, social, and environmental conditions, therefore these national tools may be the only resources available to them.

The role of local governments, local NGOs, and the private sector in adaptation and mitigation planning is critical (International Federation of Red Cross and Red Crescent Societies et al., 2009) and national support must be directly linked to, and aligned with, the local communities building resilience against coastal threats. However, we have little understanding of how useful national tools are for their intended audiences. In this manuscript we explore the utility of available tools for on- the-ground adaptation planning and implementation and generate a distilled set of principles that can be used by any national agency or organization involved in the tool development process to improve the usability of future tools. As described previously, state CZM Programs partner with a wide range of state, federal, and NGO tool developers and serves as a bridge between national programs and coastal communities. We focused on understanding community needs from the perspective of state CZM Programs, as they are trusted brokers of information for these end-users. CZM Staff work with communities throughout their coastal zone, therefore we also gained a comprehensive perspective for a broad range of community types by using this approach.

2.2. Methodology

2.1.1. Interviews

To understand the relationship between national-level tools and the needs of local communities, 22 state agency employees representing CZM Programs, along with a local planner, and three federal agency partners were interviewed in 2016[4]. In an effort to create a national picture of the issue, interviewees were selected from four regions: the East Coast (New Hampshire, Rhode Island, and Maine), Gulf Coast (Florida), the Great Lakes (Illinois, Indiana), and the West Coast (California, Washington). We specifically sought out state CZM Program staff that work directly with local communities on coastal adaptation and implementation efforts. In addition, three interviews were con- ducted with federal employees whose agencies are responsible for tool and/or toolkit development[5]. To ensure consistency, a set of defining terms was provided at the beginning of each interview[6]. We use the terms "externally-developed" or "national tools" to distinguish tools created by federal agencies or NGOs that are national in scope

[4] The coastal program interview questions used can be found in Appendix A.
[5] The "developer" interview questions used can be found in Appendix B.
[6] The terms are provided in the Glossary.

and not developed with a single state or community in mind. This terminology is continued throughout the report, and definitions for these and other common terms can be found in the Glossary (found at the end of the chapter).

2.3.2. Internal Reviewer Input

Using the information collected during our interviews, a manual, qualitative content analysis (Bengtsson, 2016) was used to generate the findings and recommendations presented in the following sections. In order to create a cohesive narrative that reflects the common views expressed by CZM Programs, this manuscript was reviewed by all interviewees, Coastal States Organization (CSO) Staff, additional state CZM Program staff not involved in the initial interviews, and NOAA-OCM Staff working on the Digital Coast. CSO is a nonpartisan nonprofit organization whose Staff works to support the work of the CZM community and to help unify these national programs on coastal topics. The Digital Coast is a web-based collection of resources and a partnership designed to support coastal management practitioners; these NOAA Staff are considered experts in national tool development and resource curation for coastal users. Therefore, to the best of our knowledge and ability the findings reported here represent consensus views from coastal management practitioners and expert partners knowledgeable on the needs of coastal communities. Unless otherwise stated, the recommendations provided below are intended for representatives from national agencies, NGOs, academic institutions or other groups involved in developing and implementing tools that are intended to assist coastal communities with planning for and adapting to the impacts associated with climate change.

2.3. Findings

Despite the abundance of national coastal tools, state CZM Program representatives stated that communities rarely use them and reported three key challenges to using existing tools:

1. Finding tools that suit the needs of the user to address a specific problem.
2. Intended users lack trust in tools and toolkits.
3. Tools are rarely available at sufficiently high resolution for decision-making.

Overall, we contend that tools developed to help communities in the future could be more impactful if they were more informed by the local needs and constraints of the intended end-users. The recommendations provided below are a first-step in improving and informing this process with respect to three main challenges: Discovery, Trust, and Resolution. We understand that these are overlapping categories and recommendations can address multiple issues.

2.3.1. Discovery

CZM Program Staff expressed feeling overwhelmed by the quantity of tools available and noted challenges with the search process due to limited program capacity and the non-specificity of the term "tool." The challenges described here were also identified by a California Energy Commission 2007 study, which found that the ability of local coastal managers to prepare for current and future threats is inhibited by monetary constraints and limited staff resources (Moser & Tribbia, 2007). The broad use of the term "tool" complicates the search process as it can be used to describe products ranging from phone applications, to story maps, or technical reports on best practices. Additionally, the language used to describe tools does not necessarily match the language used by local communities. For example, the word "conservative" can be read to imply "more robust" by municipal engineers while a "conservative" sea level rise viewer is inferred to produce low estimates. Both monetary constraints and limited staff resources limit program capacity and, as described by CZM Program Staff, the reality is that most local planners work across a range of projects and are not focused on coastal hazards planning alone. These are fundamental challenges given the multidisciplinary field of coastal management and below we provide several suggestions for navigating these language and information barriers.

Existing tool portals are also time-consuming to navigate and it remains difficult for end-users to readily ascertain which tools can be tailored for a community's need. In response, some state agencies have developed state-specific portals that compile resources relevant to their communities' geographic region and needs. For example, both Maine (Maine Adaptation Toolkit) and California (University of California Berkeley & The California Energy Commission, 2017) have developed sites where state-specific information on climate change is shared, including data and tools relevant to the coastal zone. Given the many actors involved in adaptation planning, tool developers would benefit from identifying these key hubs within the network to facilitate communication and tool distribution.

Recommendation 1. Tools, toolkits, and search portals acknowledge and accommodate the diverse vocabulary used by local communities to describe the issue. There are many kinds of tools available and scaled at different levels for diverse uses. The Glossary provided at the end of this manuscript demonstrates the diverse definitions of the term "tool." This confusion can complicate tool accessibility as in reality, these resources may be accessed by individuals with disparate levels of experience and expertise, unknown to the developer. At present, there is no consistent set of categorical “buckets” used across national resources. In a perfect world, a consistent vocabulary would be adopted by all coastal tool developers to help communities readily find tools relevant to their needs. However, this is unrealistic given the large number of existing tools and established sites that each define, describe, and categorize tools differently. Instead, we suggest that national tool developers acknowledge the diverse vocabulary by end-users and create a glossary for how major terms are used for the given tool/toolkit. Additionally, the service provider can design sites with broader keyword search functions.

Tools can also be better sorted by need as communities dealing with similar challenges can often be roughly sorted based on locality. We found search portals that include the functionality for sorting categories by locality (state, region) and for characteristics of localities (inland, coastal, riverine, urban, rural) are most useful (e.g., CAKE, Gulf TREE 2017). When time and other resources allow, state agency staff can be used as “human filters” to aid in curating the search process. Additionally, each state CZM Program could create their own portal(s) that categorizes relevant tools using vocabulary and “buckets” tailored to the needs of their coastal communities. These sites could also be tailored for specific industries involved in adaptation that share a common language and basic level of ability (e.g., engineers, city planners) to streamline the search process. We acknowledge that while useful, the creation of a one stop-shop developed by each state CZM Program would require sustained coordination between state and federal agencies and NGOs, as well as dedicated financial resources to develop and maintain these sites (see Recommendation 7 for more discussion on funding).

Recommendation 2. Tools explicitly state their assumptions, limitations, and requirements. In addition to the opinions expressed by our interviewees, a national report by Rozum and Carr (2013) found there can be a mismatch between existing tools and the specific needs of the project qualifications of the staff at hand. We recommend that every national tool include a list of necessary resources (both external and in-house), skill sets required, and/or specific personnel needed to fully implement a tool. For example, local planners need to know what additional departments or individuals (e.g., GIS specialists) will be needed to supplement or verify the results of a tool and the specific adaptation process it supports. Ultimately, there should be enough information for a user to determine whether it is more cost effective to use an "off the shelf" resource or to design a more customized tool in-house.

Acknowledging the tradeoffs that local communities must consider, we encourage national tool developers to also indicate the amount of time required to successfully apply the tool to a given problem. This will hopefully prevent users from becoming discouraged by how long it takes to implement and thus quitting before the task is complete, as time is an often a limiting staff resource. We found the Gulf TREE (Northern Gulf of Mexico Sentinel Site Cooperative et al., 2017) decision-support search engine does allow users to filter based on both cost and the level of effort required which should address the main concerns posed above. With adequate training and education on the limitations, assumptions, and constraints of national resources we believe tools will be better used and adapted for the specific purposes of the end-user.

Recommendation 3. Tool developers identify and utilize trusted information hubs within the network of affected communities to collect feedback and share their tools. State and territory CZM Programs are excellent examples of "hubs" within the coastal users' network. In addition to publishing new tools and sharing resources via existing distribution channels, tool developers should share their tools directly with the network of CZM Programs. Sharing tools with state CZM Programs will reduce the effort communities need to discover new tools and ensure that tools reach the appropriate end-users via established and trusted national and local networks. A primary role of state CZM Programs is to critically evaluate and relay information from a variety of sources and provide technical support to local communities. Not only would the communication channel help community end-users discover relevant tools, it would serve to increase tool use by engaging via a trusted party (National Research Council, 2012). A Government Accountability Office (GAO) report on climate information exchange, found nonfederal institutions have a significant formal role in serving as providers of technical assistance and direct work with trusted information brokers are key to successful adaptation (Government Accountability Office, 2015). The CSO network of CZM Programs provides a national platform where agencies and NGOs can share their tools directly with coastal management practitioners. CSO currently operates a webpage with resources on tools, in-person trainings, and webinars, and communicates this information in a bi-monthly newsletter received by more than 1,200 coastal management practitioners.

CZM Program Staff reiterated an important qualifier to this recommendation – not all tools should be promoted at the local level. Trust is a limited resource that needs to be carefully guarded and if a tool is irrelevant then nothing will be gained by having a

CZM Program share it with the local community, and they might even risk credibility when doing so. Therefore, tool developers should consider consulting with information brokers and end-users from the beginning of the tool development process to help ensure that resources are both needed and relevant. The Digital Coast Partnership is an example of a federal agency (NOAA) working closely with eight NGO partners on behalf of national coastal management practitioners to help ensure that tools developed and shared are relevant to the intended end-user. We build on this idea of establishing trust in the next section.

2.3.2. Trust

Nationally, trust is an important factor in how adaptation occurs at the community level and trust is needed to overcome the uncertainty prevalent in adaptation planning (National Research Council, 2012). We found that state CZM Programs have an understanding of the decision-making challenges associated with uncertainty because they build relationships with their local communities. CZM Programs attribute the limited use of externally-developed tools to a lack of confidence exhibited by local communities that stems from not knowing the developer and/or the process used to create a national resource. Often externally-developed tools do not incorporate the local data that state CZM Programs utilize, so that the assessment of the problem may not align with locally known and trusted methodologies.

A study by Reed et al. (2014) found that trusting environments are required for learning to occur and that communities of practice[7] (CoP) can facilitate social learning and action. The close relationships CZM Programs build with their local communities

[7] Communities of practice are "social groups bound by a common concern or passion and a desire to learn how to improve their practice" (Reed et al., 2014, p. 231).

establishes a CoP and consequently, local communities often seek help and recommendations directly from CZM Programs. For example, coastal communities in Maine look to the state for guidance when they need a trusted expert to walk them through analysis and application of data for a given problem. The Maine Coastal Program fosters this relationship by giving multiple presentations each year to the public and local decisionmakers on coastal hazards and municipal adaptation strategies. Lindeman et al., (2015) found that participants of science-based adaptation planning workshops, emphasize the need for local champions to relay adaptation issues to local audiences. These examples highlight the significance of a trusted information broker in the field of adaptation. National tool developers could benefit from leveraging the established relationships that local communities have with CZM Programs in order to give their tools a trusted "face."

Recommendation 4. Those seeking to develop new coastal tools or toolkits consult with end-users from the beginning of the project. This recommendation is corroborated by the General Services Administration (GSA) that described the need to develop tools through a user-focused, iterative approach (General Services Administration, 2016). CZM Program Staff agreed that this process should include close consultation with end-users and information brokers before the tool is fully developed. States have detailed understanding of the challenges at the local level and if/how new ideas might fit those needs. Some local challenges do not necessarily require more tools, so it is important to seek feedback during the conceptual phase. When creating new resources, we recommend that tool developers consider four key questions:

1. Who is the intended audience?

2. What decision is the tool trying to inform?
3. Is this the right question to be asking given the problem at hand?
4. Does an existing program or tool already answer the question?

Federal agency staff supported this recommendation and stated that a bottom-up approach helps to justify the need of a given tool or toolkit. State agencies are also able to identify factors that an outsider would not know to include (e.g., agency consensus documents, existing models, property rights issues). This consultation does occur, as our federal representatives indicated, and in certain cases agencies convene focus groups with members of state CZM Programs to present ideas for new tools. Based on the feedback received, the agency decided to forgo the development of a new tool in at least one case. In the age of tool proliferation, this type of collaboration can save both time and agency financial resources and should be the norm.

We acknowledge that providing and receiving input on a new tool is time intensive for all parties and it can be difficult for locals to allocate the time when the benefit of the tool to the end-user is unclear. Therefore, developing tools that are requested or initially vetted by end-users may help ensure that state or local feedback is later volunteered. On our panel of interviewees alone, several examples for new tools needed in California were identified, including estimating sedimentation rates for San Francisco Bay, and models that account for the changing frequency in coastal storms and extreme rain events in the region. We contend that communities are more likely to use a tool if they are created with stakeholder input from the beginning (i.e., the idea phase) and this also results in superior tools. We would encourage that more formal engagement mechanisms are incorporated into the tool development process so that strategic needs are addressed, and the usefulness of tools clearly discerned prior to creation. Building closer relationships among tool developers, information brokers, and end-users through a CoP will also instill greater faith in the products ultimately developed.

Recommendation 5. Tool developers regularly offer end-user training and tutorials, in conjunction with community-trusted programs. As time was frequently cited as a limiting factor in a CZM Program's ability to find and use new tools, we recommend that holding targeted trainings can build capacity and trust in local communities and ultimately reduce the time needed to learn how to use a new tool for decision-making. If national tool developers face similar resource limitations as their end-users, tools could be incorporated into existing trainings hosted by community-trusted programs. For example, state CZM Programs hold regular trainings with local planning bodies and, when appropriate, they partner with NOAA to include trainings on materials and resources found on Digital Coast. These state-federal partnerships are beneficial because NOAA is given the opportunity to showcase national tools while state CZM Programs share their local resources, which results in the education of both the end-user and national tool developer. The federal representatives on our interview panel reinforced this view and shared that agencies do conduct "road shows" by visiting state CZM Programs and their affiliates to promote and provide training on new tools. CSO hosts an online calendar featuring state and regional CZM Program meetings that could be used to identify and coordinate these opportunities.

Additionally, promoting case studies of how tools have been utilized by communities help demonstrate the benefit to local decision makers. CZM Programs benefit from learning about successful adaptation projects at a national level, especially learning about the maintenance required, environmental outcomes achieved, and whether local communities felt it was a good use of public dollars. This information could be included in case study reports to help CZM Programs identify appropriate projects and encourage, or require, long-term monitoring of outcomes. Digital Coast, CAKE, and the Adaptation Clearinghouse (Georgetown Climate Center, 2018) do help promote tools by messaging through "stories from the field" and "case studies." These examples are drawn from local communities and help demonstrate the value of a given tool. In the future, this demonstration of value could occur through consultation with end-users during tool development phase, as described above in Recommendation 4. Communities willing to pilot a given resource by conducting iterative trials and in-situ testing could be identified.

