ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

PAPER • **OPEN ACCESS**

Cross-boundary risks of hinterland hazards to city infrastructure

To cite this article: Macie Joines *et al* 2024 *Environ. Res.: Infrastruct. Sustain.* **4** 035004

IOP Publishing Environ. Res.: Infrastruct. Sustain. 4 (2024) 035004 https://doi.org/10.1088/2634-4505/ad5fb4

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

CrossMark

OPEN ACCESS

RECEIVED
2 January 2024

REVISED
23 May 2024

ACCEPTED FOR PUBLICATION
5 July 2024

PUBLISHED
17 July 2024

PAPER

Cross-boundary risks of hinterland hazards to city infrastructure

Macie Joines[1,2], Madison Horgan[1,2,*], Rui Li[1,2], Alysha Helmrich[3], Abbie Dirks[1,2], Kayla Tarr[1], Ryan Sparks[1], Ryan Hoff[1,2], Mindy Kimball[1] and Mikhail Chester[1,2]

[1] Arizona State University, 660 S College Ave, Tempe, AZ 85281, United States of America
[2] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, United States of America
[3] University of Georgia College of Engineering, 500 DW Brooks Drive, Athens, GA 30602, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: mhorgan@asu.edu

Keywords: climate hazard, urban infrastructure vulnerability, infrastructure resilience, transregional hazard analysis, hinterland hazard, cross-governance, cascading effects

Abstract

Extreme weather-related events are showing how infrastructure disruptions in hinterlands can affect cities. This paper explores the risks to city infrastructure services including transportation, electricity, communication, fuel supply, water distribution, stormwater drainage, and food supply from hinterland hazards of fire, precipitation, post-fire debris flow, smoke, and flooding. There is a large and growing body of research that describes the vulnerabilities of infrastructures to climate hazards, yet this work has not systematically acknowledged the relationships and cross-governance challenges of protecting cities from remote disruptions. An evidence base is developed through a structured literature review that identifies city infrastructure vulnerabilities to hinterland hazards. Findings highlight diverse pathways from the initial hazard to the final impact on an infrastructure, demonstrating that impacts to hinterland infrastructure assets from hazards can cascade to city infrastructure. Beyond the value of describing the impact of hinterland hazards on urban infrastructure, the identified pathways can assist in informing cross-governance mitigation strategies. It may be the case that to protect cities, local governments invest in mitigating hazards in their hinterlands and supply chains.

1. Introduction

Cities and their critical infrastructure networks (CINs) often rely on external services, systems, and conditions separate from their geopolitical jurisdiction. This is in part because critical infrastructure assets that service urban populations are physically located in a city's hinterlands—the peripheral or outlying rural areas that provide resources, services, and markets to an urban center (Storper and Walker 1989). It is well-documented that city inhabitants' reliance on vast, intricate infrastructure networks that span multiple geographies inevitably creates vulnerabilities (Graham 2009). These vulnerabilities are revealed during major infrastructure disruptions like the 2003 Northeastern Blackout, which was initially caused by a series of electricity system failures and miscommunications in Ohio (Graham 2009). Because dependencies between different infrastructures are vast and complex, a failure in one CIN (in this case, the electricity generation and transmission system) can cause failures across other infrastructures, a concept known as a cascade (Ruhl 2019). Numerous CINs reliant on electricity were impacted across the northeastern U.S. and Canada as a result of the blackout, including food supply, communication, and transportation (Little 2004, Ontario-U.S. Power Outage-Impacts on Critical Infrastructure 2006).

Infrastructure disruptions are occurring more often due to the increasing frequency and severity of climate hazards like droughts, floods, storms, extreme temperatures, wildfires, and landslides (Reder *et al* 2018, Hill and Kakenmaster 2020, D'Ayala *et al* 2021, USGCRP 2023). There is ample evidence from recent events that urban infrastructure services are not only impacted when a climate hazard occurs in a city, but also as a result of hazards impacting areas peripheral to a city's geopolitical boundary (Serre and Heinzlef 2018). For example, a climate hazard-induced cascade occurred in 2017 when Hurricane Harvey made landfall near Fulton, Texas. The hurricane disrupted water supply, distribution, and drainage across Texas and Louisiana (Palin *et al* 2018). Similarly, the Tubbs Fire of 2017 and Camp Fire of 2018 in California negatively impacted water quality and supply in surrounding cities such as Santa Rosa and Paradise (Proctor *et al* 2020). Infrastructure disruptions can be felt in locations far away from the hazard impact.

