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**Key Points:**
- We analyze the interdependencies mediating the cascading negative consequences on people and FEW systems triggered by the 2013 floods in Boulder
- Historical actions and polices helped to mitigate risks but could not counteract the negative impacts of infrastructural interdependencies
- Boulder's high institutional and learning capacity is not enough to affect integrative and transformative understanding and action

**Supporting Information:**
- Supporting Information S1
- Data Set S1
- Data Set S2

**Correspondence to:**
P. Romero-Lankao,
paty.romerolankao@nrel.gov

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# Interdependencies and Risk to People and Critical Food, Energy, and Water Systems: 2013 Flood, Boulder, Colorado, USA

**Patricia Romero-Lankao[1,2,3] and Rachel Norton[4]**

[1]National Center for Atmospheric Research, Boulder, CO, USA, [2]Currently at National Renewable Energy Laboratory, Golden, CO, USA, [3]Mansueto Institute for Urban Innovation, University of Chicago, Chicago, IL, USA, [4]University of Colorado at Denver, Denver, CO, USA

**Abstract** This paper examines the interdependencies mediating the cascading negative consequences triggered by the September 2013 flood, in Boulder, Colorado, USA. By illustrating the risks to people and critical food-energy-water systems of a low probability, high-impact event, we draw lessons on what is likely to occur in the future. Other scholars have modeled the influence of interdependent infrastructures on cascading effects. But this is one of the first studies integrating stakeholders' understanding of the influence of interdependent actions, institutions, and infrastructures. These interdependencies create the conditions for vulnerability, which is a product of multiscale and dynamic sociodemographic, economic, technologic, environmental, and governance interactions. Political histories and historical decisions on where and how to design infrastructure exert a deep influence on short- and long-term capacity to manage risk. Boulder's high socio-institutional and learning capacity, while key, is not enough to influence integrative, transformative changes. Contrary to current approaches to nexus thinking, the regimes in which emergency and recovery actions are embedded are dynamically stable, thus imposing a logic for incremental change along established pathways of understanding and action. Our study offers some lessons on the challenges of bringing together diverse sectoral and jurisdictional sectors during and after an extreme event.

**Plain Language Summary** We analyze the influence of infrastructures, institutions, and actions on cascading effects triggered by the 2013 floods in Boulder. With input from stakeholders, we connect analyses from different disciplinary lineages to examine how these conditions may lead, during an extreme event, to cascading negative consequences. While other scholars have modeled the influence of infrastructural interdependences on cascading effects, this is one of the first studies integrating stakeholders' understandings in order to examine some of the mechanisms by which critical infrastructural and socio-institutional interdependencies and actions can mitigate or amplify the cascading effects from an extreme event. Our analysis suggests that interdependent actions and governance regimes are as relevant as infrastructures in amplifying and mitigating risks. We can conclude that the high socio-institutional capacity and ability for learning from extreme events characteristic of Boulder County, while key in mitigating risk, is not enough to influence deeper, transformative changes in understanding and practices among public and private actors. On the contrary, and in support of sociotechnical transitions theories, the socio-institutional regimes in which the emergency response and recovery actions are embedded are dynamically stable, thus imposing a logic for incremental change along established pathways of what is appropriate understanding and action.

## 1. Introduction

Urbanization and environmental change are coevolving to create increased risk of floods, wildfires, and other extreme hazards. As they interact with social-ecological systems through a series of interdependencies, these hazards heighten the potential for cascading negative effects that threaten people and critical food, energy, and water (FEW) systems. In a recent example, in September 2013 Boulder County, Colorado, USA, experienced unprecedented, weeklong rainfall corresponding to about 80% of its annual average. The extreme event brought interdependencies and cascading effects into high relief by showing how flood impacts on transportation can trigger a breakdown of energy systems, leading to failures in water treatment, and food distribution and storage that differently affect people and critical FEW systems. Although they are never welcome, such events provide opportunities to learn how to better mitigate risks, adapt, and foster capacity (Pescaroli & Alexander, 2015; Romero-Lankao et al., 2018).

With collaborative input from stakeholders, we examine the interdependent infrastructural and socio-institutional conditions, during the 2013 Flood, that amplified or mitigated cascading negative consequences on people, critical FEW systems, and places in Boulder County, which includes mountain, plains, and foothill areas that depend on, and affect, the social-environmental dynamics of a broader region. We also explore the limits and options for transformative learning processes that enhance capacity to mitigate risk and adapt in sustainable ways. We use semistructured qualitative interviews and fuzzy cognitive maps (FCMs), a semi-quantitative and participatory method, to illustrate these conditions and learning processes.

Governance or socio-institutional regimes prioritize the influence of government, private and civil society actor-networks, property rights, and the dynamics of political engagement in planning and risk management actions (Shi et al., 2016). Infrastructures, the material and physical elements of these plans, include capital-intensive, reinforcing, or retrofitting power plants, buildings, open space, and other physical means to protect people from extremes while pursuing other development goals (Dawson, 2015). Both governance and infrastructure create the conditions for vulnerability and capacity or the potential of populations or decision makers to modify their behavior so as to better mitigate or adapt to extremes, that is, to be resilient. Vulnerability is determined by multiscale sociodemographic, economic, techno-infrastructural, environmental, and governance (SET*E*G) factors in addition to exposure to an extreme event (Arup, 2014; Romero-Lankao et al., 2016; Romero-Lankao & Qin, 2011). These factors include unequal access to resources, assets, networks, and decision making, as well as understanding, learning, and actual actions.

Although our study is not the first to examine these issues, our innovation lies in the integration of scholarship on FEW nexus risks, sociotechnical transitions (STT), social-ecological systems (SES), and political ecology, with research on interdependencies and cascading effects, to examine how interdependent governance, actions, and infrastructures influence the cascading consequences of extreme events. This scholarship is concerned with broader discussions about the possibilities and constraints to policy integration and to transformative learning and action. We posit that interdependent actions and governance regimes are as important as interdependent infrastructures in amplifying or mitigating risk triggered by extreme events and in shaping the potential for transformative changes in learning and action.