2.3.3. Resolution

When CZM Programs identify resources that address a relevant issue for their communities, they find the tool is often not developed at a fine enough spatial scale to be used in decision-making. Many nationwide tools use data that is interpolated across broad areas and based on the availability of national data. Additional challenges are presented when tools are older and do not reflect the latest science or current land-uses. This is especially a concern in coastal areas, as NOAA data demonstrates that coastal land cover changes twice as fast along the coast as in the rest of the nation (Coastal States Organization, 2018). CZM Programs understand the difficulty federal agencies face with developing national tools at a fine resolution and also see the needs of local users that must consider the unique physical, social, and political circumstances of their communities. For instance, to update coastal plans, planning for sea level rise, or addressing other coastal hazards at the local level, individual property-level data (parcel) is often needed for tools to be useful. Federal tools are often limited to a minimum of 50m grid resolution while locally-developed tools can meet 5m or 1m grid data requirements. Therefore, rather than adapt national tools, some CZM Programs fill the need by providing technical and financial resources that empower local planning agencies to create their own tailored resources.

While developing tools tailored for a specific community or audience is ideal, the budgets and time constraints on CZM Programs do not allow for individualized tools to be developed for all issues associated with the suite of coastal hazards impacting our nation's coasts. Though the coarse granularity of national tools often prevents them from being used to assess site suitability, states and local communities can still benefit from the resources developed by federal agencies and NGOs if the user understands that most national tools are intended for general planning. CZM Program Staff report that they often use external tools to access certain GIS layers or other geospatial data that can be incorporated into state or community-specific viewers. Some programs use federal tools for screening purposes, or a first-level analysis to identify whether there is a potential problem in an area. After an initial assessment, they can then pursue a more in-depth analysis. However, using these tools may require expertise by the end-user to understand the data requirements of the tool and/or the ability to code. This ties into our earlier recommendation that addressed the need to build trust and facilitate trainings that educate end-users on the feasibility of using national tools to address local needs.

Recommendation 6. When possible, tools are designed to be customizable at different spatial scales and relevant for community needs. There are mechanisms to bring coarser national models down to the property scale and tool developers could accommodate certain modifications by providing instructions and assistance that can help communities working to customize tools. For example, for software tools, the underlying code can be shared which will allow end-users to tailor the tool to suit their needs. This could mean requiring standards for metadata such as the inclusion of explicit instructions on how to incorporate new data sets and to add/adjust parameters. Many tools available on Digital Coast, for example, are screening-level tools that can be customized by local communities to incorporate local and/or higher resolution data and often the code to develop the tool and access to underlying data services is provided. This sort of modularity could be incorporated into other tool's design such as building GIS tools with a user-friendly "data import" functionality or including an application programing interface (API) with the software. For example, the U.S. Department of Transportation's [climate] Vulnerability Assessment Scoring Tool designed for the Gulf Coast, allows users to input data and select or de-select what data is included in a given analysis (ICF International, 2015).

Future tools could benefit from incorporating known and trusted datasets, including those hosted on Digital Coast. The basic tool could report national averages to accommodate new tool users and those looking for first-level uses, while the ability to import customized data sets could accommodate more advanced users. We understand that this would increase the costs of national tool development but argue that making customizable tools would increase tool utilization rates. This recommendation is supported by the GSA study that found private sector planners and municipal analysts often seek raw data because these can be tailored to individual needs and situations (General Services Administration, 2016). Some federal agency partners reported that they increasingly see their role as developing basic platforms that provide a starting point for data and mapping and empower end-users to customize the tool. Some NGOs and federal partners, including The Nature Conservancy, Association of State Floodplain Managers, and NOAA-OCM reach out to local communities to stay informed of local needs in order to best use the funding to ensure national coverage of locally-scalable and necessary data.

Recommendation 7. End-users are appropriated funding and/or given in-kind support to create tools specific to the needs of on-the-ground adaptation projects. Monetary constraints and limited staff resources are some of the greatest challenges facing local coastal managers, and financial resources are required to both build custom tools and maintain them. While helping all states create in-house tools is likely not feasible, prioritizing funding for these uses could help areas that do not have in-house resources, such as rural, underserved, or inequitably represented communities. Because state CZM Programs know their end-users well, they have the knowledge and expertise to create tools but often lack funding for tool development. This emphasis on funding is supported by Curtice et al. (2012) who explained that because tool development is time and resource intensive, end-users need sustained, reliable funding streams to hire the appropriate staff with skill-sets that ensure a quality product. We know that funding for adaptation-specific needs helps catalyze change; and communities are more likely to pursue adaptation strategies if they know they can find resources to support their actions. Currently, many state CZM Programs fund local projects through federal investments that are passed through the state to local communities and coupled with technical assistance provided by the state agency. In the future, federal grant funding to states and their NGO partners could explicitly set funds for broader impacts and specify that trainings and/or tools developed to help ensure that results of the project, and any relevant data, are made available to local communities and decision-makers.

Another benefit to increased communications would be to help reduce tool redundancies. The GAO report on geospatial information found that the federal government invests billions of dollars on geospatial data, but duplication of effort is common (Government Accountability Office, 2013b). In the CZM community there is the perception that more financial resources are available for creating new tools than are committed to maintaining, monitoring, and adapting existing tools. Improving existing tools relies on the availability of quality data as a tool is only as good as the data that supports it. CZM Programs recommended national entities focus on updating and improving data quality which could improve usage of current resources and reduce the need to develop new, but similar tools. This process could also be better informed if tool developers understand which tools are being regularly accessed and used by the intended end-users and for which states or communities' finer resolution tools have been developed. Online tracking of downloads or user surveys could be conducted to achieve these results.

Experts are needed throughout the decision-making process, as supported by the GAO report (Government Accountability Office, 2013a), because local decision-makers require assistance in translating climate data into locally relevant information. Trusted information brokers such as state CZM Programs, can provide technical expertise for communities to help them make location-specific decisions. Allowing in-kind support could also benefit end-user development efforts. National tool developers could also support CZM Programs in their development of new tools by acting as consultants for the creation of location-specific resources. In many cases, the highest-utility application of national tool developers' expertise is in assisting local end-users to help themselves through the tenants of cooperative federalism. The Great Lakes Restoration Initiative, a partnership of federal agencies with input from states, tribes, universities, and private sector partners collaborate to strategically spend federal funds to support locally-relevant and strategic restoration projects including an intensive wetland monitoring program (Uzarski et al., 2017). From this effort, the Great Lakes Coastal Wetland Decision Support Tool was created that allows local decision-makers to set coastal wetland conservation and restoration priorities, including defining actions that will help communities mitigate impacts of coastal hazards. This initiative is a successful example of federal, state and local agencies partnering with on-the-ground NGOs and universities to create a tool that is regionally significant. The Adaptation Clearinghouse is another example of a multi-level partnership that helps local users search adaptation plans by state and even community.

Finally, we acknowledge that issues could arise if a federal agency acting in a consulting role identifies problems in community plans but lacks the ability to assist in the appropriate actions required to address the problem. This could have negative consequences for both outcomes on-the-ground and for building and maintaining trusting relationships. Therefore, any issues identified by a federal partner in a product or tool should be discussed with the state or local manager before the information reaches the broader community and time should be allowed for fixes to be employed. Working with local managers to develop effective communication and outreach strategies is very important to building trust and promoting appropriate actions. While CZM Programs may be the appropriate mechanism for generating certain tools, we want to be sure to communicate that end-users should be included in the process directly and provided resources to develop their own tools at the local level. CZM Programs should not necessarily be the sole tool developers in the coastal area because this raises questions about feasibility, transferability, and parity in access to resources. We believe that establishing a CoP and increased communication between end-users, national agencies, and national NGOs will help clarify the necessary scale of a given tool and the appropriate producer.

2.4. Concluding Remarks

CZM Programs cite a variety of factors that spur the need for adaptation in their local communities, such as severe storm events that serve as a call to action, availability of new funding streams, and the influence of trusted individuals that advocate for communities to prioritize adaptation needs. National tools developed by federal agencies and NGOs can be part of the solution for communities addressing these challenges. Interviews conducted with a selection of CZM Program Staff across the nation helped us identify existing challenges that end-users face, given the broad number of national resources currently available. We hope that this manuscript helps outline opportunities for national tool developers to shape effective products that address coastal adaptation planning and implementation. Strategies can include developing nationally-applicable tools in consultation with end-users or providing financial assistance that enables communities to develop locally-relevant tools. Threading throughout our paper is the important role of state and territory CZM Programs operating as trusted information brokers at the nexus between national resources and local needs. Our overarching recommendation for national coastal tool developers is to leverage CZM Program resources, expertise, and relationships to build a Community of Practice that helps local decision-makers address current and future resource needs. While the recommendations presented here rely on the perspectives of state CZM Programs and their partners, we believe that the lessons learned may apply to national-level tool development for other resource management fields.

2.5. Glossary

- **Tool**: a device or implement used to carry out a particular function. See tool categorizations below.
- **Toolkit**: a collection of tools and resources addressing a specific challenge. For example, Georgetown Climate Center's Adaptation Clearinghouse- a collection of resources addressing the policy challenges associated with adaptation.
- **Portal site**: a website containing many tools and toolkits all relating to a central theme. Portals are often intended for broad audiences and contain many sub-themes. For example, toolkit.climate.gov or CAKE.
- **Planning document**: a written document that provides guidance and support on a given topic. Scale and scope of applicability varies. Non-interactive, static.
- **Information sharing tools/portals**: used to disseminate best practices. Can include case studies.
- **Data portals**: used to disseminate data.
- **Analysis tools**: GIS or other platforms that allow you to collect data and characterize/visualize problems and conduct analysis.
- **Process tools**: help support a process to evaluate and prioritize actions.

- **Policy and Regulatory Tools**: help support the implementation of strategies.

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CHAPTER 3: EXPLORING THE FOOD-ENERGY-WATER NEXUS APPROACH TO ENHANCE COASTAL COMMUNITY RESILIENCE PLANNING[8]

Abstract

Coastal communities strive for resilience in the face of an ever-growing suite of threats by planning and preparing for numerous uncertain futures. Food, energy, and water systems (FEW) are highly interconnected and essential to the well-being of coastal communities. However, coastal resilience research does not often include FEW nexus considerations. This study uses a systematic literature review of 176 peer-reviewed research articles to address the question: How has the food, energy, and water nexus been integrated into coastal resilience? This review identified fourteen relevant papers focused broadly on the subject of coastal resilience and the FEW nexus. Results reveal three main findings: 1. The FEW nexus approach provides a method to consider systems interdependencies in the context of coastal resilience planning, 2. Coastal resilience planning should consider an energy-centric perspective of the FEW nexus, and 3. The FEW nexus should be expanded to include other systems, namely, transportation.

3.1. Introduction

Climate change is causing extreme conditions in coastal communities including (but not limited to) sea level rise, flooding, and an increase in the frequency and severity of storms. Communities that do not have the capacity and are not resilient to these threats are facing the worst crisis. Hence, there is heightened interest in building resilient coastal

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communities to withstand the threats of growing climate change. While there is no universal definition of resilience within the field of community planning, resilience planning often includes vulnerability identification and subsequent planning to build capacity to respond to and recover from predicted threats (Desouza & Flanery, 2013; Lu & Stead, 2013). There is also no agreed upon method for operationalizing resilience as each system is unique and, therefore, requires a unique approach. For example, resilience is used differently within multiple contexts including community resilience (Berkes & Ross, 2013; Norris et al., 2008), urban resilience (Meerow et al., 2016), infrastructure resilience (Curt & Tacnet, 2018), ecological resilience (Adger, 2000), and social resilience (Adger, 2000; Davidson, 2010).

Food, energy, and water systems are integral pillars of coastal infrastructure and essential for human wellbeing. These systems each have many individual components that may be compromised due to climate emergencies. For example, the food system involves production, processing, packaging, distribution, retail, and consumption (Tendall et al., 2015). Climate change and climate emergencies can impact food security by directly reducing crop production, food supply/delivery, and access (Bizikova et al., 2016). Energy systems may be impacted by extreme temperature, storms, and floods which pose damage to transmission lines and substation equipment (Panteli & Mancarella, 2015). Similarly, water and sanitation systems are at risk from climate-related hazards, including drought, flooding, wind, and saline intrusion (Luh et al., 2017). Coastal communities are at increased risk to groundwater infiltration and salinization which may result in corrosion of pipes, loss of hydraulics and pumping pressure (Allen et al., 2019).

The nexus of food, energy, and water systems (FEW nexus or 'nexus') is increasingly advocated as its own unit of analysis as the three systems are heavily interconnected (Cairns & Krzywoszynska, 2016; Endo et al., 2015; Gallagher et al., 2016; Howarth & Monasterolo, 2016). Specifically, there is a growing body of research dedicated to identifying and understanding the implications of the interdependencies of critical infrastructure (Choi et al., 2001; Chtioui et al., 2016; Nan & Sansavini, 2017). Critical infrastructure refers to the systems relied on to support day-to-day life, such as, the energy grid, food distribution, or water treatment plants. As technology and society have advanced, the resilience of the critical systems depends upon understanding the integrated and interconnected nature of these systems (Nan & Sansavini, 2017). System interdependence means that a disruptive event in one critical infrastructure system can induce devastating consequences, or subsequent failure, within each system dependent on it.

The resilience of food (Tendall et al., 2015), energy (Burkhard & Gee, 2012; Panteli & Mancarella, 2015; Roege et al., 2014) and water systems (Diao et al., 2016; Gonzales & Ajami, 2017; Juan-García et al., 2017; Luh et al., 2017) have individually been studied. However, resilience of the FEW nexus within the coastal context has been less examined (de Grenade et al., 2016). Therefore, this study implemented a systematic literature review to better understand how food, energy, and water systems are integrated into coastal resilience research. The key research question was: How has the food, energy, and water nexus been integrated into coastal resilience?

3.2. Methods

The systematic literature review was performed in May, 2020 and yielded 176 papers from Web of Science. The search terms were chosen to reflect the broad variety of terminology (Table 3.2) that is used to describe FEW systems, their nexus, coastal communities or systems, and resilience. FEW systems can be referred to as critical infrastructure and the "nexus" as critical infrastructure interdependencies. The terms resilience, adaptation, sustainability, management, planning, mitigation, policy, governance, regulation, and disaster risk reduction were used to search for studies in the context of coastal resilience. Terms marked below in Table 3.2 with an asterisk mean that any multiples of that root word were included in the search (e.g., adapt* would include adapt, adapted, and adaptation in the search).

Table 3.2: Systematic literature review key search terms

FEW	Nexus	Coastal	Resilience
• (food OR agriculture OR grocery) NEAR (energy OR electric* OR power OR fuel) NEAR (water OR irrigat* OR sewage) • critical NEAR infrastructure* • WEF • FEW	• nexus • interdepen* • interconnect*	• coast* • hurricane* • tsunami* • (sea NEAR level NEAR ris*) • ocean* • sea OR seas • Atlantic • Mid-Atlantic • (Gulf NEAR Mexico) • Pacific • (Great NEAR lake*) • shore* • cyclone*	• resilien* • adapt* • sustain* • manag* • plan* • mitigat* • policy* • govern* • regulat* • (disaster NEAR risk NEAR reduc*)

The search terms detailed in Table 3.2 were used to create a Boolean search in the Advanced Search portal from the Web of Science. No limit was placed on when the studies were published, but they were restricted to peer-reviewed journal articles written in English.

The search results were then reviewed in two stages. First, the titles and abstracts were reviewed to select preliminary matches of the criteria listed below, and then a full-text search was performed. This resulted in narrowing the pool of papers ultimately analyzed to address the research question. This two-stage search process will be referred to as the Title & Abstract Search and the Full-Text Search.

3.2.1. Title & Abstract Search

To determine how the FEW nexus has been incorporated into coastal resilience, the search terms and inclusion criteria were intentionally designed to cast a wide net. The abstract or title were required to meet the criteria defined in Table 3.3 to be selected for analysis. Criteria from both the "FEW" and "Resilience" categories (Table 3.3) had to be met in the title and/or abstract. If specific systems were mentioned, then food, energy, and water must have been included or the paper was excluded (e.g., if only energy and water were mentioned, the study was excluded as it did not discuss food). The paper was included if the study only mentioned "critical infrastructure" so that the full-text could be searched.