While there is significant emerging knowledge on the direct impacts of climate hazards on city infrastructures (Moteff and Parfomak 2004, Kim *et al* 2017, Liu and Song 2020, Bondank *et al* 2022), there is a dearth of work that explicitly outlines the risks to cities from hazards occurring in their hinterlands. Existing research connecting urban and hinterland areas focuses on the impacts of urban man-made systems on the hinterland environment (Bergqvist and Egels-Zandén 2012, Billen *et al* 2012, Güneralp *et al* 2013, Lee *et al* 2016). For example, a study showed how increased greenhouse gas emissions and water usage from urban households can transcend urban boundaries into the hinterlands and throughout the continent (Lenzen and Peters 2010). Further, Urban Metabolism literature has explored how the widespread mobilization of people, materials, and food requires extensive energy, resources, and time due to growing interdependencies (Lee *et al* 2016). More recently, the climate community has begun to recognize the vulnerabilities of cities from hinterland system disruptions (UNEP 2016, Verschuur *et al* 2022); yet, no systematic study explores and describes hinterland hazards and their significance for urban areas. As the connections between local and hinterland areas are many and diverse (UNEP 2016, Carson *et al* 2021, Verschuur *et al* 2022, Brunner *et al* 2024), such a study allows for systematic exploration and planning of cross-boundary climate risks and helps city infrastructure managers reduce vulnerabilities to local systems.

Filling this knowledge gap involves identifying, characterizing, and outlining the potential impacts of hinterland climate hazards on city infrastructure. To this end, the impacts of hinterland instances of fire, smoke, precipitation, flooding, and post-fire debris flow (PFDF) on urban infrastructure function are systematically researched and mapped. While there are many potential climate hazards that can disrupt infrastructure function, fire and precipitation are chosen given the spate of their recent disruptions across the U.S. (Fischer and Knutti 2015, Westerling 2016, Radeloff *et al* 2018, AghaKouchak *et al* 2020, Jia *et al* 2021). PFDF, or the rapid, downhill movement of sediment and debris triggered by heavy rainfall on recently burned areas, is also of particular interest due to its relevance to areas that recently experienced fires (Fraser *et al* 2020, Li and Chester 2023). Fire and precipitation on their own can also cause significant smoke and flooding respectively; therefore, these hazards are considered as well (Bollinger and Dijkema 2016, Serre and Heinzlef 2018, Wetterberg *et al* 2021, Behrer and Wang 2022).

The following sections detail and present findings of a systematic literature review that describes dependencies, interdependencies, and feedback loops of diverse CINs, including transportation, electricity generation and transmission, communication, fuel supply, water distribution, stormwater drainage, and food supply. The aim of the literature review was not to exhaustively catalog every available source but rather to systematically gather evidence supporting documented connections between climate hazards, hinterland infrastructure assets, and urban infrastructure function. The collected literatures informed a description of how hinterland fires, smoke, precipitation, flooding, and PFDF affect cities. The description is supplemented with an influence diagram (figure 2 in the Results) to clarify and illustrate the intricate web of connections. Following an analysis of the pathways through which urban infrastructure function is impacted by climate hazards in their hinterlands, the relevance of the findings and implications for cross-governance planning is discussed. This exploration into the connections between hinterland and city infrastructure can serve as a guide for how to understand the myriad of impacts of hinterland climate hazards on urban infrastructure and will support adaptation activities.

2. Methodology

To reveal how hinterland infrastructure disruptions impact downstream city services, linkages between hinterland hazard occurrences to urban infrastructure disruption must first be identified. A three-step literature review process was used that: (i) describes the potential relationships between cities, their hinterlands, and fire and PFDF hazards, (ii) expands on the relationships between infrastructures and the resulting dynamics from climate perturbations, and (iii) validates the relationships and dynamics. In total, 99 sources were incorporated with approximately 50% coming from a U.S. perspective, 25% from Africa, Asia, Europe, or Australia, and the remaining being non-region specific. The review focuses on the CIN sectors of transportation, electricity generation and transmission, communication, fuel supply, water distribution, stormwater drainage, and food supply. We focus on these sectors as they align with Federal Emergency Management Agency (FEMA) (2023) CIN classification, but exclude health & medical and hazardous waste as these two sectors are generally localized in nature and therefore not directly affected by city-hinterland dynamics (but quite possibly indirectly).