Historically, actor networks in Boulder County have shown high socio-institutional capacity and ability for learning and action from extreme events (MacClune et al., 2014). With this in mind we ask two questions: Is this capacity enough to manage risk by learning from past experience and introducing changes in understanding and actions that sustainably foster science and policy integration? Or are the features of the governance and infrastructural regimes in which actors are embedded so dynamically stable that they impose a logic for incremental change along established pathways.

## 2. Tracing Key Concepts and Lineages

In this section, we explore the concepts of FEW nexus and risk and trace relevant approaches developed by social, engineering, and ecological sciences to understand how interdependent governance, infrastructure, and actions influence the cascading effects on people and critical FEW systems of an extreme event.

*FEW Nexus*. The term nexus refers to the connections between two or more elements. FEW nexus underscores interdependencies between two or more food, energy and water resources, and systems and the need for integrated management across sectors and jurisdictions (Leck et al., 2015; Romero-Lankao et al., 2017). Still, differences in definition and scope exist. Of the many framings of FEW nexus, two are relevant for this paper (Leck et al., 2015; Romero-Lankao et al., 2017). First, the focus is on an existing threat to an object (e.g., a cyberattack threatening a population or infrastructure) and a series of policies and actions to protect it (Trombetta, 2008). Second, it is on the social-environmental factors such as unequal utilization of land and FEW resources and services or deterioration of ecosystem services such as flood mitigation determining the risk of harmful impacts (Romero-Lankao et al., 2018). While security thinking leads us to look for the *direct causes* of unequal harm to urban populations and systems, risk analysis leads us to examine the factors determining whether people and places are vulnerable or able to mitigate or adapt to possible harm, that is, resilient (Corry, 2012). This paper focuses on risk and seeks to understand the role of interdependent infrastructural and governance arrangements in shaping the possibility for uncertain and harmful impacts on things people value, such as quality of life, economic growth, health, or property. Risk results from the multiscale interplay of socio-institutional (governance), techno-infrastructural, and environmental factors (Field et al., 2014).

According to FEW nexus thinking FEW systems are so interconnected that actions in one frequently have impacts on the others. Thus, integrative approaches are suggested to analysis and decision making seeking to reduce trade-offs and enhance synergies among FEW systems. However, bringing together diverse policy domains creates its own set of challenges. Moving decision makers beyond their accustomed ways of understanding and policy involves a collective engagement of disparate sectors, levels of government, and values. Often, a mismatch exists between topical sectors and the jurisdiction or knowledge necessary to manage risks to FEW systems (Romero-Lankao et al., 2017). This paper seeks to explore some of these challenges to integration.

*Interdependencies and Cascading Effects*. Scholars have analyzed the risk relevance of interdependent networks of social-institutional (governance) and technoinfrastructural elements that provide a reliable flow of products and services essential to providing shelter, water, and electricity and protecting people and places from extreme event and disruptions (Fu et al., 2014; Pescaroli & Alexander, 2015). We focus on governance and FEW infrastructures including electric power, natural gas and oil, water supply, and food and agriculture. However, we acknowledge the role of transportation, telecommunications, health, emergency, and other services. Therefore, we suggest the term critical FEW systems to include both FEW and other systems. These networks interact and communicate with one other; they receive inputs and send outputs, including water and energy resources, services, food and other products, and information such as weather forecasts and guidelines to respond to emergencies.

Interdependencies and dependencies are at the heart of the concept of cascading effects triggered by extreme events. Both refer to a connection between two infrastructures. However, while a dependency denotes a process through which the state of one infrastructure unidirectionally influences or correlates to the state of the other, an interdependency denotes a bidirectional relationship or correlation between the two infrastructures (Rinaldi et al., 2001). Cascading effects are effects that occur as a direct or an indirect result of an initial event. They depend, to some extent, on their context, and thus, their diffusion is associated with enduring vulnerabilities of interdependent critical FEW systems (Pescaroli & Alexander, 2015). The cascading effects of extreme precipitation, for example, include the initial flood impacts. Because of complex interdependencies, floods are followed by secondary effects such as transportation disruptions and tertiary cascading effects such as disruptions in food, energy, and water distribution and utilization (Rinaldi et al., 2001). Depending on characteristics such as location, extent, capability, and directionality of the linkages among system elements (Rinaldi et al., 2001), critical governance and infrastructural FEW systems can either mitigate or transmit shocks in cascading fashion within and beyond a city (e.g., Longmont or Boulder), a locality (e.g., Lyons and Jamestown), a region such as Boulder County, Colorado, and even distant areas.

*Connecting Social*, *Ecological*, *and Engineering Sciences*. Various disciplinary domains have examined the role of the infrastructural and social-institutional elements in mitigating or amplifying the cascading effects from extreme events. The first applies modeling approaches, such as resource network analysis, to simulate the cascading effects triggered by extreme events (Berardy & Chester, 2017; Dawson, 2015; Fu et al., 2014; Khoury et al., 2015). The goal is to evaluate the performance during this event of the broader network of delivery and storage of food, energy, and other resources and services (Rinaldi et al., 2001). To measure performance, these scholars use metrics such as the level of connectedness (i.e., how many nodes are still connected to the largest node), and the failure threshold, defined as the minimum size of disruption that leads to failure. They also measure the resilience performance of infrastructures through three metrics: extent, redundancy, and directionality (Fu et al., 2014).

While actors' actions, cultural perceptions, and capacity to mitigate risk and adapt also contribute to risk amplification or mitigation, these are often not included in the modeling efforts. At most, different interventions and strategies in resource delivery and storage are included as model inputs to simulate risks. Furthermore, governance arrangements influence both path dependencies and changes triggered by extreme events. In particular, they do this by changing understanding and awareness and creating—or constraining—changes in practices among public and private actors that enhance their capacities to mitigate risks from extreme events and adapt (Pelling et al., 2008).