Table 3.3: Categories of inclusion for the Title & Abstract search.

Category	Criteria
Food, energy, water systems	• If specific systems were mentioned, then food, energy, and water must have been included • Only mentioned "critical infrastructure"
Nexus	• Reference to connections or interconnections between systems
Coastal	• Riverine communities or systems • River basins • Coastal communities or regions • Coastal countries
Resilience	• Any management or decision-making related to human populations or systems upon which humans rely
Other	• Either the criteria for "Nexus" or "Coastal" must be met, one category may be missing • Both the "Food, energy, and water systems" and "Resilience" categories must be met • Must be relevant to human populations

While not specified in the search terms, the criteria for "Coastal" was relaxed to include studies of riverine systems, river basins, as well as coastal regions and countries. A riverine focus was allowed at this stage of analysis because these regions and communities are also near bodies of water and can face similar challenges as coastal communities. The term resilience has many different definitions and is applied in a variety of ways, so the criterium describing "resilience" was broadened to include any sort of management or decision-making related to human populations or systems upon which humans rely. One keyword from either the "Nexus" category or "Coastal" category (Table 3.2) must be present, but one may be excluded at this level of analysis. If no keywords from the "Coastal" or "Nexus" category were included, the paper was excluded.

Finally, the article must be relevant to human populations (i.e., not a study of an animal or other species). Papers with a sole focus on engineering resilience were not included as the term tends to be used differently, unless it was in the context of management.

Forty-two papers met all the criteria of the Abstract & Title and their PDFs were collected for use in the Full-Text Search.

3.3.2. Full-Text Search

Each of the forty-two articles selected during the Title & Abstract Search were then manually analyzed during the Full-Text Search. Papers were included or excluded based on the criteria for including “Food, energy, and water systems,” “Nexus,” “Coastal,” and “Resilience.”

3.2.2.1. Food, energy, and water systems

Papers had to incorporate food, energy, and water systems into their methods, results, and discussions or be included as more than a buzzword. Inclusion of a term as a buzzword meant that the FEW nexus was only used once or twice, often in the introduction and one line in the discussion or conclusion section. A “mention” was defined as the inclusion of a specific term or system one to three times throughout an entire paper without meaningful discussion. Papers were excluded if the critical infrastructure referred to in the abstract of the study only referred to coastal protection measures (e.g., seawalls).

3.2.2.2. Nexus

The study was considered for further analysis if it incorporated a discussion or consideration of the interconnections between the food, energy and water systems, either directly or indirectly. Directly meant that the nexus and interconnections among its components were analyzed as a central part of the study. Indirectly meant that the study did not have a nexus focus but happened to include a discussion of how two or more systems were connected, or may have impacted one another.

3.2.2.3. Coastal

Papers were included if they focused on a coastal system, population, or community, or if the study was of a coastal area or coastal hazard (e.g., flood event). Studies were initially included if they focused on a riverine system or river basin, but were later excluded during the Full-Text analysis if they did not also consider an acute hazard (e.g., a flood event). Studies were included if they focused on an entire country (e.g., Australia), but were later excluded during the Full-Text analysis if the focus was not on the coast or a coastal hazard.

3.2.2.4. Resilience

Papers were included if they incorporated a management perspective, which means they considered how to make better decisions or manage a particular system for the benefit of human populations. The management perspective was considered if the paper was from a resilience, adaptation, planning, mitigation, and policy perspective (to name a few).

Forty-two studies were included in the Full-Text Search. After this Full-Text Search, twenty-eight studies were eliminated and fourteen studies were found to meet all of the search criteria (see Appendix C for a list of the fourteen studies). Of the twenty-eight studies that were eliminated, ten had only passing mentions of, or did not include, one or more of the food, energy, or water systems in the methodology or analysis (Abdalla et al., 2007; Fekete, 2019; Gurdak et al., 2017; Little et al., 2015; Montgomery et al., 2012; Saladini et al., 2018; Samimi et al., 2020; Veijalainen et al., 2019; Wang, 2013; Zimmerman et al., 2019). Eleven were eliminated because they were of riverine locations which did not consider any acute hazards (Bekchanov & Lamers, 2016; Dombrowsky & Hensengerth, 2018; Intralawan et al., 2018; Jalilov et al., 2018; Keskinen et al., 2015; Mamatova et al., 2016; Martin-Gorriz et al., 2014; Payet-Burin et al., 2019; Rasul et al., 2019; Shi et al., 2020; Zeng et al., 2019). Three studies were eliminated because they focused on entire countries and were not of a fine enough scale to provide useful insight into coastal resilience (DeLonge & Basche, 2017; Taniguchi et al., 2017; Zeng et al., 2017). One study was eliminated because it was of an inland floodplain but did not incorporate any riverine or flooding considerations (Fan et al., 2020). One study only considered food, energy, and water systems from a health perspective (i.e., food borne illness, water contamination, energy related heat illness/death) and did not consider FEW systems interconnections (Bambrick et al., 2011). One study presented a hypothetical model and then mentioned FEW systems in the case study application, but chose to focus on transportation and education infrastructure (Cheng, 2017). The last study to be eliminated had one mention each of hydropower and farming/fishing for food security, but did not discuss them specifically in the context of the power and governance perspective of their study (Bréthaut et al., 2019).

3.2.3. Data Analysis

Once the sample of papers to be analyzed was determined following the Full-Text Search, the following information was extracted from each study: Article date; journal; keywords; geographic location of the study; any hazards considered; the research question of the study (if specified); the goal or objective of the study (if specified); how each of the food; energy and water systems were included; other systems or perspectives that were included; how the nexus was defined or included; what the resilience perspective was; and if there were any recommendations or broad conclusions from the study.

3.3. Results

The fourteen papers that met the search criteria offer insights into the location and hazards considered, how the FEW nexus was conceptualized, the benefits of nexus approaches and other methodologies, perspectives on community resilience from extreme events in urban areas, and other systems that were included in addition to the FEW nexus (e.g., transportation).

3.3.1. Summary of Locations and Hazards

The fourteen studies that met the search criteria were all published recently, considered predominantly acute hazards, and focused on locations from around the world. The studies examined were conducted between 2016 and 2020. The oldest study that met the search criteria was from 2016, indicating that the incorporation of FEWs within coastal resilience planning is relatively new. Most of the studies (10 of 14) focused on acute hazards from extreme climate events, two did not consider any hazard, and three studies considered chronic hazards (Table 3.4). Most of the studies focused on urban locations (8 of 14), four considered both rural and urban areas, and two considered purely rural locations (i.e., Cordova, Alaska and the Chamela-Cuixmala Biosphere Reserve, Mexico). Five of the studies were situated in the US, two were of hypothetical communities, two were island communities (i.e., Puerto Rico and Zanzibar), one was of the Taipei metropolitan area, one was of a biosphere reserve in Mexico, one was of the

Persian Gulf, one was jointly of Manila, The Philippines and Rotterdam, The Netherlands, and one used many examples from around the globe.

Table 3.4: A summary of the studies categorized by kind of location and the hazard considered by each. Multiple hazards were considered in several studies.

Hazard		**Urban**	**Rural**	**Both**
No Hazard		Manila, The Philippines and Rotterdam, The Netherlands (Dal Bo Zanon et al., 2017) Hypothetical coastal community (Luqman & Al-Ansari, 2020)	n/a	n/a
Chronic Hazards	Climate change	n/a	Cordova, Alaska (Whitney et al., 2019)	Zanzibar (Newman et al., 2020) Global examples: e.g., Kuala Lampur, Australia (Perth and Melbourne), United States (NYC), South Korea (Seoul and Bogor City), United Arab Emirates, etc. (Brown, 2019)
Chronic Hazards	Socio-economic development	n/a	n/a	Zanzibar (Newman et al., 2020)
Acute Hazards	Flood Event	Boulder, CO, Sept. 2013 flood (Romero-Lankao et al., 2018; Romero-Lankao & Norton, 2018) Fort Lauderdale, FL, hypothetical flood event (de Bruijn et al., 2019)	n/a	Global examples, solutions to flooding (Brown, 2019)
Acute Hazards	Hurricane	New York City, NY, Hurricane Sandy (Cimellaro et al., 2019; Romero-Lankao et al., 2018) Artificial county (pop. 0.5 million), simulated category 2, 3, 4 hurricanes (Ni et al., 2019) The Shihmen Reservoir in Taoyuan City, Taiwan and the Taipei metropolitan area, typhoon vs. non-typhoon season (Uen et al., 2018)	Chamela-Cuixmala Biosphere Reserve, Mexico, Hurricane Patricia (Maass, 2017)	Puerto Rico, Hurricane Maria (García-López, 2018)
Acute Hazards	Man-made, socio-technical disasters	n/a	n/a	Persian Gulf (Meshkati et al., 2016)

3.3.2. FEW Nexus Considerations

In urban areas and in regions that contained urban areas (12 of 14), the FEW systems were mostly (7 of 12 studies) considered in terms of water and wastewater treatment facilities, the electric grid (utilities) and generators, and supermarkets and food retailers (critical commercial services). These studies identified the centrality of energy systems, the need for electricity to pump and treat water in water treatment facilities, the need for energy for the refrigeration systems for food retailers and the energy and water inputs required to operate facilities (Cimellaro et al., 2019; de Bruijn et al., 2019; Ni et al., 2019; Romero-Lankao et al., 2018; Romero-Lankao & Norton, 2018). One study of Cordova, Alaska, a small coastal town with population less than 2,500, considered the FEW nexus similar to the urban studies with a fish processing plant and a hydroelectric facility along with power utility, food security, water utility and a wastewater treatment plant (Whitney et al., 2019).

While a majority of the studies considered the FEW nexus in a similar manner (i.e., in terms of the reliance across these systems that they be maintained to ensure uninterrupted services so they can provide resources needed to sustain human needs), there were also some outlier conceptualizations. For example, the FEW nexus was considered in terms of hydropower in the Syr Darya River Basin where the food-energy-water-ecology nexus was coupled with an optimization model (Uen et al., 2018). The nexus tradeoffs were presented as water use for either energy generation or water use for irrigated agriculture. This study explored the impact on FEW systems between typhoon and non-typhoon season and water availability and short-term versus long-term reservoir operation. Here, they recommend that an optimization model (in this case, a reservoir optimization model) can help develop governance strategies that are feasible and socially acceptable in the FEW nexus (Uen et al., 2018). Another study in the Persian Gulf conceptualized the FEW nexus in terms of the connections between nuclear power, seawater desalinization, and seafood resources (Meshkati et al., 2016). Seawater desalination produces brine, which can impact seafood resources and nuclear power could accidentally release radioactively contaminated water or cause a nuclear accident, which would negatively impact water and seafood resources that rely on the water.

The nexus was also considered in terms of modeling the interdependencies between critical infrastructure systems. In these studies, the FEW nexus was not directly targeted, but the interactions between food, energy, and water systems were found to be significant, regardless. For example, a multi-commodity disruption model and restoration model was used to better examine interdependencies between infrastructure systems (Infrastructures: power, water, wastewater, telecommunications, and transportation; Emergency Services: police, firefighters, and emergency medical services; and Critical Commercial Services: cash, fuel, pharmaceuticals, and basic food) during simulated hurricanes (Ni et al., 2019). This model suggested that well-coordinated restoration decisions can help to improve community resilience, especially with Category 4 and 5 hurricanes (Ni et al., 2019). An Interoperability Input-Output model designed for New York City found the utilities, liquid fuel, and transportation systems to be the most important systems in the network during hurricanes as they caused the most indirect impact to other systems (i.e., food, liquid fuel, healthcare, telecommunication, transportation, water and wastewater, and waste) (Cimellaro et al., 2019). This study recommended prioritizing initiatives that reduced the linkages between energy, liquid fuel, transportation and other systems. To demonstrate this, they cited examples from the New York City resilience plan, such as providing backup generators to gas stations, protecting tunnels from flooding, and developing a fuel infrastructure hardening program (Cimellaro et al., 2019).

3.3.3. Nexus Approaches and Other Methodologies

While some studies did not directly employ a FEW nexus approach, a FEW nexus approach (or similar types of approaches) was directly used and advocated for as a methodology in half of the studies (7 of 14). Intentional use of a FEW nexus approach meant that the study was designed to purposely investigate food, energy, and water systems and their interconnections within the context of a particular study location or broader research project. Results suggest that a nexus approach can ensure that the key tradeoffs are considered in resilience planning. For example, the FEW nexus approach study in Cordova, Alaska highlighted key tradeoffs between water for hydroelectric energy generation, water for use in a fish processing plant, and water for the municipal water system, which may have otherwise been overlooked (Whitney et al., 2019). This study found that "incorporating FEW interdependencies with this approach can lead to decisions that are more consistent with FEW security and community well-being" (Whitney et al., 2019, p. 849).

Many groups are consulted during a resilience planning process, so it is important to consider diverse perspectives and systems. When planning for resilience, a FEW nexus approach can ensure a more holistic perspective of the community by ensuring that multiple groups, systems and their interconnections are included. Dynamic Environmental Livelihood Sustainability (DESL) is a conceptual framework, which works to incorporate the community perspective into FEW nexus thinking (Newman et al., 2020). This study reports that nexus thinking is needed to better understand the many interconnected systems and how they impact local communities. There are many other factors outside of FEW systems that can impact security in the face of hazards. As such, two studies advocate for using a framework that integrates the connections between the socio-demographic, economic, technological, environmental, and governance (SETEG) domains (Romero-Lankao et al., 2017; Romero-Lankao & Norton, 2018). Considering SETEG domains and their interdependencies allows cities to "begin to anticipate and avoid cascading effects on WEF [water-energy-food] systems and resources" (Romero-Lankao et al., 2018, p. 221).

A nexus approach can act as a starting framework that allows the researcher or planner to consider additional linkages with other systems, such as considering the connections between the systems that support human life and the natural world they rely on. The socio-ecosystem (SES) approach was advocated for to guide food-energy-water research as it links ecosystem supporting services (e.g., energy, nutrient, and water processes) with provisioning services (e.g., food, charcoal, and clean water) (Maass, 2017). The "infrastructural ecology" planning paradigm embraces the principles of natural ecosystems (Brown, 2019). Infrastructural ecology is when human systems are designed to work together just as ecological systems do, by sharing structures or space to produce efficiencies.

Innovative, technological solutions for how a FEW nexus approach can help increase coastal resilience were incorporated in four studies (Table 3.5). Numerous examples were provided from all over the world to demonstrate an infrastructural ecology approach to show how power, water, sanitation, transport, and food systems can be combined or linked (Brown, 2019). Combining systems offers advantages such as, passing along waste, water, or nutrients for use in another system, combining resources and reducing demand for additional inputs thereby creating efficiencies. Redundant systems are important due to the cascading impacts that damage to one FEW system can have on the other (so that if one was damaged there was a redundant system available to keep operations running), such as was highlighted during the 2013 flood in Boulder, CO (Romero-Lankao & Norton, 2018). They highlight that since the city had backup generators (energy) they were able to keep the water treatment plant functional even though the broader energy system had been damaged by the flood (Romero-Lankao & Norton, 2018).

As urban areas have high population densities, they rely on surrounding areas for the provision of food, energy, and water resources. A multigeneration system (Luqman & Al-Ansari, 2020) and floating production (Dal Bo Zanon et al., 2017) were proposed to decrease the dependence of coastal cities on surrounding areas by capitalizing on the linked nature of FEW systems. The multigeneration system presented by Luqman & Al-Ansari (2020) capitalized on the interconnections between systems to create one compact system that generates energy, fresh cold water and hot water for domestic use, HVAC for space air conditioning, and food storage for coastal communities. Floating production is a technique to reduce coastal cities' dependence on surrounding areas by capturing waste and using it as an input for hydroponic systems. These hydroponic systems use waste as nutrient input to grow algae, the algae feed fish,

fish excrement provides nutrients to feed crops and both the crops and fish are used as a food source for coastal populations (Dal Bo Zanon et al., 2017).