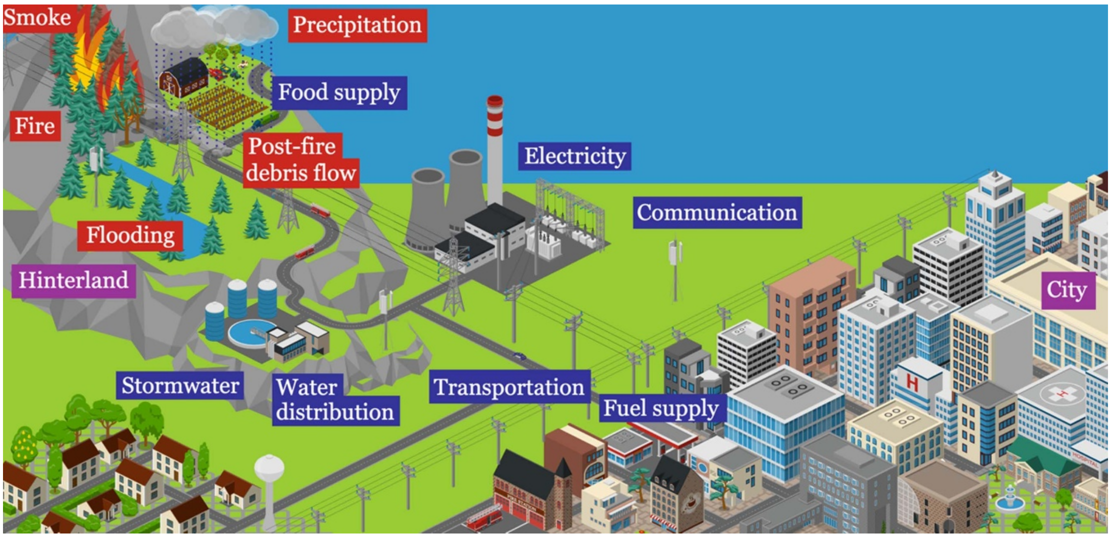

Figure 1. An artistic representation of hinterland-city dynamics. The left-hand side displays a hinterland area containing numerous hazards and infrastructure assets. These systems connect to city CINs, depicted on the right-hand side (created using Icograms Designer, 2016).

To identify the relationships between cities, their hinterlands, and climate hazards, an initial and pointed (i.e. strict filtering by keywords) search was conducted. The literature search was conducted using academic search engines including Google Scholar, the Arizona State University Library search engine (which accesses major journal article publishers), BASE, and Science.gov. Initial search keywords included 'urban infrastructure,' 'infrastructure disruption,' and 'climate hazards,' and a dedicated search also including the keyword 'hinterland.' Evidence was collected that connected hinterland infrastructure asset disruptions with a disruption in urban infrastructure function. In Step 1, a total of 21 peer-reviewed papers were identified that describe CIN infrastructure vulnerability to fire, PFDF, and flooding between cities and hinterlands. Markolf *et al*'s (2019) framing of direct and indirect physical effects of hinterland impacts from climate hazards on infrastructure assets was used as guidance, where direct effects include climate hazard impacts on users and infrastructure assets and indirect effects were impacts from disruptions in other infrastructures.

Conceptualizing the connections between hinterland infrastructure disruptions and urban infrastructure function helps map potential vulnerability, describe how hinterland-city impacts could unfold in the event of certain hazards, and identify interdependencies that could lead to cascades. Figure 1 visualizes a general cross-boundary system consisting of hinterland hazards and infrastructure services. In figure 1, infrastructure assets are labeled and distributed throughout both the city and hinterland areas. Climate hazards (fire, smoke, precipitation, flooding, and post-fire debris flow) are depicted in the hinterlands. It should be noted that some connectivity between hinterland and urban infrastructure assets within a system are clearly visible, like with transportation and electricity generation and distribution. The connectivity between hinterland assets and urban function of infrastructures, such as water distribution and communication, can be buried or otherwise harder to locate. Figure 1 is representative of Step 1 of the literature review, where relationships were described but not the specific dynamics of disruption. Thus, figure 1 is intended to serve as an artistic interpretation of the problem at hand and not an exhaustive illustration of the dynamics of disruption. Considering potential relationships between climate hazards, hinterland infrastructure, and city services in this way provides a valuable roadmap for identifying the risks to cities from physically distant disruptions.

After the initial illustration of relationships between hinterland hazards and urban CIN function, a second review was conducted to describe dynamics of CIN disruption. Step 2 returned 45 peer-reviewed articles and revealed many of the specific dynamics of disruption between cities, hinterlands, and climate hazards through regional infrastructure systems. These articles were found by conducting pointed searches for each infrastructure studied by including the terms 'transportation,' 'electricity,' 'communication,' 'fuel supply,' 'water distribution,' 'stormwater,' and 'food'. Special attention was paid to papers that described connections between fire, smoke, precipitation, flooding, and PFDF and hinterland infrastructure assets. This content provided the basis for creating the influence diagram presented in the Results (figure 2).

Lastly, in Step 3, a validation exercise was performed by expanding the previous search to include gray material and cross-referencing against other related syntheses. Gray material included government reports and news articles. Additionally, the Step 2 literature results (dynamics) were cross-referenced against those described in the US National Climate Assessment to both identify missing dynamics and confirm the