To understand the interacting influence of actions, policies, and learning, we need to draw on three strands of scholarship. The first, STT theories, STTs, examine how a socio-institutional regime organizes social practices and structures relationships among governmental, private, and civil-society actors, whose understandings of priorities, appropriate actions, and technologies are intertwined with the expectations and skills of users, with governance arrangements, and with critical infrastructures providing energy, water, food, transportation, and other resources and services (Geels & Schot, 2007). Although actors have the capacity for learning, the regime they are embedded in is *dynamically stable* and imposes a logic for incremental change along established pathways, which, in turn, create path dependency or lock in (Geels & Schot, 2007; Lawhon & Murphy, 2012). We will look into how this has played out in Boulder County, whether learning during and after the 2013 Floods resulted in changes in practices of public and private actors.

SES theories, the second strand of scholarship that we draw on, examine how policies, governance arrangements, and technoinfrastructure foster or constrain adaptability and capacity for learning in the face of extreme events. In particular, they examine their mediating influence on the following:

- shielding populations and SES from extreme events and cascading effects, by enhancing communities and actors' capacity to mitigate risk and adapt to change and uncertainty;
- creating risk mitigation and adaptation trade-offs that can decrease long-term vulnerability of people and places (Grimm et al., 2013; Pincetl et al., 2016; Romero-Lankao & Gnatz, 2013; Tellman et al., 2018); and
- determining risk mitigation and adaptation tipping points among system or actor-network after which they move to another regime.

We build on SES theories and our own prior research (Romero-Lankao et al., 2018; Romero-Lankao & Gnatz, 2016), to suggest that besides actions, risk is shaped by five multiscale and interdependent (SET*E*G) factors: *s*ociodemographics, *e*conomy, *t*echnoinfrastructures, *e*nvironment, and *g*overnance. These relate with the outcomes of interacting exogenous environmental and social processes such as environmental change and urbanization. Note that while we focus on governance and technoinfrastructure, we acknowledge the need to also include the three other domains in the analysis (see section 5.2).

In the third strand of social science scholarship, political ecology, scholars examine the interaction of social and political actors and institutions—actor-networks—in preparing for and responding to extreme events (Ahrens & Rudolph, 2006; Birkmann et al., 2010; Pelling & Dill, 2009). They suggest that the mitigating or amplifying influence of governance structures depends on political histories, a point we will come to in the next sections. Governance structures risk mitigation and adaptation actions in many ways. For instance, through

- the approach of officials to key elements of risk management, such as accountability, the role of government and civil society, the primacy of property rights, and land use and development planning, capacity, and power;
- the safety nets protecting population's quality of life that come into play during emergencies, such as hospitals, community centers, neighborhood and church associations, crime prevention, and afterschool programs;
- the quality and accessibility of public services and infrastructure such as electricity, energy and water provision, food distribution and utilization, commuting systems, and schools; and
- the financial and decision-making capacity, coordination between organizations, attitudes of local government vis-à-vis private and civil society actors, and marginalized populations.

Governance structures also influence processes of change triggered by extreme events in many ways (Pelling & Dill, 2009; Romero-Lankao & Gnatz, 2013). Here we are interested in the role learning plays in prompting social change, in particular by changing understanding and awareness, and creating—or constraining—practices among public and private actors that shape their capacities to mitigate risks from extreme events and adapt (Albright & Crow, 2015; Pelling et al., 2008).

Building on these strands of scholarship, we analyze the influence on risk and resilience, of the high socio-institutional capacity, and ability for learning from extreme events that historically has characterized Boulder County. We ask if this capacity is enough to influence changes in understanding and practices among public and private actors that enhance their capacities to mitigate risk and adapt and build long-term resilience. Or we ask if the features of the socio-institutional and infrastructural regimes in which actions are embedded are so dynamically stable that they impose a logic for incremental change along established pathways, which constrain their adaptability and transformability.

## 3. Boulder County

In September 2013, the unprecedented level of precipitation in Boulder County resulted in devastating flooding. While Lyons was exposed to a 1-in-100-year flooding, Boulder's was in the 1-in-25 to 1-in-100-year range (environmental domain). The disaster, which killed 10 people and resulted in the evacuation of 18,000 people, the destruction of 688 homes, and damages to an additional 9,900, brought into high relief the unprecedented consequences of this event. Six of the seven key roads following creeks up mountain canyons, representative of the technoinfrastructural domain, failed and left affected populations isolated and unable to leave the area (MacClune et al., 2014; Romero-Lankao et al., 2018). Apartments affected by sewage upwelling were below grade and frequently occupied by lower-income families and university students. Wastewater treatment plants in Lyons and Longmont were disrupted, and it was only through the resourceful action of operators that Boulder's plant remained in operation. Of course, Boulder's Greenways Program allowed some areas to function as storm water routes to mitigate flood damage. Strong preexisting relationships and a culture of cooperation were key governance resources that sped response and enabled effective recovery, for example, through learning from previous experiences such as the Four Mile Fire of 2010, and construction permits to expedite recovery.

We selected Boulder County located in the Colorado Front Range United States and ranging in elevation from 1,000 to 4,300 m, for several reasons. While floods and fire differ in nature, the county has shown a rich institutional and civil society capacity for learning from and applying the lessons learned from several extreme events in the years leading to the 2013 flood (the 2009 Olde Stage, the 2003 Overland, and the 2010 Fourmile Canyon fire). However, Boulder is still recovering from the 2013 Flood, which offers a glimpse of how even an effectively managed county can be overwhelmed by the extreme events and fluctuations that will likely be exacerbated in a warming world.

Much of the Colorado Western Slope to the West of Boulder County has ranching, farming, tourism attractions, and mountain settlements that directly or indirectly serve the county demand for water and food, thereby shaping interconnected regional risks and vulnerabilities. Similarly, rural areas to the east of the county, such as Weld County, produce energy resources, some of which feed Boulder County demand.

Boulder is representative of rapidly urbanizing mountain regions with an industrial and service economy, which depends upon their forests, water bodies, and other surrounding ecosystems. Boulder also includes cities, suburbs, and exurban areas constituting a rapidly changing wildland urban interface with expanded settlements and infrastructures that are influencing landscape dynamics and flood risk regimes.