Table 3.5: The innovations or technologies that four studies highlight for how to increase resilience in coastal areas.

Title (Author, Year)	Innovation/ Technology	Nexus Strategies
Thermodynamic analysis of an Energy-Water-Food (EWF) nexus driven polygeneration system applied to coastal communities (Luqman and Al-Ansari, 2020)	Multigeneration system (E-W-F)	A system driven by renewable energy that fulfils coastal communities needs of electricity, fresh water, hot water for domestic use, HVAC for space air-conditioning and food storage.
Infrastructural ecology: Embedding resilience in public works (Brown, 2019)	Floating PV over reservoirs (E-W)	Floating PV over reservoirs to produce energy and reduce evaporative losses. The bodies of water act as a thermal mass, which in turn cools the panels and extends their life.
	Seawater greenhouses (F-E-W)	Often used in desert climates, it uses solar energy and seawater to produce crops and surplus fresh water.
	Multifunctional solutions to flooding (W-E-F)	*Kuala Lumpur*: a double-decker bypass tunnel (transportation) coupled with a temporary stormwater reservoir. *Rotterdam, The Netherlands*: Water retention squares which couple urban flood solutions with urban renewal. *Vietnam*: Mangrove restoration reduces storm damages, improves shrimp farming and wood harvesting. *South Korea*: Sihwa tidal power plant produces power, flushes seawater (water quality), and has a four-lane highway on the barrage.
	Rainwater harvesting (W-F)	*Seoul, Korea*: Rainwater harvesting pilot program captured 67% of on-site rainwater which was then used to flush toilets, wash the development site, and water the gardens (as opposed to relying on reservoirs from distant locations).
	Urban forests/tree planting (W-E)	Planting trees in urban areas to combat the urban heat island effect, sequesters carbon emissions, which leads to reduced air conditioning demand, improves urban drainage and water storage.
Potential of floating production for delta and coastal cities (Dal Bo Zanon et al. 2017)	Floating production (F-E-W)	Capturing nutrients from waste and carbon capture to produce algae. The algae used as biofuels and in hydroponics (algae feeds fish, fish excrement feeds crops, water sustains both fish and crops).
Interdependencies and risk to people and critical food, energy, and water systems: 2013 food, Boulder, Colorado, USA (Romero-Lankao and Norton, 2018)	Redundant infrastructure (W-E)	During a flood event, redundancies, like backup generators allowed the wastewater treatment plant to remain functional.

3.3.4. Acute Events in Urban Areas

Flood events and hurricanes (acute hazards) were the primary connecting point across the FEW nexus in the majority (9 of 12) of urban areas (and regions that contained urban areas) studied. The studies examined Hurricane Sandy in New York City (Cimellaro et al., 2019; Romero-Lankao et al., 2018), the 2013 flood in Boulder, CO (Romero-Lankao et al., 2018; Romero-Lankao & Norton, 2018), simulated hurricanes in a hypothetical county (population 0.5 million) (Ni et al., 2019), a hypothetical flood event in Fort Lauderdale, FL (de Bruijn et al., 2019), and typhoon season in the Shihmen Reservoir in the Taipei Metropolitan area (Uen et al., 2018). The importance of the energy and transportation systems was particularly evident. For instance, losing power during a hurricane and flood event impacted all the other critical infrastructure systems in studies focused on New York City and Fort Lauderdale, FL (Cimellaro et al., 2019; de Bruijn et al., 2019). Further, the lack of power created health issues via its impact on food and water systems. Specifically, loss of power for refrigeration and water sanitation increased the risk of waterborne and foodborne illness in a study of the 2013 flood in Boulder, CO (Romero-Lankao & Norton, 2018).

Results revealed that damage to the transportation system negatively impacted many other systems, primarily the food system (Figure 3.1). Disruptions to the transportation system during the 2013 flood in Boulder, CO, amplified the flood impacts (Romero-Lankao & Norton, 2018). Critical commercial services, like food, are heavily linked to the transportation system (Ni et al., 2019). Urban areas are heavily reliant on global food supply chains, for example, New York City's food is transported by truck and depends on transportation infrastructure (Romero-Lankao et al., 2018). There was a food shortage crisis that resulted from Hurricane Maria in Puerto Rico (García-López, 2018). Many could not access supermarkets due to blocked roads and, since the island relies on imported food, they suffered from a delayed delivery of food and other aid. Commercial food facilities were found to keep small inventories, which exacerbated the challenges when new supplies were limited due to disruptions to the transportation system (Romero-

Lankao et al., 2018). It is recommended that retailers increase their inventory when a Category 3 hurricane is predicted (Ni et al., 2019).

Many studies note the cascading impacts that damage to both the energy and transportation systems could have on other systems (Figure 1). A study conducted in Fort Lauderdale, FL, classified the food system as a commercial facility (e.g., supermarkets), and the study found that during a flood event disruptions to power, transportation, and financial services resulted in a lack of food supplies (de Bruijn et al., 2019). During Hurricane Sandy, direct damage to the food system included physical damages to the facilities, indirect damages to operations due to electrical outages, lack of access to water, and transportation in New York City (Cimellaro et al., 2019). Food suppliers (i.e., supermarkets, warehouses, and restaurants) in NYC were impacted by the shutdown of the transportation system and power outages after Hurricane Sandy (Romero-Lankao et al., 2018). A study of the 2013 Flood in Boulder, CO highlighted the links between food, transportation, and power systems (Romero-Lankao et al., 2018). This study found that lack of power to refrigerators and freezers caused food to spoil and the damaged transportation system prevented food deliveries from reaching stores (Romero-Lankao et al., 2018).

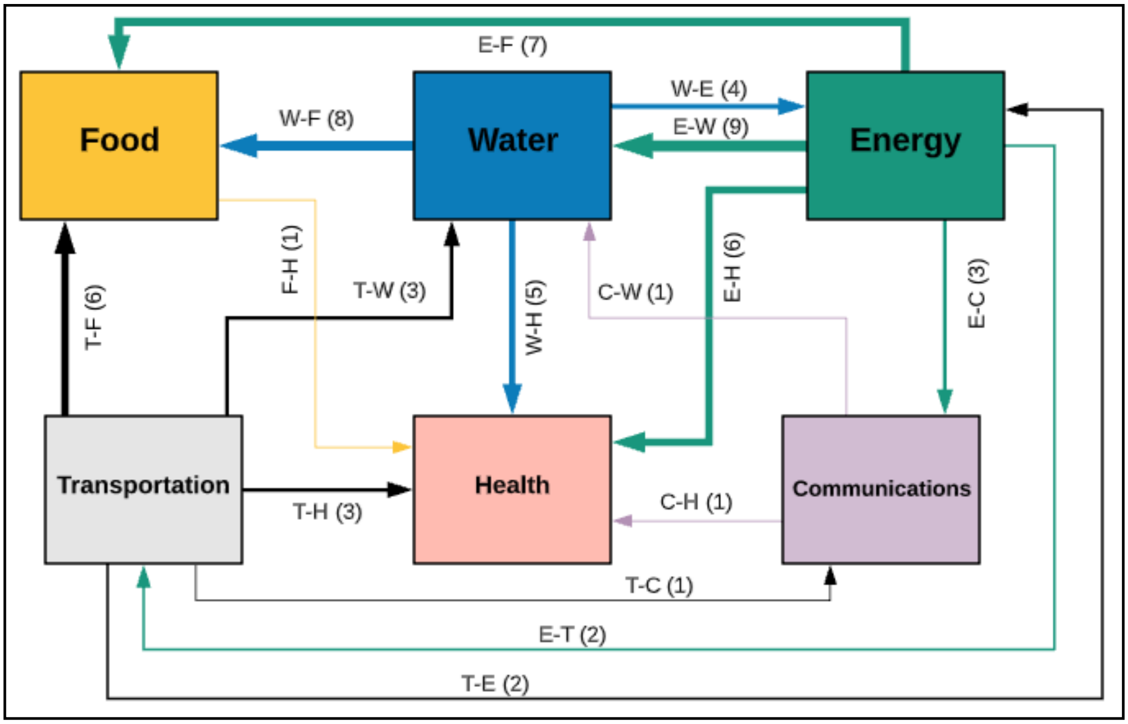

Figure 3.1: The connections between systems highlighted in each of the fourteen studies. Each system is represented by a box and the directional lines between systems show connections. For example, a line between energy and water system means that water was described as being dependent on the energy system. Line weight and the numbers in parentheses indicate the number of studies that described a connection between systems.

3.3.5. Other Systems

While food, energy, and water systems were the focus of this study, the results show that three other systems were commonly included in the relevant studies (Figure 3.1). Transportation was the most common system to be included along with FEW systems (6 of 14). Health was the next most common (5 of 14) followed by communication/telecommunication (4 of 14).

As previously detailed, transportation was often incorporated into the FEW nexus as it relates to food retailers in urban areas. Transportation was also included in several studies and its indirect impact to multiple other systems after an acute event. If roads are closed or blocked, fuel and supplies cannot be obtained to operate backup generators (Cimellaro et al., 2019; de Bruijn et al., 2019; Romero-Lankao et al., 2018; Romero-Lankao & Norton, 2018). A closed or blocked transportation system can also mean personnel cannot reach other systems to repair them from acute hazard damage, such as downed power lines (de Bruijn et al., 2019) or bridges in need of inspection (Cimellaro et al., 2019).

Health was included in several studies as it was connected to the food, energy, and water systems, with particular emphasis on the influence of energy systems. As shown in Figure 3.1, health was impacted by disruptions to food, energy, water, and transportation systems. Namely, water, food, and airborne illnesses were associated with lack of power after an extreme event. After the 2013 flood in Boulder, CO, foodborne illness arose when there was not power for refrigeration units and food spoiled (Romero-Lankao & Norton, 2018). Waterborne illness can arise when there is no power for water treatment plants or when water sources become contaminated from overflowing sanitation systems after an acute event such as floods (Romero-Lankao & Norton, 2018). The use of backup electric generators led to air (respiratory illness) and noise pollution (García-López, 2018).

Studies also integrated the FEW nexus with healthcare and environmental justice issues that may impact health (Cimellaro et al., 2019; de Bruijn et al., 2019; García-López, 2018). For example, after Hurricane Sandy, healthcare facilities had to stop operations due to an electrical outage, lack of access to water, and transportation (Cimellaro et al., 2019). Health was also included in terms of heat related illness, especially with the increasing temperatures associated with climate change and the urban heat island effect (Brown, 2019). In terms of environmental justice in Puerto Rico, the lower-income communities located next to toxic storage facilities (like the mountain of coal ash from the coal power plant) were at greater risk from flood events due to potential spills (García-López, 2018).

Communication/telecommunication was included as critical infrastructure and primarily in terms of its connection to the energy system. In New York City, Hurricane Sandy caused direct damage to telecommunication facilities and indirect damage to them from an electrical outage which stopped telecommunications operations (Cimellaro et al., 2019). The communication lines suffered no direct impacts from a hypothetical flood event in Fort Lauderdale, but, equally important for functionality, the system shut down due to lack of power (de Bruijn et al., 2019). This study also noted that the communication system was dependent on the transportation system because if the roads were closed then no backup equipment could be supplied. This highlighted the importance of having multiple methods to provide FEW system services, thus minimizing the impact of any one method on the system. To exemplify this, after the 2013 flood in Boulder, CO, landlines and radios were used as backups to mitigate the impact of losing cell towers due to power outages (Romero-Lankao & Norton, 2018).

3.4. Discussion

The results support that, due to the unique nature of any given extreme event on a coastal system, there is no "one size fits all" way to incorporate the FEW nexus into coastal resilience. Nonetheless, three broad conclusions can be drawn: 1. Applying the FEW nexus approach as a methodology to coastal resilience planning has been used with some success as a framework to recognize and explore the potential interrelationships across critical infrastructure systems, 2. Coastal resilience planning should consider an energy-centric perspective of the FEW nexus, and 3. The FEW nexus should be expanded to include other systems, such as transportation.

1. Applying the FEW nexus approach as a methodology to coastal resilience planning has been used with some success as a framework to recognize and explore the potential interrelationships across critical infrastructure systems, and this approach is ripe for future research. Considering the FEW nexus during coastal resilience planning provides a method to consider systems interconnections that can reduce illness, loss of life, and damage to infrastructure that may result from an extreme event. While the results found that some studies did not directly employ a FEW nexus approach, they all recognized the potential impacts one FEW system might have on another. The studies suggested that considering the linkages between multiple critical systems was beneficial to community resilience planning as tradeoffs were able to be identified, and subsequently, the suite of systems and perspectives incorporated into resilience planning could be expanded.

Incorporating the FEW nexus approach into coastal resilience planning provides a framework for how to consider the interconnections and inherent tradeoffs between multiple systems (food, energy, water and more). Multiple benefits and efficiencies can arise when systems are considered together. For example, in a study of infrastructural ecology, Brown (2019) demonstrated that intentionally linking power, water, sanitation, transport, and food systems "may produce efficiencies simply by sharing structure or space. Once conjoined, these otherwise unrelated sector systems may additionally achieve lower first- and/or operating costs" (p. 22).

Applying the FEW nexus approach in the context of coastal resilience planning can help bring a diversity of perspectives to the planning process. Resilience planning involves internal coordination between those in a planning body and with external actors (Sellberg et al., 2018). This is evidenced by the study that applied the Dynamic Environmental Livelihood Sustainability (DESL) framework on the island of Zanzibar, which found that the combined participatory and nexus framework approach "supported learning between both communities and professionals as well as among institutions, which ordinarily work in isolation" (Newman et al., 2020, p. 13). A study of knowledge co-production across the energy-water-food nexus intentionally sought to learn from the expertise of stakeholders that work across the nexus to overcome the limitation of siloed approaches (Howarth & Monasterolo, 2017).

Applying the FEW nexus framework to coastal resilience is supported by Stringer et al. (2018) who developed a framework for how to integrate the nexus approach with resilience thinking, which they call the WEF-PIK resilience framework (water-energy-food nexus and connections between policies, institutions, and knowledges). This study reports that the WEF-PIK framework can go beyond what either a nexus approach or resilience thinking could do on its own, particularly in terms of equitable outcomes.

All the studies in this analysis were published within the last four years (since 2016), which means that this is a relatively new area of research. The multiple benefits of the FEW nexus approach, which include considering tradeoffs, linkages, and bringing diverse perspectives into consideration, are a natural complement to resilience planning and merits further research.

2. Coastal resilience planning should consider an energy-centric perspective of the FEW nexus. Results from this study suggest that the FEW nexus could be approached from an energy-centric perspective when applied to coastal resilience. Especially in more urban areas where the FEW nexus interconnections are more pronounced, several of the studies found that the damage to the energy system was a central link and had the most cascading, indirect impacts to other systems, such as water, health, and food (Cimellaro et al., 2019; de Bruijn et al., 2019; Romero-Lankao et al., 2018; Romero-Lankao & Norton, 2018). This is supported by other studies, such as how the energy system was found to be the "key sector to propagate risks to other sectors" in New York City after Hurricane Sandy (Haraguchi & Kim, 2016, p. 133) and a study of Puerto Rico after Hurricane Irma and Maria found that "understanding the relationships of infrastructure recovery efforts between power infrastructure systems and the other [critical infrastructures] has the potential to be a key in developing an effective recovery plan leading to resilient infrastructure systems, and thereby a more resilient community" (Sarker & Lester, 2019, p. 1).

Applying an energy-centric approach to the FEW nexus within coastal resilience would tie to the prior discussion of which groups and systems are brought to the table during research and planning. Hypothetically, this could manifest as the energy system and its critical ties to other systems being highlighted by inviting members of the local utility to meetings, through the systems inclusion in questionnaires and interview guides, or including the energy system centrally in modeling endeavors. This is supported by a study of system restoration interdependencies, which found that "information from and communications with the restoration efforts of the energy sector could be quite valuable in restoration efforts across sectors" (Sharkey et al., 2016, p. 8).