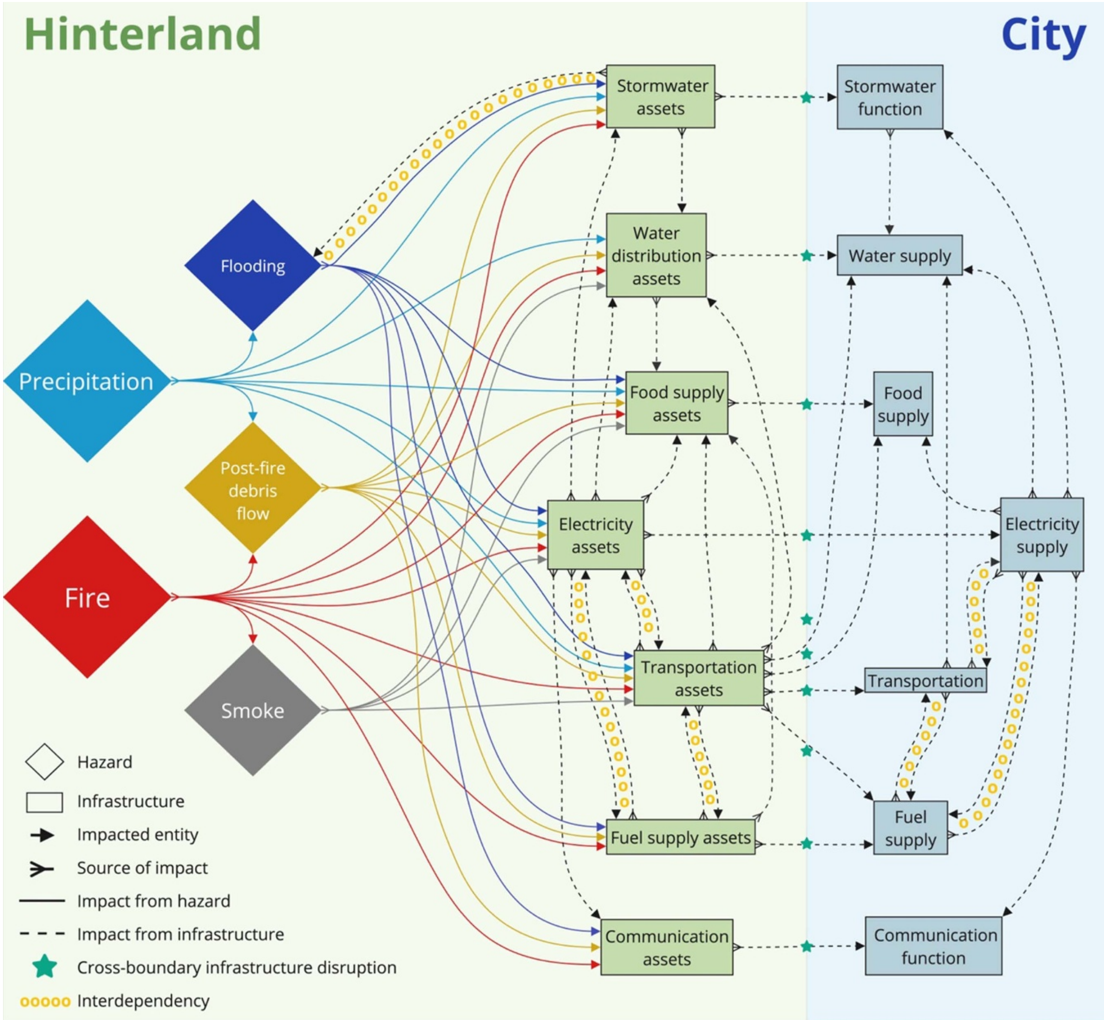

Figure 2. Influence diagram visualizing cross-boundary infrastructure disruptions (identified with a star) from hinterland hazards found in the literature review.

dynamics identified. In total (Steps 1, 2, and 3) 99 sources were reviewed and serve as the basis for the analysis.

3. Results

The findings of the literature review are synthesized by infrastructure sector (transportation, electricity generation and transportation, communication, fuel supply, water distribution, stormwater drainage, and food supply), allowing for an examination of each sector's specific challenges in the context of fire, smoke, precipitation, flooding, and PFDF. Each subsection will first describe evidence of specific infrastructure asset vulnerability to the climate hazards. Then, the connection between hinterland asset disruption and each urban infrastructure function will be described by discussing the broader system impacts stemming from individual asset disruptions and disruptions in connected infrastructures, allowing for consideration of cascading impacts.

3.1. Transportation

Transportation systems, including roadways, railways, maritime transport and transit services, provide the foundation for daily mobility and movement of goods and are often essential for evacuation and rescue during climate hazards. Functionality of transportation assets, such as roadways and stop lights, can be impacted by fire, PFDF, and flooding. Fires near transportation infrastructure can cause direct physical damage, such as burning bridges (Hansen 2022) and pavement deterioration (Peker 2021). Extreme heat from fires can also deform railroad tracks (Said-Moorhouse 2022). After a fire, precipitation-induced PFDF can carry large boulders and debris from fire burn scars downstream, blocking or damaging bridges, roadways, railroad tracks, and vehicles (Cova and Conger 2004, Kean et al 2019, Kolden and Henson 2019, Fraser *et al* 2020, Jakob 2021, Li and Chester 2023). Furthermore, debris from fires and PFDF can block culverts and erode pavement foundations (Valentin and Stormont 2019). Flooding from intensive precipitation can wash away bridges and railways (Jakob 2022) and damage railway system assets (Chester *et al* 2015, Bešinović 2020).