With changes such as shifts in environmental dynamics associated with pathways of development come questions regarding the role that these processes play in driving interdependencies amplifying or mitigating the cascading negative consequences of extreme events. As we will indicate in section 5.2, although Boulder is one of the wealthiest and more resilient counties in the United States, the impacts of this 1-in-25 to 1-in-100 years flood event lead us to ask: What can we expect in a changing world? What are the options and limits to learning processes that help navigate risk under conditions where non stationarity is the norm?

## 4. Methods

Tools to map interdependencies and cascading effects include input-output models combined with network models (Dawson, 2015; Fu et al., 2014; Khoury et al., 2015), some of which examine their influence on the failure of the overall infrastructural system. It is also common to use matrices, wheels, fuzzy mental models, and tables to represent dependencies and interdependencies as they influence the direct or indirect path of events involved in cascading effects (C40_AECOM, 2018; Pescaroli & Alexander, 2015; Rinaldi et al., 2001). Secondary data, focus groups, workshops, and semistructured interviews help to analyze different understandings of interdependencies and cascading effects (City of Amsterdam, 2017; Pescaroli & Alexander, 2015; Rinaldi et al., 2001). To understand how FEW relevant governance and infrastructural arrangements amplify or mitigate the impacts of the flood, we used a mixed-methods approach in the form of a semistructured interview guide, which included, as a subset, the development of FCMs with our participants.

**Table 1**
*Jurisdictional Level and Sectoral Representation of Study Participants*

| Level | Sectors | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Other | Food | Energy | Water | Emergency response | Infrastructure | Public health | Flood recovery |
| Local | #5 | #12 and #16 | #16 | #11, #6 and #16 | #16 | #10 | | #14 |
| County | #8 and #10 | #3 and #15 | | #2 | #1, #4, and #17 | #9 | #1 | #7 |
| State | | | | | #13 | | | |

*Note*. Note that a respondent appears in multiple sectors because she works in all of them.

### 4.1. Interviews

Over the course of 5 months during 2017, we conducted 17 semistructured qualitative interviews. Using a strategic snowball approach (Atkinson & Flint, 2001), we interviewed stakeholders from most of the key FEW system sectors and jurisdictions from the local, county, and state levels. Our sample also drew from the Cities of Boulder and Longmont on the plains and the towns of Lyons and Jamestown in the mountains. Most of the interviews lasted longer than 60 min, with several requiring a follow-up interview or an email conversation to fill in the necessary responses (Table 1).

While such a small sample size can make generalizations difficult, we carefully selected our respondents to represent key sectors and jurisdictions (Table 1). Furthermore, we reached saturation with our data to the point where a shared narrative emerged, and we could draw conclusions from the information collected from our interviews and from participants' FCMs. The small sample size results in distinctive data points emerging from the data (e.g., the impact of the 2013 floods on the community food share). The data also reflected multiple similar perspectives of participants on the amplifying and mitigating risks from interdependencies between FEW systems. Therefore, the interviews and FCMs provided us with context-specific and distinctive results as well as with more generalizable conclusions. Given that only one representative from the state government was interviewed, information and knowledge on statewide efforts are limited. However, this interview does provide context for local and countywide experiences and efforts.

The interview guide consists of 13 questions mapping respondents' understandings of the influence of interdependent institutions, infrastructures, and actions on cascading effects triggered by the September 2013 floods in Boulder (see supporting information Text S2). It also incorporates questions regarding learning following the events and around collaborations and networks that organizations worked with during and after the extreme event. Using both an inductive approach and a deductive approach, we utilized the computer software program *NVivo* to analyze participants responses (NVivo (version 11), 2016). Codes included the following: amplification or mitigation of impacts, economic and social disruptions, SET*E*G conditions, resilience, vulnerability, and lessons learned (see additional supporting information NVivo S1 to S9).

### 4.2. FCMs

FCMs are a semiquantitative method that captures the diversity of understandings of risk to people and critical FEW systems from the point of view of actors. FCMs include systematic graphs representing the entities and concepts, such as institutions, infrastructures, and actions that compose the system in question. Each concept is described with values ranging from $[0 \dots n]$ or $[-1 \dots n]$, and the relations between those concepts are represented with arcs associated with a weight with range $[-10 \dots 10]$, whereby positive weight represents a causal increase (risk mitigation in our study) and negative weight represents a causal decrease (risk amplification in our study). See Figures 1 and 2 (Carvalho, 2013; Kok, 2009; Özesmi & Özesmi, 2004).

FCMs are useful semiquantitative scenario and learning tools (van Vliet et al., 2010) that integrate mapping efforts, developed together with our respondents, with whom we have collaborated since September 2013. The FCMs are useful in illustrating the complex relationships between critical sectors and jurisdictions that play a role in mitigating or amplifying FEW risks or that are themselves impacted by breakdowns in infrastructural systems.

We used the online software, *Mental Modeler* (Nyaki et al., 2014), to solicit participants' perspectives on which systems were directly and indirectly impacted by the 2013 floods and whether the components of system