As the cascading impacts of damage to the energy system were highlighted in several of the studies, it was curious to see a lack of consideration or discussion of SmartGrid technology in the studies that met the selection criteria. SmartGrid solutions, such as energy storage, distributed generation (via microgrids), and demand side management, could help increase the resilience of the energy system in the face of disasters (Panteli & Mancarella, 2015). Future research would benefit from including a consideration of SmartGrid technologies into the study of coastal resilience using a FEW nexus approach.

3. The FEW nexus should be expanded to include other systems, such as transportation. The results indicate that just a FEW nexus approach may be too narrow for coastal resilience planning. Transportation was shown to have direct and indirect impacts to many other systems, most notably, the food system in urban areas. The urban food system is dependent on food retailers (critical commercial services), which, in turn, rely on the transportation system for the delivery of food from surrounding areas and the global market. This is supported by Paci-Green and Berardi (2015) who note that the food system primarily relies on the transportation and energy systems and regional farm production can increase resilience from natural hazards when combined with a regional food resilience strategy. The FEW approach should include the transportation system in the nexus (the FEWT nexus, if you will).

Given the reliance of the food system on transportation and surrounding regions/networks, the locavore movement seems a natural connection that was curiously missing from all of the studies. Aside from the two innovations, the multigeneration machine and floating production, none of the studies considered resource production more locally as a component of resilience. Local food production as a component of resilience is supported by Smith et al. (2016) who studied long and short food chains after a flood event in Queensland, Australia. The flood event cut off roads, which resulted in food shortages. Short (more local) food chains were found to be more resilience than long (supermarket-based) food chains (Smith et al., 2016).

Results suggest that considering how the FEW nexus connects to other systems should be encouraged in coastal resilience planning. For example, while health was not shown to have an impact on other systems in the sample of studies used in this analysis, food, energy, water, and transportation systems were each shown to impact health.

3.5. Future Research

The scope of this study only considered resilience work from an academic perspective. For example, there is much being done by US cities, towns, and states that has not been published in peer-reviewed journals and was therefore not captured in the scope of this study. Resilience planning can be found in grey literature, such as city Comprehensive Plans, the Resilience Plans produced through collaboration with 100 Resilient Cities, and Hazard Mitigation Plans. Future research is needed to determine how the nexus of food, energy, water, and transportation systems have been included into grey literature, specifically, city resilience plans.

Many studies were excluded during the Title & Abstract search because they did not include food, energy, and water systems or they focused on only a subset of the systems. An avenue for future research would be to expand the systematic literature review search criteria to discover, broadly, which interconnected systems are most commonly included in studies of coastal resilience. The transportation, health, and communications systems could be used as a starting point. Expanding the search criteria could confirm what the small sample size of articles revealed in this study.

Most of the studies considered an acute hazard (10 of 14) and were of purely urban areas (8 of 14). This emphasis on urban areas and acute hazards may partially be an artifact of the search criteria. For example, the definition of "coastal" was expanded to include riverine locations but only if those studies incorporated an acute, water-related hazard. Therefore, additional research is needed to better understand how the FEW nexus could be applied to coastal resilience planning in rural areas and with chronic hazards. Additionally, this future research could compare how the FEW nexus has been incorporated into studies of coastal resilience with those of riverine resilience.

3.6. Conclusion

This study conducted a systematic literature review to better understand how the FEW nexus has been incorporated into the study of coastal resilience and to determine what recommendations exist for doing so. Results highlight that most studies examined impacts to FEW systems from acute hazards and most were focused on urban areas with a diversity of FEW nexus considerations identified. With the number of acute events projected to increase in severity and frequency in coastal areas due to climate change, applying a FEW nexus approach to the study of coastal resilience could help ensure that critical infrastructure systems and their interconnections are considered. This is important as several studies highlighted how damage to the energy system could impact nearly every other system it was connected to and how the food system, in terms of critical commercial services, relies on the transportation system to replenish its supplies. With both the energy system and transportation system vulnerable to acute coastal hazards, such as hurricanes and flood events, results suggest that potentially applying the FEW nexus from an energy-centric perspective and intentionally broadening the FEW nexus to include other systems, namely transportation, could be considered in the context of coastal resilience. While there is no established method to build resilience in communities, the results from this study suggest potential new strategies to investigate.

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CHAPTER 4: RESILIENCE PLANNING AT THE NEXUS OF FOOD, ENERGY, WATER, AND TRANSPORTATION SYSTEMS IN COASTAL U.S. CITIES

Abstract

Climate change poses increased risks to coastal communities and the interconnected infrastructure they rely on, including food, energy, water, and transportation (FEWT) systems. However, most coastal communities in the US are ill-prepared to address these risks, and resilience planning is inconsistently prioritized and not federally mandated. This study examines the resilience plans of eleven coastal US cities to understand how the interconnected risks to FEWT systems are addressed, including through the development of a Nexus Index. Results show that FEWT systems are not equally or consistently included in the plans and a FEWT nexus approach did not appear to have been explicitly employed during plan development. The Nexus Index showed that indirect nexus elements were inconsistently employed in the development of resilience plan actions. The heterogeneity among the systems and themes that each plan emphasized could reflect the heterogeneity among the challenges that each city faces.

4.1. Introduction

Coastal communities are at increased risk from climate change-related threats, such as storms, flooding, fire, and sea level rise, which are exacerbated by anthropogenic factors. These climate related hazards also pose extreme risks to our built environment and essential infrastructures such as food, energy, water, and transportation (FEWT) systems (Dargin et al., 2020; Raub et al., 2021). Coastal resilience has been defined as "the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions" (Masselink & Lazarus, 2019, p. 1). While there is no standard way to operationalize coastal resilience, it has been applied in terms of coastal communities' decisions to rebuild or relocate after a hurricane (Binder et al., 2015), to develop frameworks for disaster risk management (Almutairi et al., 2020), and to assess the impacts of climate and policy changes on coastal communities (Mills et al., 2018).

In the United States, the concept of resilience has been incorporated into a variety of agency and planning efforts. Examples of where resilience has been incorporated into community planning include the Federal Emergency Management Agency's (FEMA) Hazard Mitigation Plans via the Stafford Act and Coastal Zone Management Plans via the Coastal Zone Management Act. The Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act) is the policy that guides the disaster assistance purview of FEMA. FEMA, under the Department of Homeland Security, manages the National Flood Insurance Program (NFIP) and requires a Hazard Mitigation Plan for states and local communities to access federal funding. The FEMA Resilience Office "works to fulfill FEMA's vision of a prepared and resilient nation through its programs and partnerships" (FEMA, n.d.). The Coastal Zone Management Act (CZMA) grants funding and the authority to manage coastal zones to coastal and great lakes states. These states are required to have approved Coastal Zone Management Plans. While the term "resilience" never appears in the CZMA (Coastal Zone Management Act, 1972), the Coastal States Organization, which is the national office supporting the state Coastal Zone Management Programs, cites several initiatives to support coastal resilience within state CZM Programs (Coastal States Organization, n.d.).

Currently, there are no formal requirements or policies that mandate or incentivize US cities to engage in resilience planning. However, 100 Resilient Cities (100RC), a program by the Rockefeller Foundation, began in 2013 to aid cities around the globe in becoming more resilient (*100 Resilient Cities*, n.d.). 100RC provided selected cities with funding to hire a chief resilience officer and resources to develop a resilience plan. 100RC, while international in scope, charged municipalities with the responsibility to overcome urban resilience challenges (Zebrowski, 2020). Participation in 100RC afforded each city access to a global network of cities and encouraged the consideration of shocks (e.g., hurricanes, flood events, earthquakes) and stresses (e.g., inequality, aging infrastructure, unemployment) and to include physical, social, and economic considerations. The 100 Resilient Cities program includes twenty-nine cities from North America (twenty-three from the United States), fifteen cities from Latin America and the Caribbean, seventeen cities from Europe, ten cities from Africa, five cities from the Middle East, four from Oceania, five from South Asia, and fifteen cities from East Asia. Cities were selected to participate in the 100 Resilient Cities program in three waves between 2013 and 2016. As it takes several years to complete a resilience plan, some cities have not yet published plans. The 100RC program ended in 2019 and has been succeeded by the Resilient Cities Network (*Resilient Cities Network*, n.d.).

Coastal community resilience planning efforts could benefit from employing a food-energy-water (FEW) nexus approach. Urban areas are densely populated with highly interconnected systems, namely, food, energy, and water (FEW) systems. FEW systems are all critical infrastructure necessary for human wellbeing and are essential for the resilience of communities over time. For example, a disaster could cause disruptions to the energy and transportation systems on which the food system relies, thus limiting a communities access to food (Paci-Green & Berardi, 2015). The US energy system is highly interconnected and vulnerable to disruptions (Roege et al., 2014), therefore it is necessary for resilience in that its disruption impacts nearly all other critical infrastructure systems (de Bruijn et al., 2019). Similarly, water provisioning, namely via water and wastewater treatment plants, is vulnerable to disturbances to the electrical system, especially during flood events (Romero-Lankao & Norton, 2018). A nexus approach, or framework, identifies that relationships and feedbacks between the sectors are inextricably linked and encourages decision-making in coordination with other sectors rather than working in silos (Belinskij, 2015). Additionally, sectors can become more efficient if multiple are considered together (Minne et al., 2011). A FEW nexus approach has been recommended as an effective management strategy of these systems and to efficiently meet the food, energy, water needs of the public and industries (Zhang et al., 2019). The food-energy-water (FEW) nexus approach has been advocated to address the United Nations Sustainable Development Goals, which include the providing food, energy, and water for everyone (Liu et al., 2018).

Nexus approaches also go beyond just considering connections between food, energy, and water systems to include other systems. For example, the nexus of water, energy, land use, transportation, and socioeconomic systems was studied in the context of sustainable urban systems (Minne et al., 2011). To measure urban resilience, the FEW nexus was connected to environmental sustainability and equity (Schlör et al., 2018). The land-water-energy nexus has been studied in agricultural systems (Fan et al., 2020). Even outside of explicit nexus approaches, public health has been linked to water infrastructure in the context of flood resilience in coastal cities (Allen et al., 2019). A recent study of the FEW nexus in the context of coastal resilience suggested that the FEW nexus approach be expanded to include the transportation system, especially in urban areas - also known as the food-energy-water-transportation nexus (FEWT) (Raub et al., 2021).

A recent review of peer-reviewed academic studies found that only fourteen publications that incorporated the FEWT nexus approach within coastal resilience analysis, modeling, and planning (Raub et al., 2021). This study found that coastal resilience is enhanced when FEWT systems and their interconnections are included in coastal resilience planning. However, this has yet to be explored in grey resilience literature, that is, if and how the FEWT nexus is incorporated into coastal resilience planning in practice. Therefore, this study conducts a document analysis of the resilience plans from eleven coastal US cities developed through their inclusion in the 100 Resilient Cities program. The objectives of this study were to: 1. Explore the extent to which communities have considered the FEWT nexus in the context of coastal resilience planning, and 2. In general, understand if and how nexus principles were employed in the context of coastal resilience planning.

4.2. Methods

4.2.1. City Selection

This study focuses on US cities that were part of the 100 Resilient Cities program, as the country had the most cities included in the program (twenty-three) and it would allow for a shared political context. Additional criteria for inclusion within this analysis included: 1. Having a publicly-available resilience plan (as of September 2020), and 2. Being coastal. For the purpose of this study, ‘coastal’ was defined as having a portion of the city touch an ocean or gulf. Eleven US cities listed in Table 4.6 met the inclusion criteria and represent a range of regions across the US: East Coast (Boston, New York City), Mid-Atlantic (Norfolk), South Atlantic (Miami), West Coast (Seattle, Los Angeles, San Francisco, Oakland, Berkley), the Gulf Coast (New Orleans), and an island (Honolulu).

Table 4.6. The eleven coastal cities included in the document analysis, their population, and region of the United States.

	City	State	2019 Population[1]	Region
1	Berkley	CA	121,363	West Coast
2	Boston	MA	692,600	East Coast
3	Los Angeles	CA	3,979,576	West Coast
4	New Orleans	LA	390,144	Gulf Coast
5	New York	NY	8,336,817	East Coast
6	Norfolk	VA	242,742	Mid-Atlantic
7	Oakland	CA	433,031	West Coast
8	San Francisco	CA	881,549	West Coast
9	Seattle	WA	753,675	West Coast
10	Miami	FL	467,963	South Atlantic
11	Honolulu	HI	974,563	Pacific Island

[1]US Census, 2019. Population estimates, July 1, 2019 (V2019). U.S. Census Bureau, Population Estimates Program, updated annually.

4.2.2. Anatomy of a Resilience Plan

The resilience plans were published between 2015 and 2019 and included the following basic components: a letter from the mayor of each city and/or the chief resilience officer; an overview of the plan; the history of the city and often a list of other planning efforts that the resilience plan built upon; a description of the planning process; the visions, goals, actions, and supporting initiatives for how the city will increase its own resilience; and finally, a list of contributors, references, and appendices. Many resilience plans had dedicated sections or had references to how they learned from the efforts of other cities, which was one of the main goals of the 100RC program. The majority of each plan was typically dedicated to describing the specific actions that each city proposed to undertake to increase its resilience and advance the specific goals or visions it had outlined.

4.2.3. Data Collection

Each resilience plan was analyzed for the following themes: food, energy, water, and transportation systems as well as communication, health, and proximity to the coastal. These themes were selected based on the systems interconnections found in a systematic literature review of coastal resilience studies by Raub et al. (2021). Additional themes were included as they were identified during the analysis including: housing; diversity, equity, inclusion, and justice; economy, environment, and references to other types of plans. As each theme was added, prior plans were reanalyzed for material that may have applied to the new theme. Finally, nexus-related themes were identified and used to create a "Nexus Index" (e.g., references to interconnected systems, partnerships between different departments, interdisciplinary approaches, or anything related to the connection between multiple systems or perspectives). Overall, thirteen themes were analyzed for in this study. Data collection involved not only coding for specific words related to each theme, but also for the context in which the themes were incorporated (e.g., enough surrounding text was collected to show that the energy system was in the context of energy efficiency upgrades to buildings or in the context of rooftop solar panel deployment).

4.2.4. Data Analysis

4.2.4.1. Defining an "action"

Each resilience plan was composed of a series of broad goals or visions and then a series of actions or initiatives that detailed the specific ways the resilience goal would be addressed. Each plan followed a different method of defining visions, goals, actions, and supporting initiatives (including using different vocabulary), but they each followed a similar nested structure. That is, each plan defined a small number of overarching visions, a set of more detailed goals within each vision, and a set of specific actions within each goal. Some plans included only two levels and others had up to four. The third level, hereby called "action," was chosen as the unit of analysis for this study as it was the most consistent across all the plans in terms of level of detail provided (see, Table 4.7 for an example of how three plans created actions for electric vehicle adoption). If the plan provided four levels, the themes found within the "supporting initiatives" were classified within the "action" it fell under as they were only included for some actions but not others (e.g., the New York City resilience plan) or the supporting initiatives were very brief and acted as specific examples for the action (e.g., the Boston resilience plan). Only material included within each action was included in the analysis, meaning any introductory material, case studies, or supplementary sections were excluded from analysis.

Table 4.7. An example of the different hierarchical levels defined within three resilience plans. This study will use the vocabulary, "vision" to define the top level, "goal" to define the second level, "action" to define the third level, and "supporting initiative" to define the fourth level. The third level, "action" was targeted for analysis in this study.