In addition to causing direct physical damage to infrastructure assets, climate hazards occurring in hinterlands can disrupt the combined hinterland-urban transportation network. Any sort of physical asset damage previously described can lead to the cutoff of critical transportation pathways and can strain alternative routes or modes (Mo *et al* 2023). Similar strains and disruptions can be triggered by smoke or precipitation, both of which can reduce visibility on roadways, contributing to slower travel speeds and increased congestion during fire evacuation, even limiting road use in some cases (Cova and Conger 2004, Biging *et al* 2012, Cahoon *et al* 2015, Goldbeck *et al* 2020, Wetterberg *et al* 2021, Intini *et al* 2022). Evacuees displaced to neighboring communities can also increase traffic (Spearing and Faust 2020). Additionally, inland ports can be critical for urban-rural access and supply chain function (van Ruiten *et al* 2016, Kuang *et al* 2021, Jamac and Ahlgren 2023); therefore, damaged roads and railways can disrupt the supply chain of critical goods (e.g. food, fuel, water) to urban areas (Biging *et al* 2012, Cahoon *et al* 2015, Goldbeck *et al* 2020). Finally, in the aftermath of climate hazards, heavy trucks used for both PFDF removal and the rebuilding of infrastructures can increase traffic loads (McCoy *et al* 2016). Since roadways in hinterland areas are generally designed for small traffic loads, the increased loads from trucks can lead to further physical damage on the pavement and road foundation (Oh *et al* 2007).

Transportation system function can also be impacted by interruptions to other CINs. Electricity outages caused by hinterland climate hazards can either: (1) induce cascading failures on a hinterland transportation system, affecting mobility into the city it services, or (2) affect electricity supply in the city, disrupting urban transportation networks. For example, traffic light outages during blackouts can induce traffic jams and accidents (Matthewman and Byrd 2014, Melnikov *et al* 2015). Additionally, electric trains are often used to move coal to and from marine ports (Matthewman and Byrd 2014, Melnikov *et al* 2015), and loss of electricity can cause crossing signal and switch outages, shutting down rail lines until electricity is restored (Chang *et al* 2007). Transportation is also dependent upon fuel supply, as diesel and gasoline are necessary for the majority of cars to operate (Bicknell *et al* 2009). Therefore, interruption in fuel supply can impact supply chains or even emergency evacuation from hinterland areas. As the means for powering transportation is shifting, vehicles are becoming increasingly dependent upon electricity to operate (Vilathgamuwa *et al* 2022), potentially increasing transportation's vulnerability to electricity outages.

3.2. Electricity generation and transmission

Electricity infrastructure consists of a system of transregional assets that connect generation technologies into cities (Singh and Papalexopoulos 1999, UCTE 2008, Javadi and Javadinasab 2011, Chowdhury *et al* 2013). Electricity assets, including generation plants and technologies, substations, and transmission and distribution lines, are vulnerable to the hinterland hazards of fire, smoke, PFDF, precipitation, and flooding. Fires pose a threat to electric infrastructure through the overheating of equipment, potentially damaging conductors and jeopardizing the transmission network (Choobineh *et al* 2015, Saeed and Nazaripouya 2022). Fires can also cause smoke that reduces generation capacity of solar photovoltaic systems (Donaldson *et al* 2021). PFDFs can cause physical damage to transmission lines (Petrova 2022). Electricity supplied by hydroelectric plants can diminish if precipitation is too low (Kreimer *et al* 2003). At the other precipitation extreme, flooding can cause contamination and failure in electricity generation plants, limiting the ability to generate electricity (Bollinger and Dijkema 2016). Substations also contain highly sensitive electrical materials that are at risk to flooding (Bollinger and Dijkema 2016).

Natural hazards affecting electricity infrastructures in hinterland regions can disrupt electricity supply in distant city areas. For example, modeling electricity networks has shown that fires in the hinterlands threaten distribution of electricity to customers far away (Sfetsos *et al* 2021). In another study, it is revealed that a lack of precipitation can decrease electricity production from hydroelectric dams, which in turn decreased electricity supply to dependent, often urban, areas (Kreimer *et al* 2003). Transmission line interruption can also cause distant blackouts through cascading failures, as seen in the 2003 Northeastern Blackout (Graham 2009).

Interruptions in fuel supply and transportation assets can also impact the functionality of electricity infrastructure. For example, the availability and price of fuel can impact electricity generation. Fuel shortages can produce electricity outages, exemplifying the dependence of electricity on fuel wellheads, pipelines, and processing facilities (Crivelli 2014). In emergency situations, disruptions in gasoline can impact backup generators (Bicknell *et al* 2009). Further, with the increased electrification of transportation assets (e.g. electric vehicles), it is possible that evacuation-induced electric vehicle charging could place a strain on the grid (Vilathgamuwa *et al* 2022). On the other hand, researchers are considering how electric vehicles with full batteries might be used for backup electricity supply in future electricity outages (Vilathgamuwa *et al* 2022).

3.3. Communication

Communication infrastructure includes the physical and digital networks and systems that enable the transmission and exchange of information. Physical communication infrastructure (e.g. cellular towers, data centers, long-haul fiber cables, electrical support facilities) can be directly damaged by fire (Hirsch and Fuglem 2006, Chang 2016, Anderson *et al* 2020), flooding (Zimmerman and Faris 2010, Chang 2016, Padmanabhan *et al* 2019), and PFDF (Chang 2016, Petrova 2022). While communication infrastructure tends to be clustered in urban areas, large data centers can be found in hinterlands, such as the world's largest data center market in northern Virginia near Washington D.C. (Chowdhury *et al* 2013, Federal Communications Commission 2021, Barkham and Whelan 2022).