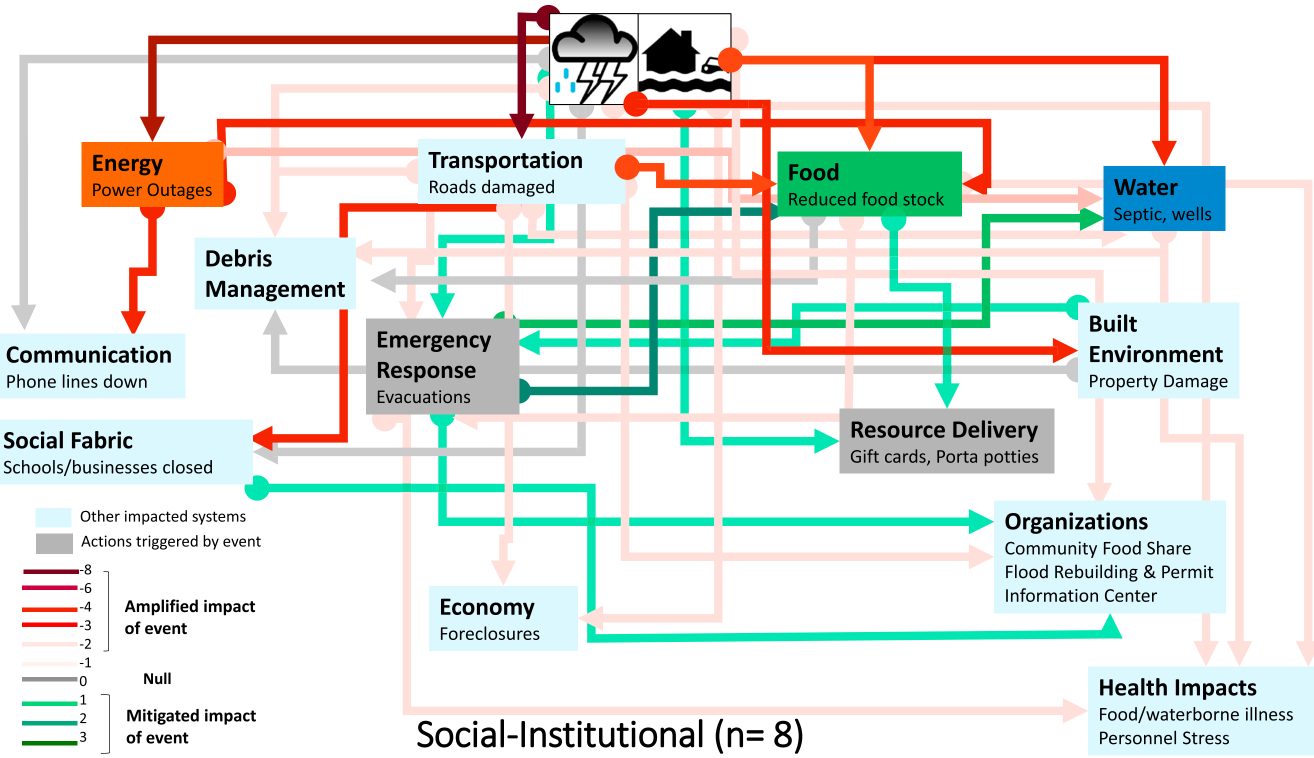


**Figure 1.** A fuzzy cognitive map of factors that amplified/mitigated cascading effects triggered by the September 2013 Boulder Floods (social-institutional).

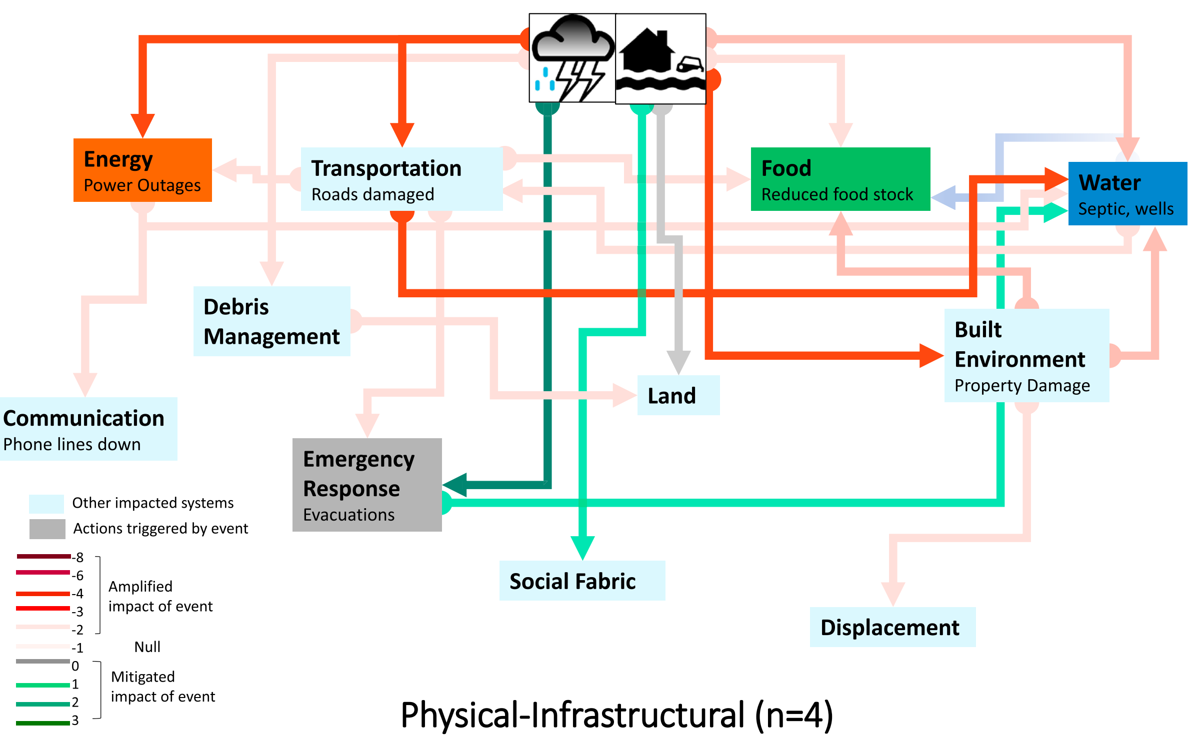


**Figure 2.** A fuzzy cognitive map of factors that amplified/mitigated cascading effects triggered by the September 2013 Boulder Floods (techno-infrastructural).

interdependencies amplified or mitigated these impacts. Mental Modeler helped to create maps in real time that facilitated learning by showing participants their thoughts on the direction (amplifying or mitigating) of key relationships between actions, infrastructures, and socio-institutional regimes.

We used Mental Modeler to create 16 FCMs, 12 of which focused on the 2013 Boulder Floods (the other focused on the 2016 Cold Springs Fire near the town of Nederland). We further aggregated the 12 maps into two FCMs based on the participant's area of focus, that is, social-institutional ($n = 8$) and infrastructural ($n = 4$; see additional supporting information FCM S1 to S12). The social-institutional included those roles that deal with organizing people or providing community level services including public health and food services as well as those participants whose main role is that of connecting resources. The infrastructural included those roles that deal with critical infrastructural systems such as transportation, energy, agriculture, and water. While the two maps are divided according to stakeholder role, they include both critical infrastructural (i.e., food, water, energy, and transportation) and social-institutional systems (i.e., the provision of resources and services).