City	Level 1: "Vision"	Level 2: "Goal"	Level 3: "Action"	Level 4: "Supporting initiative"
Berkeley (City of Berkeley, 2016)	n/a	Accelerate access to reliable and clean energy	Electrify Berkeley's vehicles (p. 29)	n/a
Miami (Miami-Dade County et al., 2019)	Places: aims to address place based challenges by enhancing climate resilience through design and planning; creating, connecting, and improving mobility and housing options; and safeguarding ecosystems.	Create mobility options	It's Electric: prepare and catalyze the growth of the electric vehicle market (p. 66)	n/a
New York City (City of New York, 2015)	Our Sustainable City: New York City will be the most sustainable big city in the world and a global leader in the fight against climate change (p. 160)	Air Quality: New York City will have the best air quality among all large US cities by 2030 (p. 161)	Develop a mode shift action plan to reduce greenhouse emissions from the transportation sector (p. 172)	Reduce carbon emissions from the City government's vehicle fleet (p. 173)

4.2.4.2. Primary or partial focus of each action

The final stage of analysis was to classify each of the thirteen themes as either a "primary focus" of the action or a "partial focus." A theme was classified as the "primary focus" of an action if it was a key focus of an action, where partial focus refers to a system that was only mentioned or incorporated along with many others in an action. For example, the food system was deemed the primary focus of Action 89 of the Los Angeles resilience plan: "The City will work with the Los Angeles Food Policy Council (LAFPC) to identify opportunities to increase the resilience of the City's food network for all communities" (City of Los Angeles, 2018, p. 142). Whereas food was deemed a partial focus of Action 15 of the Honolulu resilience plan: "Resilience Hubs should be defined by each neighborhood or local community for their own needs and goals, however many are focused on providing the following during a disaster: 1) Emergency shelter during a disaster; 2) A central community gathering/information site and distribution center post-disaster; 3) Renewable energy and energy storage/supply even if the grid is down; 4) Water and food stores; and, 5) Medical supplies" (City and County of Honolulu, 2019, p. 60). Each action can have multiple themes classified as "primary focus" or "partial focus." For example, the prior example, Action 15 of the Honolulu resilience plan, would be classified as a partial focus for housing, communication, energy, water, food, and health.

4.2.4.3. The Nexus Index

A "Nexus Index" was created to score each action on how many nexus related components it included. Each action was assigned a score between zero and eight based on the following criteria: partnerships and collaborations, reference to another plan or report, discussion of co-benefits, cascading impacts, and inclusion of interdisciplinary or cross-silo principles. One to two points were assigned for the inclusion of partnerships or collaboration. Initially, if an action provided a list of partners or collaborators, the number listed was recorded. If an action did not provide a list, the number of partners or collaborators referenced within an action was counted and recorded. If an action did not name partners and simply referred to partners or collaborators, it was recorded if the there was a singular partner or plural partners mentioned. The mean number of partners was calculated for each plan. Zero points were assigned if the action included no partners or collaborators, one point if the number of partners was below or equal to the mean, and two points if the number of partners was above the mean. One point was assigned to each action that referenced another plan or report. One point was assigned for the inclusion of co-benefits, meaning referencing how the action would benefit other systems. Two points were assigned for the inclusion of cascading impacts, meaning referencing how damage to one system could negatively impact others within the context of the action. Finally, two points were assigned if the action included the terms “cross-silo,” interdisciplinary, multidisciplinary, or if the action intentionally sought to bring together multiple departments, fields, or disciplines to collaborate or work together to advance the actions resilience principles.

The plans were then compared by the percentage of their individual highest score they attained. As each plan had a different number of actions, they each had a different potential Nexus Index score. For example, New York City had 101 actions with a highest possible Nexus Index score of 808, whereas Boston only had 23 actions or a possible Nexus Index score of 184. Therefore, Boston and New York City were compared based on the percentage of their actual Nexus Index score from their highest possible Nexus Index score.

4.2.4.4. Coding Reliability

To ensure coding reliability, a codebook was developed to determine if an action included one of the target systems or themes, if that system or theme was a primary or partial focus, and to provide a score for each element of the Nexus Index. Two coders were given five randomly selected actions and used the codebook to identify which systems or themes were present and to assign a Nexus Index score. The two sets of code were then compared. Once the two sets of code were 90% in agreement or higher, the codebook was considered reliable. Until 90% was reached, the codebook was updated to account for any disagreement or nuance, and an additional five actions were selected to check for reliability.

4.3. Results

Five hundred and ninety-three actions were identified collectively across the eleven city resilience plans. The Boston resilience plan included the least number of actions (23 actions) and the New York City resilience plan had the most (101 actions). As such, the results will be discussed both in terms of the total number of actions which included each system and theme and the percent of each plans actions that included each system and theme (to allow for consistent comparison across plans).

The cities followed or built upon the City Resilience Framework (CRF) tool developed by The Rockefeller Foundation and Arup (2015) when creating their resilience plans. The CRF highlighted four key areas within its framework: health and wellbeing, economy and society, infrastructure and environment, and leadership and strategy. While only half of the plans directly mentioned using the CRF in the development process, all of the plans used consistent vocabulary that indicated that they may have been influenced by the framework (e.g., they used the terms “shocks” and “stresses” to refer to acute and chronic hazards or challenges).

4.3.1. The Nexus Index

4.3.1.1. Nexus of FEWT Systems

There was little evidence that a FEW or FEWT nexus approach was explicitly used when creating the resilience plans. However, 15 actions (3%) considered all 3 or 4 systems together. Of those 15 actions, eight focused on the connections between systems. The other seven incorporated multiple FEWT systems into a single action. Honolulu’s plan connected energy, water, and transportation systems in that wastewater treatment plants can produce methane and use it as a redundant energy source in case of an infrastructure failure and the methane can also be used to power alternative-fuel vehicles (City and County of Honolulu, 2019). Oakland's action incorporated all four food, energy, water, and transportation systems but only considers the connections between energy and transportation and, separately, water and food (City of Oakland, 2016). These Ecoblock principles include rooftop rainwater harvesting that irrigates shared produce gardens and a solar-powered microgrid that can power electric-vehicle chargers. Conversely, Miami's action entitled "Planning efficiently & effectively together" incorporated energy, water, and transportation systems but does not consider their interconnections. In this action, water, energy, and transportation infrastructure projects will be coordinated to create efficiencies, such as coordinating underground water and energy projects so as only to have to dig up a road once. Here, there is coordination but no physical linkages between systems.

Nearly half (7 of 15 action) of the FEWT-related actions were in the context of a disaster or extreme weather event and when an action incorporated how damage to one system could negatively impact other systems (only 6 actions total), the energy system was the central focus. The disaster-related FEWT actions include Honolulu's action entitled "Develop a network of community resilience hubs" which combines energy, water, and food systems (City and County of Honolulu, 2019). The community resilience hubs will provide shelter, information distribution, renewable energy storage and supply, water and food, and medical supplies following a disaster. Additionally, 6 actions (2 of which overlap with the 15 FEWT-related actions) considered the cascading impacts that damage to the energy system can have on interdependent systems. For example, Los Angeles' action entitled "Encourage increased power for critical services", highlights how the energy system can negatively impact services such as gas stations, food businesses, and hospitals, and how the energy system should align with "interdependent lifeline services, including water availability and fire prevention strategies" (City of Los Angeles, 2018, p. 139).

4.3.1.2. The Nexus Index

The Cities of Honolulu and Miami had the highest Nexus Index scores relative to their potential scores, 43% and 42%, respectively. Seattle had the lowest Nexus Index score relative to its potential score, 15%. The Nexus Index scores as they relate to each cities potential score are listed in Table 4.8 in descending order.

Table 4.8. The Nexus Index score of each city relative to its potential score as both numeric score and the percent of the potential.

City	**Number of Actions**	**Nexus Score: Actual (Potential)**	**Percent of Potential Nexus Score**
Honolulu	44	150 (352)	43%
Miami	59	198 (472)	42%
Oakland	37	116 (296)	39%
Berkeley	27	79 (216)	37%
Boston	23	58 (184)	32%
Los Angeles	96	239 (768)	31%
New Orleans	41	94 (328)	29%
San Francisco	54	117 (432)	27%
New York City	101	211 (808)	26%
Norfolk	42	66 (336)	20%
Seattle	69	82 (552)	15%

Each of the elements of the Nexus Index were not evenly found across the resilience plans; the plans most commonly listed partners and collaborators and least included system interdependencies. In terms of partners listed, the plans achieved 61% of their maximum potential score (723 out of a potential 1186 points). In descending order, the plans achieved 45% of their potential score for including co-benefits (269 out of a potential 593 points), 36% of their potential score for referencing other plans or reports (213 out of a potential 593 points), 13% of their potential score for including cross-silo or interagency efforts (149 out of a potential 1186 points), and 5% of their potential score for including system interdependencies (56 of a potential 1186 points).

Every resilience plan had actions that highlighted forming collaborations and partnerships. Los Angeles, Miami, Berkeley, and Oakland each had the highest percentage of their potential score for the inclusion of partnerships and collaborations (71%, 71%, 70% and 70%, respectively). Seattle had the lowest percentage of its potential partnerships score with only 32%. As stated within the Honolulu resilience plan, "resilience is going to take unprecedented collaboration" (City and County of Honolulu, 2019, p. 120). Los Angeles, Oakland, and Berkeley all provide a list of partners for each of their actions and many of Norfolk's actions begin by discussing the partnerships it has formed or will form. A few specific examples include San Francisco's action entitled "Build Partnerships to Advance Resilience" and Miami's action entitled "Resilient 35 in the 305 Network." Miami's 305 Network will

> "catalyze the resilience work across Miami-Dade County by providing peer exchange and connecting local government practitioners through the planned Resilient 35 in the 305 Network. The 305 Network will facilitate intergovernmental collaborative work among practitioners by enhancing and supporting the sharing of communication and resources between cities in Miami-Dade County to advance resilience work. The 305 Network will support its member cities in their resilience work, develop multi-city collaboration projects, influence the development of policies at the local and regional level, and build a

network of trusting relationship between peers" (Miami-Dade County et al., 2019, p. 120).

The resilience plans demonstrated a consideration of how systems can impact one another within their actions more often in terms of co-benefits than interdependencies or negative cascading impacts (how damage to one system could negatively impact other connected systems). In the context of the resilience plan actions, "co-benefits" meant how positive changes in one system would create positive changes in another. Half of the plans (6 of 11) provided a list of co-benefits along with most actions, such as Honolulu's "Resilience Co-Benefits," Oakland's "Benefits to Oakland Residents," and Miami's "How this will help us." For example, the co-benefits described for Honolulu's action entitled "Reduce Taxpayer Expense and Increase Renewable Energy through City-Wide Energy Performance Contracts" include how retrofit and renewable energy projects will "both reduce reliance on imported oil and natural gas and improve air quality in O'ahu's denser regions" (City and County of Honolulu, 2019, p. 73).

Other planning efforts were referenced within the eleven resilience plans. Connecting the actions within the resilience plans to planning efforts within a variety of different fields and contexts shows a willingness to make connections between otherwise siloed sectors. Boston and Honolulu's actions referenced the most other plans or reports and achieved 52% and 50% (respectively) of their potential score for this element of the Nexus Index. Norfolk referenced the least other plans and reports within its actions relative to the potential maximum, 21%. These plans and reports include proposed plans, such as developing a comprehensive post-disaster recovery plan (New Orleans, p. 76) and aligning efforts with national plans, such as Miami aligning with the National HIV

Strategy, “Ending the HIV Epidemic: A Plan for America.” Other efforts include guides and ordinances, such as Honolulu’s Complete Streets Design Manual and Oakland’s “No to Coal”, an ordinance banning coal from being stored and handled in the city.

4.3.2. Food, Energy, Water, and Transportation Systems, Individually

Food, energy, water, and transportation systems were unevenly considered in the resilience plans. The transportation system was associated with the most actions, followed by the energy system, water system, and the food system.

Transportation: There were a total of 119 (20%) actions with either a primary or partial focus on the transportation system. New York City had the most actions relating to transportation (29 primary or partial focus actions, 29% of its total actions) and Honolulu had the highest percentage of its actions relating to transportation (30% or 13 of its 44 actions). Boston had the least (1 primary focus action total, 4%, of its total actions) actions that included transportation. Transportation was often included in the plans with actions related to physical infrastructure (30 total actions, 5%), electric and clean fuel vehicles (18 total actions, 3%), and increasing the use of, or expanding access to, public transit (14 total actions, 2%). Examples include Boston’s action entitled “Advance resilient transportation systems”, which seeks to adapt transportation infrastructure for climate change (City of Boston, 2017) and Honolulu’s action entitled “Transform the City’s public fleet to 100 renewable fuel by 2035” (City and County of Honolulu, 2019). Examples of actions with a primary focus on public transit include Miami’s action entitled “Design a better bus network”, which seeks to increase ridership (Miami-Dade County et al., 2019) and Seattle’s action entitled “Cultivate a culture of ridership among Seattle's youth", which seeks to provide free public transportation to high school students (City of Seattle, 2019).

Energy: There were a total of 100 actions (17% of all actions) with either a primary or partial focus on the energy system. New York City, Los Angeles, and Honolulu, Los Angeles had the most actions relating to energy (21, 20, and 15 actions, respectively; or 21%, 21%, and 34% of their total actions, respectively), however, Berkeley had the highest percentage of its actions that included energy (41%; or 11 of 27). Conversely, Boston only had one action (4% of its total actions) and Norfolk had none. The energy system was most commonly considered in terms of increasing the use of renewable energy (42 actions, 7% of all actions) and increasing energy efficiency (24 actions, 4% of all actions). Examples of how renewable energy was considered include Miami's action entitled "Expand renewable energy" was in an effort to reduce greenhouse gas emissions (Miami-Dade County et al., 2019) and Boston's action entitled "Expand distributed energy to vulnerable communities" was in the context of implementing a microgrid with distributed generation that would provide an alternative power source if the main grid were disrupted (City of Boston, 2017). An example of how energy efficiency was considered is Seattle's action entitled "Reduce costs for seniors and fixed-income residents" in the context of energy saving improvements to homes.

Water: There were a total of 69 actions (12% of all actions) with either a primary or partial focus on the water system. Actions relating to flood events or risk were not included as part of the water system unless they focused on stormwater management infrastructure. The actions predominantly focused on the water system in terms of physical infrastructure (31 actions, 5%) and increasing efficiency/water conservation (16 actions, 3%). Once again, the water system-related actions were not evenly distributed across the resilience plans –Berkeley, San Francisco, and Los Angeles had the highest percentages of their actions that included the water system (37%, 19% and 18%, respectively). Boston and Norfolk did not have any actions that included the water system. In terms of infrastructure, the actions were commonly about stormwater infrastructure improvements or the deployment of green stormwater infrastructure or upgrading and retrofitting water system infrastructure (e.g., water or wastewater treatment facilities, pipes, reservoirs, etc.). These actions were mostly in the context of reducing flood risk or with consideration of climate change. For example, New York City's resilience plan includes an action entitled "Protect the city's water supply and maintain the reliability and resiliency of the water supply system" (City of New York, 2015). In terms of increasing efficiency, the actions were commonly about upgrading residential or commercial buildings to have more efficient water use. For example, the Honolulu resilience plan has an action entitled "District cooling: Tap the ocean to cool our buildings", which seeks to use seawater for cooling buildings, which conserves energy and potable water on land (City and County of Honolulu, 2019).

Food: The food system was one of the least included systems in any of the plans. Out of the 593 actions detailed in the eleven plans, thirteen actions (2%) had a primary focus on food and twenty-one (4%) included only a partial focus (34 total actions, 6%). New York City had the most actions that included the food system (12 total, or 12% of its total action) and Honolulu had the highest percentage of its actions that included the food system (16%, or 7 of 44 actions). Five of the resilience plans had only one action with either a primary or partial focus on the food system San Francisco, Miami, Berkeley, Boston, and Norfolk). The food system was incorporated predominantly in terms of food access or distribution related to a disaster or hazard event (13 primary or partial focus actions, 2%), food access and affordability under normal conditions (6 primary or partial focus actions, 1%), and food production (7 primary or partial focus actions 1%). For example, food access related to a disaster was addressed through actions such as developing a "resilience hub" or community center that would serve as a shelter and place to distribute resources after a disaster (e.g., Berkeley's action entitled "Create safe (and green) City community centers and care & shelter facilities" (City of Berkeley, 2016) and Honolulu's action to "Develop a network of community resilience hubs" (City and County of Honolulu, 2019)). Food access and affordability was addressed in actions such as those which incentivize food retailers to provide fresh foods or providing families with the means to purchase them. For example, New Orleans's action entitled "Continue to promote equitable public health outcomes" included the "Fresh Food Retailer Initiative," which provides loans to food retailers to increase access to fresh foods (City of New Orleans, 2015).