It can be difficult to locate communication assets due to security concerns and their private nature (Burrington 2016), making it difficult understand the exact pathways through which damage to hinterland communication assets has impacted urban communication function. It appears that the most significant risk to urban communication infrastructure function is an electricity outage, due to the strong dependency on electricity infrastructure (Zimmerman and Faris 2010, Tøndel *et al* 2018, Anderson *et al* 2020, Patil *et al* 2020).

In the identified body of literature, communication infrastructure is typically referenced for its importance to emergency response during hazards (Wilkinson and Cole 2010): it plays a critical role in hazard prediction and monitoring (via satellites, drones, wireless sensors, etc.) and emergency response (e.g. warning and alert systems, responder dispatching, cellular communication, etc) (De Graff 2014, Chang 2016, Anderson *et al* 2020, Mohapatra and Trinh 2022). Communication infrastructure provides a unique ability to bridge technological and social systems and enable social resilience.

3.4. Fuel supply

Fuel supply (herein defined as the supply of coal, oil, natural gas, gasoline, diesel, and their transport mechanisms) in cities can be interrupted by fire, flooding, or PFDF in their hinterlands. Fires and PFDF can interrupt fuel refinery operations causing fuel supply shortages in dependent cities (Khakzad 2018, Buckle *et al* 2020). Floods can impact both supply of fuel and public access to fuel supply. Both floods and PFDFs can rupture oil and gas storage tanks and flow lines as well as force fuel extraction operations (e.g. oil wells, coal mines) to halt production (U.S. Department of Transportation 2014, Kean *et al* 2019, Petrova 2022, Sun *et al* 2022). Excess water from flooding can also displace oil and other fuels by infiltrating storage tanks, floating storage tanks elsewhere, or causing leakages (Ekhtiar 1996, Natural Hazards Center U. of C. B. 2014).

Changing behavior during hazard-induced evacuations can also have impacts on fuel supply infrastructure. For example, flooding in gas stations can cause supply issues during evacuation events by increasing demand at non-flooded gas stations (Wisetjindawat *et al* 2017). Additionally, hazard-induced evacuation can lead to gasoline shortages in communities, further slowing down evacuation efforts (Litman 2006).

Fuel supply can also be interrupted when other infrastructures such as transportation and electricity are disrupted (Clark and Chester 2016). Destruction or blockages in roads or railroads can disrupt the transportation of fuel (e.g. petroleum, coal), thus interrupting fuel supply and reducing system capacity (Litman 2006, Cahoon *et al* 2015, Clark *et al* 2019, He *et al* 2021, Schweikert and Deinert 2021, Library of Congress n.d.). Fuel supply can be affected by electricity outages in various ways. For one, electricity is required to pump gas (Chang *et al* 2007, Miles *et al* 2015). Loss of electricity can also cause refinery outages, which have been linked to increases in fuel prices (Chang *et al* 2007, Kendix and Walls 2010).

3.5. Water distribution

Water distribution networks, or the assets that store, treat, and transport water to cities, can be affected by fire, precipitation, smoke, and PFDF. Water supplies are increasingly outsourced from the hinterlands for urban consumption (Soll 2012, Chowdhury *et al* 2013), exposing the water distribution system to distant risks that often stem from worsening water quality. Fires impact water distribution resources by damaging assets, impacting water quality, or diminishing water supply (Bakirci 2010, Sowby and Porter 2023). Fires can increase potential for runoff during precipitation by reducing vegetation cover, which creates the potential for sediment infiltration into drinking water supply (Bladon *et al* 2014). Smoke, soot, and ash from fires can travel through the water system from the hinterlands to urban areas and require flushing and boiling of residential water to ensure its potability (Sham *et al* 2013, Kolden and Henson 2019). PFDFs can damage or clog components of water distribution networks, including pipelines, well heads, reservoirs, and storage tanks (Sham *et al* 2013, Petrova 2022). Sediment buildup in reservoirs can greatly reduce the planned life of the reservoir (Sham *et al* 2013). Water treatment plants can also experience efficiency challenges due to changes in water quality of reservoirs and other water sources (Sham *et al* 2013).

Water distribution networks are impacted by interruptions in stormwater infrastructure, electricity, and transportation. Stormwater infrastructure failures contribute to worsening surface water quality (Collins *et al* 2010). Since water quality is a significant factor affecting water treatment and distribution, stormwater infrastructure thus has an indirect effect on water distribution network function both in hinterlands and in urban areas by overwhelming treatment facilities. The magnitude of this effect depends on the type of infrastructure used and precipitation frequency, duration, and intensity (Liu *et al* 2014, McPhillips and Matsler 2018). Electricity outages can disrupt water treatment, pumping, and communication throughout the network (Sham *et al* 2013, Busby *et al* 2021). For example, municipal treatment plants often rely on flow-through systems and only have hours of clean water in their reservoir, so when the water pressure drops, there is a risk of contamination in the distribution lines (Chang *et al* 2007). Additionally, water distribution is impacted by disruptions in transportation infrastructures, since these can be vital for moving water supply from one place to another (Rodrigue 2017).