We aggregated the information based on the amplifying and mitigating intedependencies that participants listed in their individual FCMs (see supporting information Tables S3 and S4). Specifically, we allocated each interdependency identified by the participants to a broader category. For example, if someone mentioned impacts to the septic system, this fell under the broader *water* category, whereas impacts to agriculture fell under the broader *food* category (Figures 1 and 2). While aggregating to these broader categories reduces the detailed nuances of the data, it allows for analyzing on a broader scale the critical FEW systems interdependencies.

We organized the FCMs around several factors including (a) those interdependencies that amplify (red) or mitigate (green) the impacts of the floods and (b) the impacts themselves, some of which become sources of further cascading effects (Figures 1 and 2). The shades of each color included in the map indicate the number of times participants mentioned each interdependency or impact. The flood impacts on transportation in Figure 1, for instance, are symbolized as a dark red line because stakeholders highlighted these amplifying impacts eight times in their FCMs. A gray line indicates that the mitigating and amplifying factors canceled each other out, as happened with the impacts of the 2013 flood on the social interactions of participants. Examples include closing of schools and businesses, leading to reduced social interactions. However, the flood also fostered connections during the response and recovery.

## 5. Findings

### 5.1. Interdependencies and Cascading Effects

After the floods, transportation was the second foundation of cascading effects because of its links with other critical FEW systems. Figure 1 representing the aggregated social-institutional FCMs shows that after the floods disrupted transportation, negative effects cascaded to impact communication, emergency response, and debris management. The red line from energy to food highlights the dependence of food on the energy system. Many people had to throw out rotting food after their refrigerators and freezers lost power, which also impacted debris management, as food, along with damaged infrastructure, and downed trees became part of the debris left over from the flood. Another dependency highlights the negative impacts of damaged transportation systems on food through preventing deliveries of food to stores in cutoff areas. Two interdependencies are represented by the light red line from food and water to health impacts indicating the cascading effects of loss of power on refrigeration and water sanitation and the impacts of these back to foodborne and waterborne illness. Another example of this interdependency is how well contamination also impacted the effectiveness of food washing and led to farms and gardens utilizing contaminated water, potentially contributing to foodborne illness.

In many areas, the actions mitigated the negative impacts of the floods (Figure 1), for instance, the use of radios and landlines as backups to communicate when cell towers went out. Through emergency response, it was possible to evacuate over 1,800 residents even with six of the seven roads destroyed or damaged and to set up shelters and provide food and water to evacuees. Community organizations mobilized food for those affected, and gift cards provided residents with a means to offset the costs of electrical bills. The Flood Rebuilding and Permit Information Center acted as a key resource for residents during the

**Table 2**
*Examples of Factors Amplifying (Peach) and Mitigating (Green) Cascading Effects of the Flood*

| Impact | Domain | Factors |
|---|---|---|
| Amplifying | Sociodemographics | Channels of communication were culturally inappropriate to minority groups and literacy issues |
| Mitigating | Sociodemographics | Through cultural brokers, community gathering and shelters helped Latinos and minority groups |
| Amplifying | Economy | Lack of affordable workforce housing, split land tenure |
| Mitigating | Economy | Relationships with private contractors |
| Amplifying | Technology | Inundation of storm water systems, unmitigated drainage ditches, bridges, transportation, aging infrastructure, and gas lines |
| Mitigating | Technology | Redundant infrastructure, buffer areas, greenways, and flood channels |
| Amplifying | Environment | Supercharged groundwater and gravel pits |
| Mitigating | Environment | Farmland, rangeland infiltrated floodwaters, sodded soil, perennial grass, and riparian areas |
| Amplifying | Governance | FEMA regulations and staffing issues (high demands and stress) |
| Mitigating | Governance | Memorandums, zoning requirements, integrated Office of Emergency Management (OEM) command structure, emergency operation center, staffing plans, and development restrictions |

rebuilding and recovery period. The floods also brought people together, as illustrated by the creation of the Boulder County Collaborative, a group consisting of municipalities across Boulder County, which administered recovery funds. However, at the same time, damages to roads disrupted the social fabric by limiting people's social activities and access to schools and work. Students from the Lyons' High School, for example, attended school in the City of Longmont, located 19 km/12 miles away, until their school reopened. Respondents mentioned how much this disrupted the daily activities of both family heads and children.

Frequently, across both maps, a risk mitigation and amplification tension exists between interdependent infrastructures on the one hand and actions embedded in socio-institutional systems on the other. While we revisit this point in more detail in section 5.1 and Table 2, it is important to note here that elements of each help to mitigate the impacts, while other elements amplify the impacts of the event. For example, on the one hand the floods damaged roads, resulting in disruptions to the food system and to water treatment (Figure 2); however, on the other hand, within the socio-institutional system, actors mobilized to bolster resource delivery of other key supplies including porta-potties and gift cards and authorities intervened to prevent the shutdown of the Boulder water treatment plant (see Figures S1–S6 in supporting information).

Interestingly, institutions, community food share being one of them, and communication did not have a secondary mitigating impact, at least according to participants. However, the phone lines being down most likely did have an impact on other systems (emergency response for example), while the community food share most likely helped to mitigate food shortages as a result of the flood. Furthermore, as the FCMs illustrate, transportation, food, energy, and water are, together with emergency responses, the most mentioned sources of dependencies and interdependencies (as measured by the color shades in Figures 1 and 2). Although this makes sense because of the focus of this project on critical FEW systems' role as drivers of critical services and resources, each of the maps also illustrates a slightly different story.

The FCM in Figure 2 illustrates the understandings of the participants working in the techno-infrastructural realm and the critical sectors (transportation, FEW) playing the biggest role in amplifying or mitigating the impacts of the event. Similar to Figure 1, there is a darker red line between transportation and food, indicating a higher number of mentions of the negative impact of disruptions in transportation on food systems. However, here we also see how a loss of energy and roads affected food and water systems by threatening the capability of water treatment plants because of power outages and limited personnel access.