Overall, food, energy, water, and transportation systems were not emphasized within the eleven resilience plans (Figure 4.2). Diversity, equity, inclusion & justice was the most dominant theme across the plans with economy and housing as the second and third most common themes, respectively (Figure 4.2). Every resilience plan contained actions that incorporated or focused on diversity, equity, inclusion, with 245 primary or partial focus actions across the eleven plans (41% of all actions). Low-income communities (75 actions, 13%) and racial equity (29 actions, 5%) were the most considered across the resilience plans. There were a total of 188 actions (32% of all actions) that incorporated or focused on the economy. Actions regarding the economy were mostly in terms of job creation and training/preparing residents for jobs (75 actions, 13% of all actions). There were a total of 148 actions (25% of all actions) with either a primary or partial focus on housing. Housing was commonly included in the resilience plans in terms of increasing or promoting housing affordability (53 actions total, 9%) and housing or building upgrades (67 actions total, 11%). San Francisco had the highest percentage of it actions that included housing (44%, or 24 of its 54 actions).

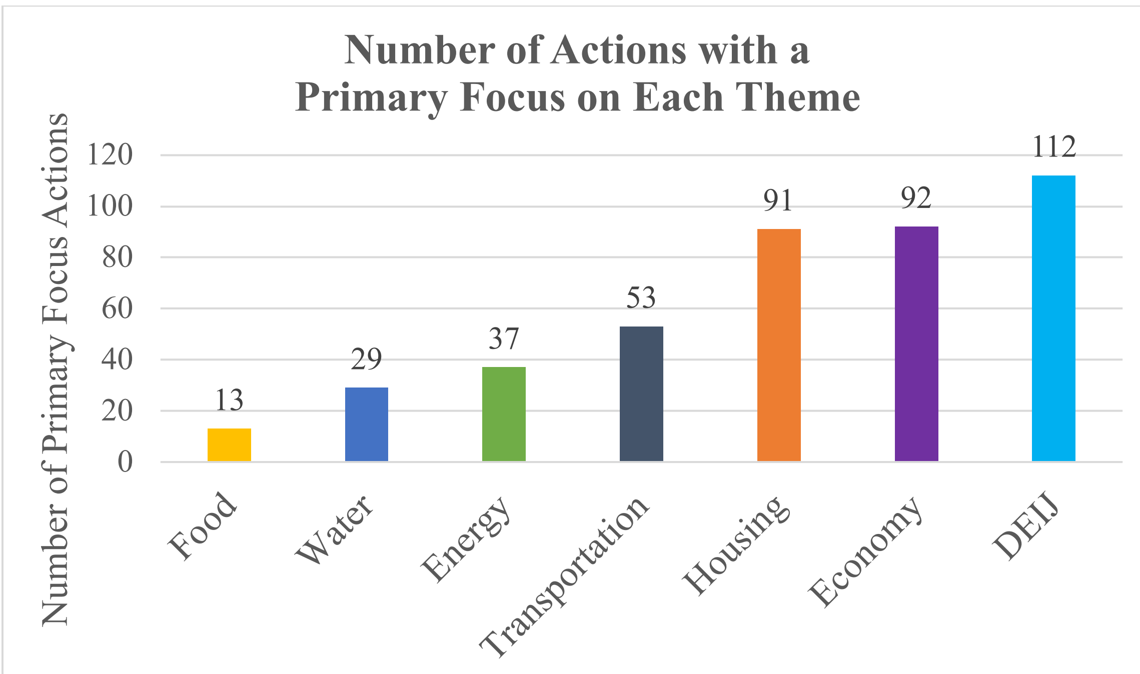

Figure 4.2. A summary of the number of actions with a primary focus on each theme: food, energy, water, transportation, housing, economy, and diversity, equity, inclusion, & justice (DEIJ).

4.3.3. Coastal Considerations

The cities designed a total of 122 actions (21% of all actions) with either a primary or partial focus on the coastal environment. Of these, 59 (10%) had a primary focus on the coastal environment or challenges. These actions were unevenly distributed between the plans; Miami had the most overall actions related to the coastal environment (25 actions, 42% of its actions) and Boston, Berkeley, and Seattle had the least (4 actions, each or 17%, 15% and 6% of their total actions, respectively). Additionally, the coastal related actions could be grouped in terms of their focus: on flood risk considerations or non-flooding related coastal considerations. In total, the Cities designed 51 actions with a primary focus on flood risk (either through a flood event or sea level rise) and only 8 actions with a primary focus on some aspect of their coastal location outside of the context of a hazard. Miami, New York City, New Orleans, and Honolulu each had the most actions with a primary focus on flooding (13, 8, 6, and 6 actions, respectively), while Seattle had no actions relating to flooding. Seattle had four actions (1 primary focus, 3 partial focus) relating to non-flooding related aspects of the coastal environment related to the economic importance of their maritime lands and redoing their waterfront.

Actions with a primary focus on the coastal proximity of the cities include those to develop or take advantage of funding sources for flood protection and implementing or developing other planning efforts. Examples of coastal actions relating to funding include Miami's action entitled "Demonstrate cost benefits of resilience," which seeks to support the city's need to invest in infrastructure to reduce the risk of flooding (Miami-Dade County et al., 2019) and Honolulu's action entitled "Increase flood insurance affordability for O'ahu residents," which seeks to do so through participation in the Community Rating System (City and County of Honolulu, 2019). Examples of other planning efforts include Oakland's action entitled "Update the Storm Water Master Plan to guide future investment in stormwater management" (City of Oakland, 2016), Miami's action entitled "Implement Sea Level Rise Strategy" (Miami-Dade County et al., 2019), and New Orleans's action entitled "Master Plan for a Sustainable Coast" (City of New Orleans, 2015), which focuses on stormwater management and flooding.

4.4. Discussion

This study sought to understand how food, energy, water, and transportation (FEWT) systems and their interconnections had been incorporated into US city resilience plans. There are three main conclusions that can be drawn from the analysis of the resilience plans: 1. There was a lack of emphasis on FEWT systems and their nexus, 2. The cities proximity to the coast was inconsistently incorporated, and 3. The heterogeneity in what was emphasized in each city's' actions reflects the heterogeneity in the challenges each city faces.

There was little evidence that a FEWT nexus approach, or general nexus approach, had been used when creating the resilience plans. There was an inconsistency in how food, energy, water, and transportation systems were included within the resilience plans, especially in how certain cities entirely excluded them (e.g., Boston had no actions that included water and Norfolk had no actions that included energy). The elements of the Nexus Index were also not consistently incorporated within the resilience plan actions. The Honolulu resilience plan had the highest Nexus Index score, which was only 43% of its potential score and the Seattle resilience plan had the lowest (15%). These low Nexus Index percentages suggest that the resilience plans were written external to a nexus approach. Partnerships and co-benefits were the most common applications of nexus principles (61% and 45% of their potential score, respectively), whereas including cross-silo or interdisciplinary teams or approaches and incorporating systems interdependencies were the least common (13% and 5% of their potential score, respectively).

While the results from this analysis cannot answer why these systems were not consistently included, they do bring into question if a more direct FEW or FEWT nexus approach could benefit the development of resilience plan actions. While not a direct employment of a nexus approach, the Nexus Index scores and the elements used to create the Nexus Index indicate that the cities may be receptive to using a nexus approach in resilience planning. A specific FEWT or FEW nexus approach encourages planners to consider systems, interconnections, or unanticipated tradeoffs that may have been otherwise overlooked (Jianguo Liu et al., 2018; Raub et al., 2021; Whitney et al., 2019). Additionally, a direct use of a FEW or other nexus approach could benefit cities by ensuring that certain systems or perspectives are not overlooked. For example, the food system was only included in 6% of the 593 actions despite the documented food insecurity many face in the US (Alaimo, 2005), which was exacerbated and highlighted by the COVID-19 pandemic (Wolfson & Leung, 2020). Further research would be needed to understand if the food system (and others) was intentionally minimized when creating resilience plan actions, or if applying a FEW nexus perspective could have been beneficial in ensuring that it was more consistently incorporated along with other systems.

There was an inconsistent focus on proximity to the coast within the coastal cities resilience plan actions. Coastal hazards are predicted to increase due to climate change, yet only 21% of the actions with the eleven resilience plans had either a primary or partial consideration of the coast. Results suggest two likely options for the lack of emphasis on the coastal environment: 1. That the coastal considerations had been addressed in other planning efforts (and, therefore, not needed within the resilience plan), or, 2. The cities felt that their coastal location was not significant to resilience planning. While additional research, including interviews with those who wrote each resilience plan, would be needed to confirm or refute each speculation, existing research suggests that regardless of the reasoning, coastal considerations should be more prominently considered within the resilience planning of coastal communities.

It is possible that a more central consideration of coastal hazards or challenges could be found in the other planning efforts referenced in the resilience plans, such as Hazard Mitigation Plans or Sea Level Rise Plans. Each plan detailed many other planning efforts that their resilience plan builds from or links to (36% of its potential Nexus Index score across plans) Some of these plans were included as actions within the resilience plans, such as Los Angeles' action entitled "Incorporate sea level rise modeling into local plans" (City of Los Angeles, 2018) and New Orleans action entitled "Master Plan for a Sustainable Coast" (City of New Orleans, 2015). Additionally, the amount of background information and details provided for each action varied greatly between plans, from a few sentences to an entire page (or more). This could suggest that the other plans contain the bulk of the actionable information and focus on coastal hazards or the coastal environment.

The other consideration would be that the coastal environment or coastal hazards were not the most pressing hazards or challenges for every city. The plans did highlight many hazards and challenges in the introductory material, such as earthquakes, high cost of living, unemployment, inequality. These perspectives were reflected in the high number of actions across the resilience plans with either a primary or partial focus on housing, the economy, and diversity, equity, inclusion, & justice. However, a recent study of coastal community resilience frameworks in the context of disaster risk management emphasized the need to consider the interconnections between multiple hazards in future frameworks (Almutairi et al., 2020).

There were inconsistencies in how systems and themes were included across the resilience plans, which reflects the heterogeneity among the challenges that the cities face. FEWT systems and their interconnections were not emphasized in the resilience plans, which could be due to the heterogeneity between cities in terms of geography, history, economic, and political circumstances. Each city faces a different set of challenges and hazards, which may require them to emphasize different systems. For example, San Francisco's resilience plan had the most actions out of any plan with either a primary or partial focus on housing (24 out of the 593 total actions or, 44% of its own 54 actions), Miami's resilience plan had the most actions with a primary or partial focus on the coastal environment (25 out of the 593 total actions or, 42% of its own 59 actions), and Berkeley, San Francisco, and Los Angeles had the highest percentages of their actions that included the water system (37%, 19% and 18%, respectively). This is consistent with San Francisco's housing crisis (Caldararo, 2017), Miami's location atop porous limestone bedrock and pronounced vulnerability to sea level rise (Molinaroli et al., 2019), and California's water crisis (Chung et al., 2002; Pincetl et al., 2016; Tanaka et al., 2006). The differences between these coastal cities' resilience plans relates to one of the challenges with resilience; resilience is unique for every situation.

One of the key benefits to the heterogeneity between the resilience plans and the cities themselves, is that there is now a wealth and diversity of experiences to draw from when designing future resilience building actions. Many of the challenges that are pronounced in specific locations are reflective of national challenges. For example, while San Francisco has a housing crisis, there is also a housing affordability crisis across the US (Rohe, 2017). One of the key challenges to operationalizing resilience is that there is no established set of actions to draw from. The resilience plans produced from the 100 Resilient Cities program provide a valuable starting point, and as reflected in the resilience plans that reference others cities efforts, cities are willing to learn from one another even though no two cities are the same. There have now been many actions tried in a variety of contexts, for a variety of systems, and from a variety of perspectives.

4.5. Limitations and Future Research

One key limitation of this research is that there is little to no way to know the intent of those that wrote the plans. It cannot be known if the plan developers had any working knowledge or consideration of FEWT or general nexus approaches and how this knowledge, or lack thereof, contributed to the development of each plan. Additionally, it is unknown how actionable each plan was intended to be or has been since the release of the resilience plan (i.e., were the plans meant as a summary of actions with the method of implementation detailed elsewhere, or where the plans written to be followed themselves). Therefore, a critical avenue for future research is to interview those who wrote the resilience plans. A series of interviews with plan writers would reveal more about the decision making process and why certain systems were highlighted, others were excluded or minimized, and their perspective on the importance of system interconnections as they relate to resilience building. Additionally, since the plans were written as far back as 2016, interviews with resilience planners could reveal how actionable these plans were and if they have been updated (or plan to be updated).

Additionally, each of these plans followed the Community Resilience Framework that was provided by the 100 Resilient Cities (100RC) program. This common guidance could limit the chances of plan developers adding additional frameworks, such as a nexus approach, to the development of their plans. This could potentially bias the sample of plans to mean that either all plans would incorporate nexus approaches or none of them would. Future research could consider implementing the methodology from this study on resilience planning efforts that were developed outside of the 100RC program.

4.6. Conclusions

This study sought to understand how the food, energy, water, and transportation nexus had been incorporated into the resilience plans of eleven US coastal cities and to develop a Nexus Index to score resilience plans for how they incorporated nexus principles into their actions. Results show that the FEWT nexus approach as a methodology did not appear to have been used directly and FEWT systems were inconsistently included within the plans. Additionally, while housing, the economy, and diversity, equity, inclusion & justice were the most dominant perspectives within each plan, the coastal environment was not. Future research is needed to better understand the planners intentions for emphasizing certain systems and sometimes excluding others, however, it is possible that a more direct use of a nexus approach during plan development could ensure that certain systems are given stronger consideration and that systems interconnections are better assessed. In general, the resilience plans written as part of the 100 Resilient Cities program provide a starting point from which other cities can learn. One of the biggest challenges with resilience is how to operationalize it, the actions developed within each resilience plan are each efforts to operationalize resilience and can now be adopted and revised by other communities seeking to build resilience.

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CHAPTER 5: CONCLUDING REMARKS: THE FUTURE OF COASTAL RESILIENCE PLANNING

This dissertation provided insight into the challenge of operationalizing resilience that incorporates the food-energy-water (FEW) nexus. In the second chapter, interviews with state Coastal Zone Management (CZM) programs revealed that the key challenges in existing resilience tools relate to tool discovery, lack of trust, and the coarse spatial resolution of national tools. Findings suggest local community needs are better addressed when end-users play a role in the tool development process and that CZM Program connections should be leveraged because they have the knowledge and expertise to identify solutions and disseminate information. In the third chapter, a systematic literature review of academic studies that incorporate the FEW nexus with coastal resilience showed that the FEW nexus provides a method to consider systems interconnections in the context of coastal resilience planning, that the FEW nexus should be used as a starting point and expanded to include other systems (e.g., transportation), and that there may be value in applying the nexus from an energy-centric perspective in the context of coastal resilience. In the fourth chapter, a document analysis of eleven US coastal city resilience plans found that a FEW nexus approach did not appear to be explicitly used when creating the resilience plans, there was an inconsistent focus on the coastal proximity of each city, and that the heterogeneity in what was focused on in each plan reflects the heterogeneity among the cities. While not directly targeted, each study produced insights that contribute to advancing our understanding of how to overcome the four challenges with building coastal resilience at the nexus of food, energy, and water systems: Collaboration, Scale, Heterogeneity, and Solutions.