3.6. Stormwater

Stormwater infrastructure consists of the network of drains, pipes, channels, pumps, and detention basins designed to manage and mitigate surface runoff from rain, reducing flooding and preventing water pollution. Stormwater infrastructure is directly impacted by precipitation and flooding. An increase in the amount and intensity of precipitation can impact the ability of stormwater infrastructure to function properly, as it increases stormwater runoff volume (Pyke *et al* 2011, Davis 2021). Though stormwater systems are built to mitigate flows of excess precipitation, not all stormwater systems can be equipped to handle extreme flooding events. Stormwater systems become especially vulnerable when flooding occurs beyond what the systems are designed for (Rodrigue 2017).

The impacts on soil and water quality caused by fire and PFDF also have an impact on the function of stormwater infrastructure (Kolden and Henson 2019). Fire-burned soils exhibit lower water retention than non-burned soils (California Water Science Center 2018). This decreased retention results in greater quantities of stormwater, risking asset exceedance and flooding. Fire also introduces new or additional contaminants to stormwater runoff, as materials from damaged physical structures end up in runoff along with excess nutrients (e.g. copper, lead, zinc, nitrate, and nitrite) from burn sites (Stein *et al* 2012, Chang *et al* 2021). Runoff from these areas results in surface water contamination downstream, including urban areas where stormwater infrastructure are not designed to treat these constituents (Tran *et al* 2019). PFDFs also increase the demand on stormwater infrastructure in a similar way due to the high quantity of water and pollutants entering the system (Kolden and Henson 2019). In terms of dependence on other infrastructures, some stormwater pumps require electricity; therefore, there could be an indirect disruption to stormwater infrastructure if electricity is disrupted (Bigger *et al* 2009).

3.7. Food supply

Food supply refers to the system of producing, processing, transporting, storing, and distributing food products from farms and factories to consumers. Food supply is impacted by fire, smoke, precipitation, PFDF, and flooding. Forest fires can scorch or burn significant portions of agricultural land (Easterling *et al* 2007). Additionally, fires can impact farmland vegetation by increasing soil erosion, depositing ash, and decreasing soil nutrients (Kpienbaareh and Luginaah 2019). Smoke from fires reduces air quality which can impact crop yields (Behrer and Wang 2022). Precipitation can directly impact agricultural production by limiting freshwater availability or impacting soil moisture (Calzadilla *et al* 2013). Lower-quality soils resulting from either fire or precipitation can reduce hinterland crop yields (Akpoveta *et al* 2014, Kpienbaareh and Luginaah 2019). Flooding can cause oversaturated soils, drowning and destroying crops (Derbile and Kasei 2012, Calzadilla *et al* 2013). PFDF has been shown to damage farmland or farm facilities by depositing rocks or sediment which can bury crops and damage buildings or equipment (Bera *et al* 2021, Petrova 2022). Any decrease in or destruction of hinterland crop yields can reduce the quality or quantity of food sent to urban centers, which is especially problematic since cities today are heavily reliant on outsourcing food.

Disruptions in electricity, fuel supply, transportation, and water distribution can also cause disruptions in urban food supply. Agriculture outputs can be affected in various ways by electricity outages, such as hindering the ability to heat or circulate barns, rendering machinery inoperable, and making it impossible to refrigerate produce (Chang *et al* 2007). Many irrigation systems and agricultural and storage machinery are dependent on fuels. Fuel shortages can decrease agricultural outputs by preventing proper irrigation of crops, delaying planting or harvesting of crops which is time sensitive, or preventing proper processing or storage of food (Shahbazi 1992, Peters 2010). Urban food supply is also dependent on transportation infrastructure. Disruptions in the transportation network can impact supply chains and constrain the transport of food to cities (Cahoon *et al* 2015, OECD 2020). Damage to or impairment of hinterland water infrastructure, either by fire or precipitation, also threatens urban food supplies. Reduced water supply availability can prevent sufficient irrigation of crops and impact food processing, leading to reduced hinterland crop yields (Zimmerman *et al* 2016, Casellas Connors *et al* 2023). These various impacts on agricultural production, storage, or transportation can negatively impact urban food supply.

3.8. Summary of findings

The literature review allowed for the construction of an influence diagram that describes the pathways from which climate hazards impact hinterland infrastructure assets and, in turn, urban infrastructure function. The influence diagram is presented in figure 2. Diamond shapes represent hazards, and infrastructures are represented by rectangles. The green (left) portion of the diagram shows how hazards impact infrastructure assets in the hinterland, whereas the blue (right) portion of the diagram shows urban infrastructure function. Arrows represent the direction of impact, with the tail of the arrow indicating the source of the impact and the head indicating the impacted entity. Solid arrows represent impacts from hazards, whereas dotted arrows indicate impacts from infrastructure disruptions or interactions. Finally, interdependencies, or areas where impact arrows flow in both directions between two entities, are identified with yellow circles.