Similar to Figure 1, Figure 2 shows how the flooding triggered an emergency response that included the referred evacuation of 1,800 people, a huge number of pets and animals (respondent), and efforts to maintain the provision of water to the City of Boulder. As indicated by the green line from emergency response to water, the response was effective in keeping the water treatment plant functioning. The other green line indicates the impacts the flooding had on bringing people together following the event. It also includes the impacts of the flood on the land, where open space acted as green infrastructure. Yet the sheer amount of water, as well as the deposition of debris, contributed to damages to open space.

Figures 1 and 2 show the existence of different levels of dependent and interdependent actions, institutions, and infrastructures. They also illustrate that singular actions helped to minimize some negative cascading effects. However, we do not see highlighted in either figure how amplifying interdependencies (e.g., between energy and water) could have been transformed into mitigating interdependencies (e.g., a darker green line rather than a dark red one). Rather, the figures illustrate how the mitigating impact of actions, such as the emergency response, could not counteract negative effects such as those of infrastructural interdependencies (for more detail, see Figures A1–A6 in Annex).

### 5.2. Multiscale SET*E*G Factors

Besides interdependent institutions, actions, and infrastructures, other multiscale SET*E*G factors influenced the cascading effects of the September 2003 floods. Frequently, as can be seen in Table 2, a risk mitigation and amplification tension exists between these factors. In some cases, each of these or their dependencies and interdependencies helped to mitigate, while in others they amplified the cascading effects of the event.

Participants mentioned structural sociodemographic factors such as race, language barriers, isolation, and minority status as risk-amplifying factors related to higher levels of vulnerability among some of the elderly, disabled, Latino, and lower-income populations. While community gathering places and shelters helped these groups mitigate the impacts of the flood, a lack of communication channels for non-English speakers acted to amplify the impacts.

Within the economy domain, the unequal distribution of resources and assets such as secured land and affordable housing amplified the cascading effects (Table 2). While the flood affected many homes, it hit low-income houses the hardest. Of over 1,000 mobile homes damaged, almost 300 were deemed uninhabitable or not cost effective to repair. Mobile homes provide two assets to low-income populations: affordable housing and home ownership (City of Boulder, 2018). However, in the face of extreme weather events, mobile homes do not provide adequate defense, often being flimsily built, without adequate insulation or weather protection, and being of ill repair (City of Boulder, 2018). In Boulder, mobile house ownership works under a *split tenure*, whereby residents own their home but not their land as they rent the lots on which they live. Therefore, mobile-home owners are especially vulnerable to extreme events, since they are not eligible for the financial support for recovery that home/land owners receive. Participants also mentioned that residents who had access to financial resources were able to rent a hotel room and file for reimbursement online, while mobile home communities and homeless populations came to shelters.

Within the technology domain, the breakdown of transportation was a key amplifying factor. The inundation of storm water systems and unmitigated drainage ditches also amplified the impacts of the floods on the water system, as this infrastructure was not designed to handle the intensity of this precipitation event.

Within the governance domain, zoning regulations and development restrictions were key in mitigating the impacts of the floods. The existence of an integrated Office of Emergency Management structure provided for effective coordination between sectors such as fire and utilities. Through emergency preparedness, different sectors knew what to do during the flood, for instance, that they would need to open a departmental operating center to organize the emergency response. However, participants mentioned that there is less coordination among county governmental and nongovernmental entities with state and federal government (e.g., Federal Emergency Management Agency [FEMA]).

The SET*E*G factors also interacted with each other to contribute to vulnerability or resilience (Table 2). Road closures and construction following the floods, for example, affected people's ability to participate in social activities. Relationships built prior to the floods, among the county and private contractors, played an important role in mitigating the impacts of the flood. Supercharged groundwater put pressure on pipes in the ground, and the cascading failure of gravel pits in Longmont influenced the direction of the floodwaters into areas that otherwise might have remained less impacted. Although Boulder County is one of the wealthiest counties, with a relatively resilient governance in the United States, given the unprecedented nature of this event, in the years after it, floodplains and zoning regulations are still being updated.

Breakdown of the transportation systems contributed more to amplifying the flood impacts, whereas governance actions such as zoning requirements and green ways mitigated these impacts (Table 2). For example, redundancies such as backup generators ensured that the water treatment plant stayed online in Boulder. While open rangeland and farmland mitigated the floodwaters, had the flood occurred earlier in the agricultural season, this point of resilience would have been a point of vulnerability—with floodwaters destroying crops. Particularly in places more negatively impacted, people were surprised of how much “we take FEW for granted” (respondent). Electricity, gas, and refrigeration systems in the mountain were off and affected food suppliers, restaurants, markets, and school services, which are key within the touristic and service sector. Without electricity, alarm systems could not work, and food safety issues became a frightening concern for business and households. Especially as the season changed from late summer to the winter, it was terrifying to think of the electric grid being frozen.

Ultimately, what these results illustrate is that actions occurring within domains can be useful for mitigating the impacts of extreme events. Further, the relationships built between organizations and actors within domains reduce the impacts of events. However, efforts to look beyond the singular silo within which stakeholders work and planning for different futures and conditions could play an even bigger role in preparing for and withstanding the impacts of the next hazard.

### 5.3. Learning and Concerns for the Future

As part of its political culture, Boulder County has historically shown leadership and capacity for learning. We asked questions that allowed us to explore changes in awareness and learning from extreme events in order to do things differently. Almost across the board respondents indicated that their organizations and many organizations they worked with implemented a variety of changes following the 2013 floods. For example, they reviewed and updated contingency, communication, and recovery plans within each department; they introduced updated building and land use codes within sewage and other specific systems. Some organizations joined the Boulder County Voluntary Organizations Active in Disaster or became a part of an Emergency Support Function at the Emergency Operations Center at the county Office of Emergency Management. Other changes include creek restoration with future events in mind and arranging backup power and water.

While each department instituted certain changes, throughout our interviews, transition from short-term response to long-term recovery has been challenging as ongoing *business as usual* demands are coupled with the contingency of having to deal with the recovery. For some departments, this means hiring a full-time employee to support emergency management and the integration of lessons learned into their short- and long-term processes. For others, the burden of the floods on staff, both emotionally and functionally, instigated changes in hiring processes as well as the delegation of responsibilities during an extreme event.