5.1. Collaboration

First and foremost, results from this dissertation indicate that the "collaboration" challenge can be viewed as another way to conceptualize "nexus." This dissertation targeted the FEW nexus, however, this may just be a starting point for which to consider how the interactions between systems, more broadly, impact coastal resilience planning. Chapter 3 provided insight into "who" or which sectors should be targeted for collaboration and Chapter 4 provided insight into "how" this collaboration could be initiated.

Chapter 3 results provided insight on which sectors should be included to collaborate. Specifically, these results revealed that the transportation system is linked to the FEW nexus, especially the food system, and should be included in nexus considerations. Additionally, this chapter revealed that the FEW, or FEWT, nexus may benefit from an energy-centric perspective in the context of coastal resilience, which indicates that any collaboration efforts should consider centralizing how the energy system could impact all other systems considered.

In Chapter 4, many of the resilience plans included actions that had co-benefits or that included forming or leveraging partnerships - these are all examples of how the collaboration challenges can be overcome. For example, Oakland's resilience plan included an action entitled "Open a Civic Design Lab for problem solving across City departments in collaboration with partners," which described how they would bring together members of different departments to think through projects and come up with creative solutions (City of Oakland, 2016). Additionally, several resilience plans described the co-benefits associated with each action, such as increased energy efficiency improving housing affordability in terms of decreased costs (City and County of Honolulu, 2019) or how having a goal of 100 percent renewable energy can lead to new job opportunities (City of Oakland, 2016). This framing of the "collaboration challenge" is less about physical system interdependencies and more about intentionally connecting different systems to create efficiencies. For example, 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" (Miami-Dade County et al., 2019, p. 134). Infrastructure work could be coordinated so that a road, or other job site, would only need to be dug up once, thus creating efficiencies in terms of time money saved and a reduction in disruptions to transit.

5.2. Scale

This dissertation was able to shed light on the "scale" challenge primarily through how the CZM Programs facilitate information sharing in Chapter 2 and how states constructed their actions in the resilience plans analyzed in Chapter 4.

Chapter 2 recommended that those seeking to develop resilience tools should find connected hubs in the network of experts and potential users, such as state CZM programs. This recognizes one challenge of scale: at the national level there are only a handful of groups looking to develop resilience tools, while at the state level there is one CZM program per coastal and Great Lake state, and then these state level programs then have established relationships with the numerous local towns, programs, and planners that are the targeted end-users of many resilience tools. This means that the number of contacts increases as you move from the federal to state to local level. One scale challenge highlighted is how the handful of tool developers can engage the numerous potential local-level end-users. The study recommends using CZM programs, or an intermediary scale, as a link between the national and local level by leveraging their established relationships. Essentially, this study is recommending that existing networks of users should be leveraged so that “reinventing the wheel” can be avoided.

This principle of “not reinventing the wheel” extends to resilience planning more broadly, especially when incorporating the FEW nexus. Many of the resilience plans included in Chapter 4 designed their actions to include partnerships and collaborations with multiple governmental agencies, local organizations, and city residents. This collaboration is a form of leveraging established relationships and working across scales. At the end of the day, resilience planning is about protecting people and the systems they rely on -resilience planning is for people, therefore people (local level) must be included and consulted from the beginning.

5.3. Heterogeneity

Results show that the heterogeneity challenge may not be as great of a challenge as initially anticipated. While there is no doubt that there are distinct differences in terms of geography, political landscape, and hazards faced between the many locations seeking to build resilience, there are still a great deal of commonalities as well. As stated within the Honolulu resilience plan (City and County of Honolulu, 2019, p. 13):

> 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.

In Chapters 3 and 4 there were a variety of different hazards and challenges (shocks and stresses) addressed by the studies and resilience plans, these range from drought, hurricanes, and earthquakes, to aging infrastructure, housing affordability, and systemic racism. Each location has a different history, geography, and demographics which meant that no two locations would require the same set of resilience building actions. However, as shown in the resilience plans, many cities still took inspiration from one another. Many resilience plans reference actions from other cities resilience plans and, most importantly, the entire purpose of the 100RC program was to create a resilience network so that expertise could be shared and cities could learn from one another. A lot of what is being tried has never quite been done before so the 100RC is jumpstarting the learning process.

Additionally, even with the heterogeneity shown between the locations represented in Chapter 3, the studies suggest that the FEW nexus approach is relevant to resilience planning. The FEW nexus is a broad framework that encourages diverse perspectives to be brought to the table, and tradeoffs and cascading impacts to be considered. This broad approach provides a starting point that can be adapted to the heterogeneity of different locations and hazards to aid in the resilience planning process.

So, while heterogeneity can be a challenge, this dissertation shows that it can also be a strength. It forces cities and towns to try new things, but as long as these new things are shared within a broader network to facilitate learning, progress can be made.

5.4. Solutions

First and foremost, the term “solutions” in the context of resilience is challenging as resilience is a constant process and not something to be achieved. In this context, the term “solution” will be used to mean a step forward in advancing resilience. Solutions to building resilience at the nexus of food, energy, and water systems were addressed in three ways: Chapter 2 revealed ways for tools and toolkits to better facilitate use, Chapter 3 highlighted several specific innovations, and Chapter 4 showed some potential methods in terms of flood control and energy system upgrades.

While the FEW nexus was not directly targeted in Chapter 2, tools and toolkits were demonstrated to be a common way that potential "solutions" are shared with states and local communities. As such, this chapter provided several recommendations for how the tool development and distribution process could better facilitate use. These recommendations include using a trusted intermediary, such as state CZM programs, to connect national tool development efforts to local communities and ensuring that target local end-users are consulted in the tool development process from the beginning. Ideally, if any future tools or toolkits arise to facilitate applying a FEW nexus perspective to coastal resilience planning, they would follow the recommendations outlined in this chapter to facilitate the spread of potential solutions.

Chapter 3 presented several innovations and technologies that combine the FEW nexus approach with coastal resilience. These include a model for floating production, a multigeneration machine, and the "infrastructure ecology" framework. Additionally, Chapter 3 provided evidence to the potential benefit of an energy-centric perspective of the nexus when applying the approach to coastal resilience in urban areas. While not a complete solution, it is a valuable finding that is a step towards framing potential future solutions.

While the FEW nexus approach was not found to have been applied to resilience planning in Chapter 4, results did indicate potential "solutions" for the water and energy systems. The water system was commonly referenced in terms of solutions to flooding and the energy system was commonly referenced in terms of resilient upgrades to the physical energy grid. The plans indicate that green infrastructure as a stormwater management technique is being applied in a number of locations across the US and that several cities have been increasing their use of renewable energy. While these upgrades were not specifically referenced in terms of how they interconnect with other systems, there is a starting point to analyze how these strategies have fared in a variety of locations. It provides the basis for future study and subsequent analysis for how these improvements have impacted the resilience of other systems.

While this dissertation can provide no single path to guide the coastal resilience planning process, it does offer a step in the right direction. The three studies presented in this dissertation offer insight into the prominent challenges that arise when planning for resilience that incorporates the FEW nexus.

5.5. Future Research

Applying a FEW nexus approach to coastal resilience planning and policy is an area ripe for future research. Three examples of necessary future research include a comparison of how the FEW nexus has been applied to riverine and coastal resilience (and/or other environments that are not coastal, such as arid communities), interviewing those involved in writing US city resilience plans, and an exploration of how other city planning efforts have incorporated the FEW nexus and how these other plans intersect with resilience planning. First, the systematic literature review of how the FEW nexus was combined with coastal resilience only focused on coastal communities or water-related hazards. As many communities are not coastal but also face water-related hazards, it would be interesting to conduct the same study but target riverine resilience instead.

This study could additionally perform a comparison of how the food-energy-water nexus has been incorporated in terms of riverine and coastal resilience. Second, it will be important to conduct a series of interviews with those involved in resilience planning to better understand the decision-making process when writing a resilience plan. The interviews could be used to better understand how plan writers consider the interconnections between systems and how they feel a food-energy-water nexus approach would benefit or not benefit the resilience planning process. Finally, future research is needed to better understand how other city planning efforts intersect with the city resilience planning process. Specifically, Hazard Mitigation Plans or municipal Comprehensive Plans should be analyzed for how food, energy, and water systems and their interconnections have been incorporated, how resilience concepts have been incorporated, and how much overlap there is between these planning efforts and city resilience plans. This avenue of research could shed light on how the city resilience plans were intended to be used and it could act as a starting point to better understand the intersection of the many city planning efforts.

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APPENDIX A

The following are the questions used to guide the interviews with members of coastal programs.

1. Please give me a brief description of your role within, or relationship to, the Coastal Program.
2. What do you think of when we use the word “tools” or “toolkits”?
    a. Does it match with the definitions we have listed above?
3. Broadly, what types of tools do you use?
    a. How do you use them?
    b. What is your primary mechanism for finding or learning about new (or existing tools)?
4. Have you, or someone else on your team, been to CAKE, toolkit.climate.gov, Georgetown Climate Center, Digital Coast or other summary/portal sites?
    a. Why or why not? If so, what was your impression?
    b. Were you able to find what you were looking for?
5. Which specific tools are you actively using?
    a. How are the tools being used?
    b. How often and in what capacity?
6. Which tools, or categories of tools, have been tried in the past but are no longer being used?
    a. Why are they no longer being used? What were the limitations you found? Did you develop something better?
    b. Is there a specific tool that does not currently exist but you wish did?

7. Has your program developed any of its own tools?
    a. How and why were these tools developed?
    b. Were any existing tools used in the development of the personal tool?
8. In your experience, what is driving adaptation response?
    a. Do you have any specific examples?
    b. Is there a specific tool that does not currently exist but you wish did?
9. How do coastal programs match community needs with available resources?
    a. Are any of these resources tools or toolkits?
    b. Can you describe the relationship of the coastal program with the local communities?
10. What drives adaptation response at the state or state government level?
    a. Are actions taken on a state level opposed to the community level?
11. Have you ever been contacted to consult in the development of a tool or toolkit?
    a. If so, could you please describe the process?
    b. Did you find it helpful and was your feedback incorporated?
    c. Do you know anyone else who has been consulted?
12. How would you like to be included in toolkit development?
    a. Is there a particular mechanism you think would work best?
13. Are there any other topics relating to tools that you'd like to address?

APPENDIX B

The following are the questions used to guide the interviews with tool developers.

1. Please provide a brief description of your role within your agency.
2. What do you think of when we use the word “tools” or “toolkits”?
    a. Does it match with the definitions we have listed above?
3. Broadly, what types of tools do you personally use?
    a. How do you use them?
    b. What is your primary mechanism for finding or learning about new tools?
    c. Are these tools generally from within your agency?
4. Have you, or someone else on your team, been to CAKE, toolkit.climate.gov, Georgetown Climate Center, Digital Coast or other portal sites?
    a. Why or why not? If so, what was your impression?
    b. Were you able to find what you were looking for?
5. Broadly, what kinds of tools are developed in your agency?
    a. Could you provide some specific examples of tools or toolkits?
6. Specifically, which tools have you, or are you, involved in developing? Please describe them.
    a. What is the target audience or end user for each tool?
7. Could you describe the overall development process? From idea to product release?
    a. Could you describe where the idea to create a new tool generally comes from?
    b. Was there research done into existing tools to check for overlap?

c. How did you engage with stakeholders?
    i. How frequent was the consultation?
    ii. How did you incorporate feedback?
    iii. Can you describe the relationship you have with this stakeholder group?

8. How do you measure how many people are using each tool?
    a. And what they are using it for?
9. Do you ever add to or update existing tools?
    a. If yes, what was the motivating factor to do so?
10. In your opinion, what drives an adaptation response?
    a. At the local, state, regional, and national levels?
    b. What role do you see your tool(s) playing in adaptation planning?
    c. How do you determine if it will have the intended impact?
11. Many states express a need for data at a property scale, is this something you can provide?
    a. What are the challenges/limitations with providing data at such a fine scale?
12. Have you ever assisted state-level or local organizations in the development of a property-scale tool?
    a. If so, how did it go?
    b. If not, is this something you/your agency would be open to?
    c. Ideally, what role would you like to play?

13. If you found it beneficial, how would you ideally like to engage the coastal programs in tool/toolkit development?
    a. Is there a mechanism you think would work best?
    b. What level of involvement would you seek?
14. If asked, what role would you like to, or be willing to, play in a coastal programs development of a tool?
15. Are there any other topics relating to tools that you'd like to address?

APPENDIX C

Table C.9: Summary of the fourteen articles from the systematic literature review

#	Year	Author	Title	Journal
1	2020	Newman, RJS; Capitani, C; Courtney-Mustaphi, C; Thorn, JPR; Kariuki, R; Enns, C; Marchant, R	Integrating Insights from Social-Ecological Interactions into Sustainable Land Use Change Scenarios for Small Islands in the Western Indian Ocean	*Sustainability*
2	2020	Luqman, M; Al-Ansari, T	Thermodynamic analysis of an Energy-Water-Food (Ewf) nexus driven polygeneration system applied to coastal communities	*Energy Conversion and Management*
3	2019	Cimellaro, Gian Paolo; Crupi, Pietro; Kim, Hyong Uk; Agrawal, Anil	Modeling interdependencies of critical infrastructures after hurricane Sandy	*International Journal of Disaster Risk Reduction*
4	2019	Whitney, E; Schnabel, WE; Aggarwal, S; Huang, D; Wies, RW; Karenzi, J; Huntington, HP; Schmidt, JI; Dotson, AD	MicroFEWs: A Food-Energy-Water Systems Approach to Renewable Energy Decisions in Islanded Microgrid Communities in Rural Alaska	*Environmental Engineering Science*
5	2019	de Bruijn, KM; Maran, C ; Zygnerski, M; Jurado, J; Burzel, A; Jeuken, C; Obeysekera, J	Flood Resilience of Critical Infrastructure: Approach and Method Applied to Fort Lauderdale, Florida	*Water*
6	2019	Ni, N; Little, RG; Sharkey, TC; Wallace, W	Modelling the recovery of critical commercial services and their interdependencies on civil infrastructures	*International Journal of Critical Infrastructures*
7	2019	Brown, H	Infrastructural Ecology: Embedding Resilience in Public Works	*Public Works Management & Policy*
8	2018	Romero-Lankao, P; Bruns, A; Wiegleb, V	From risk to WEF security in the city: The influence of interdependent infrastructure systems	*Environmental Science & Policy*
9	2018	Romero-Lankao, P; Norton, R	Interdependencies and Risk to People and Critical Food, Energy, and Water Systems: 2013 Flood, Boulder, Colorado, USA	*Earths Future*
10	2018	Uen, TS; Chang, FJ; Zhou, YL; Tsai, WP	Exploring synergistic benefits of Water-Food-Energy Nexus through multi-objective reservoir optimization schemes	*Science of the Total Environment*
11	2018	Garcia-Lopez, GA	The Multiple Layers of Environmental Injustice in Contexts of (Un)natural Disasters: The Case of Puerto Rico Post-Hurricane Maria	*Environmental Justice*
12	2017	Dal Bo Zanon, BD; Roeffen, B; Czapiewska, KM; de Graaf-Van Dinther, RE; Mooij, PR	Potential of floating production for delta and coastal cities	*Journal of Cleaner Production*
13	2017	Maass, M	Integrating Food-Water-Energy Research through a Socio-Ecosystem Approach	*Frontiers in Environmenta*

				l Science
14	2016	Meshkati, N; Tabibzadeh, M; Farshid, A; Rahimi, M; Alhanaee, G	People-Technology-Ecosystem Integration: A Framework to Ensure Regional Interoperability for Safety, Sustainability, and Resilience of Interdependent Energy, Water, and Seafood Sources in the (Persian) Gulf	*Human Factors*