Another common theme related to staffing was the need for time and space to learn from the response while transitioning to recovery. For many, the burden on staff arose during the response but continued well into recovery as organizations scrambled to fulfill recovery needs while also continuing business as usual. Hiring additional staff and hiring based on flexibility and adaptability are two ways in which organizations are implementing changes to alleviate some of the stresses of the response and recovery phases.

Notably, most of the learning occurred within organizations with a focus on the systems and infrastructure that each controlled rather than on interdependencies between systems that participants noted during their interviews. Exceptions to this include the creation of the Flood Rebuilding and Permit Information Center, staffed by experts in transportation, septic infrastructure, and floodplain management. One participant mentioned the links between transportation and water. Often, roads are parallel to river systems, and he referred to the ensuing changes—enforced banks, setbacks from waterways—that they implemented following the event. Similarly, another participant mentioned moving water lines farther away from rivers as well as burying gas lines 5–6 m underground.

Participants recognize critical FEW system connections. However, when explicitly asked what their organization learned to do differently after the event, many focused on one system at a time rather than on FEW as a larger interconnected system. This is mostly likely due to job function, institutional practices, and expectations rather than a conscious decision to focus just on one system. While focusing on shoring up the vulnerabilities within each system is valuable, space remains for implementing institutional and organizational changes that deal with identified vulnerabilities in dependencies and interdependencies among critical FEW infrastructural systems.

As a parting question, we asked respondents what their main concerns were in looking toward the future. While some mentioned singular issues, many described the cascading effects on critical FEW systems and people within those systems that each issue might have. Interestingly, inadvertently, by incorporating these responses within our integrated framework, we were able to see the ways in which their knowledge touched on most of the critical FEW institutions, infrastructures, and actions as well as on the interdependencies between them.

## 6. Concluding Remarks

With input from stakeholders in Boulder, Colorado, we connected analyses from different disciplinary lineages to examine dependencies and interdependencies that may lead, during an extreme event, to cascading negative consequences. We interviewed participants from the social-institutional and infrastructural realms to map risks to people and FEW systems and to learn from the perspectives of public and private sector actors. We used NVivo and FCMs, a semiquantitative method to map participants understandings.

While other scholars have modeled the influence of infrastructural interdependences on cascading effects, this is one of the first studies mapping and integrating stakeholders' understandings in order to examine some of the mechanisms by which critical infrastructural and socio-institutional interdependencies and actions can mitigate or amplify the cascading effects from an extreme event. Our analysis suggests that interdependent actions and governance regimes are as relevant as infrastructures in amplifying and mitigating risks. However, our look at Boulder County also reminds us that political histories matter. Historical decisions on where to build and how to design gray and green infrastructure (e.g., treatment plants and green ways) exert a deep, positive influence on the short-term capacity to mitigate risks and adapt to effects triggered by extreme events. They may also determine the long-term resilience of a region.

Boulder vividly illustrates the risks to people, critical FEW systems, and places posed by the 2013 September flood, a low-probability, high-impact, extreme event. The intense precipitation that brought on the Boulder flood can be seen as a harbinger of more frequent extreme events which environmental change is likely to deliver and intensify in many places. The flood triggered impacts in the transportation, energy, and water sectors that generated negative cascading effects. The results could be felt across the diverse sectors, livelihoods, and interests that were intricately woven into the social fabric itself, affecting everything from the mountains to the plains, from transport and communication to emergency response, profoundly changing the experience of everyday life. Interestingly, while actions by different sectors and jurisdictions helped to minimize the negative cascading effects represented by the darker red lines in our FCMs, mitigation actions (in lighter green) were not enough to counteract, during the emergency, the negative impacts of infrastructural interdependencies.

While our findings may be the result of higher number of social-institutional participants (as compared to infrastructural), the goal of the study was not to examine differences in perspectives but to assess critical FEW system dependencies and interdependencies. It may be that the social-institutional participants tend toward more cross-sectoral thinking; however, this is a subject for future research.

This study represents a contribution to the broader and growing literature on FEW nexus, STT, and SES theories. Our approach allowed us to come up with nuanced insights on how these affects were pushed toward mitigation or amplification depending on how infrastructure, governance, and action interacted with each other and with multiscale SET*E*G factors to contribute to longer-term conditions of vulnerability or resilience. For instance, while cultural brokers helped to assess and attend to the needs of Latinos and mitigate risks, the channels used to communicate during emergency response were culturally inappropriate to help the same Latinos. Actions were not enough to address root causes of vulnerability such as the split-land tenure systems making mobile-home owners vulnerable to extreme events, while giving them less capacity, as they are not eligible for the financial support for recovery.

Most importantly, by analyzing how infrastructural interdependencies interacted with governance regimes and actions, we shed light on the dynamic interactions between structural factors such as socio-institutional regimes and human agency or actions. We can conclude that the high socio-institutional capacity, and ability for learning from extreme events characteristic of Boulder County, while key in mitigating risk, is not enough to influence deeper, transformative changes in understanding and practices among public and private actors. On the contrary, and in support of STT theories, the socio-institutional regimes in which the emergency response and recovery actions are embedded are dynamically stable, thus imposing a logic for incremental change along established pathways of what is appropriate understanding and action.

Efforts seeking to achieve more effective integration of planning and action remain a challenge. Indeed, contrary to the FEW nexus ideal of integrative policy as a way to reduce trade-offs and enhance synergies, our study offers some lessons on the challenges of bringing together diverse sectoral and jurisdictions during and after an extreme event. The challenge exists even in a region such as Boulder, known for its leadership and capacity to learn. We found that the focus was on changes to the system and organizations that respondents controlled. With some exceptions, there is space to improve our capacity to manage the influence of dependencies and interdependencies, to look beyond the singular silo within which stakeholders work, and to plan for different environmental and development futures and conditions. Exercises seeking to spark learning, such as the FCMs, can be a good means to addressing these challenges and to prepare for and withstand the impacts of future extremes in a changing, nonstationary, and uncertain world.

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