4. Discussion

The multiplicity of impact pathways from climate hazards to hinterland infrastructure gives some insight into the challenges to improve the resilience of infrastructures to climate hazards. Hinterland electricity infrastructure, transportation assets, and food supply assets are directly impacted by all five hazards studied. At first it may seem that prioritizing assets based on the number of potential impact pathways is prudent. However, a particular system's vulnerability is not solely determined by the *quantity* of these pathways. It is essential to distinguish between the number of potential impacts and their actual likelihood. A multitude of possible but unlikely pathways does not necessarily mean higher risk than a few highly probable ones. Thus, both scenarios require tailored strategies: extensive planning for many low-probability impacts and focused action on a few high-probability ones. This dual approach allows for more effective management of city-hinterland resilience, acknowledging that both the number and likelihood of impacts are crucial in planning.

There are ten instances of cross-boundary infrastructure disruptions—pathways where urban infrastructure disruptions are caused by climate hazards impacting hinterland-based infrastructure assets. Seven impacts stem directly from an infrastructure's hinterland assets (e.g. electricity assets like transmission lines or generation plants located in the hinterlands) impacting urban function of the same infrastructure in the city (e.g. urban electricity supply). Interestingly, the remaining three cross-boundary infrastructure disruptions are caused by hazard-induced disruption to hinterland transportation assets. Hinterland transportation assets aid in urban supplies of potable water, food, and fuel. In general, this emphasizes the need to prioritize the resilience of transportation assets to minimize indirect impacts to urban infrastructure function. That being said, when attempting to build infrastructure resilience in a specific region, it is important to understand the local conditions and context to determine exactly what assets to prioritize (Hoff *et al* 2023).

Hinterland hazards threaten the physical assets that make up cross-boundary infrastructure and create cascades due to the dependencies between infrastructures that threaten overall system capabilities. For example, though there is only one cross boundary electricity impact, electricity services are essential to both hinterland asset function and urban infrastructure function. Outages in electricity infrastructure impact the operation of hinterland assets in all CINs studied, making it especially important to consider enhancing the resilience of the electricity system and/or the resilience of dependent systems in the event of an electricity outage. Further, electricity supply connects with all the other infrastructure in the city. Therefore, when there's a problem with electricity (which is naturally a very large system that transcends borders), there is potential for a cascading failure that impacts many infrastructures.

When using figure 2 to identify the impact pathways for the purposes of increasing the resilience of infrastructures, it is more important to understand *how* impacts can occur instead of simply enumerating them as a proxy for vulnerability. There are many possible pathways from a hazard event to an infrastructure disruption. For example, fire impacts the food supply in the city by at least three pathways. First, a fire that occurs near a farm in the hinterlands could cause excessive smoke that shuts down roadways and disrupts the transport of food to the city (OECD 2020, Wetterberg *et al* 2021). Later, the land scarred by the initial fire might experience heavy precipitation, causing PFDF that runs into the farm itself and destroys crops, thus reducing the amount of food available to a nearby city (Bera *et al* 2021, Petrova 2022). While the final impact is the same—food supply to a city is disrupted—the pathways and timelines of impact stemming from the initial fire play out very differently. PFDF can occur up to five years after a fire and just minutes to hours after heavy precipitation (FEMA 2020). This is important to recognize since the land conditions favorable for the formation of PFDF after a fire can be eliminated through debris clearing after a fire (Schwartz *et al* 2021). Infrastructure managers need to recognize the different paths of impact from different hazards in order to understand the full range of threats to transregional, interconnected infrastructures. It is essential to implement place-based solutions that are tailored to local conditions and vulnerabilities, ensuring a more targeted and effective approach to building resilience in transregional, interconnected infrastructures.

There are many ways that urban infrastructure disruptions from hinterland climate hazards can occur. As such, it can be helpful to conduct a detailed examination of different scenarios to understand exactly how to make infrastructures more resilient. Interdependencies are a good place to begin focus because they can cause uncontrollable impacts after they are triggered (Markolf *et al* 2019, Ruhl 2019, Chester *et al* 2023). For example, several interdependencies exist between electricity, fuel supply, and transportation, both in hinterland asset operation and in urban infrastructure function. One scenario that could trigger a cascade because of these interdependencies might begin with a fire in the hinterlands, followed by precipitation several months later that causes PFDF. The PFDF can disrupt the urban electricity supply by knocking out key transmission lines between a hinterland generating station and the city (Choobineh *et al* 2015, Sfetsos *et al* 2021). Facilities critical to city function can then need to use diesel-powered backup generators. These facilities may need fuel delivered via transportation assets if the outage persists. A persistent outage could mean dysfunctional traffic lights that can cause backups and accidents on the roads (Matthewman and Byrd 2014, Melnikov *et al* 2015). In turn, this could affect the delivery of fuels for backup generators. Additionally, without electricity, gasoline cannot be pumped to supply gasoline-powered vehicles (Chang *et al* 2007, Miles *et al* 2015), further complicating fuel delivery. The cascade is perpetuated: a delay in fuel delivery can lengthen the electricity outage, making it harder to supply backup fuel to stop the outage. Anticipating this type of scenario through exercises like horizon scanning or scenario planning may help cities avoid this kind of disruption and build capacity to adapt.

Analyzing the transregional interconnectedness of infrastructure, which makes urban infrastructures vulnerable to distant climate hazard risks, necessitates a different approach to infrastructure governance than the current methods used to enhance urban infrastructure resilience to climate hazards. Despite the increasing interconnectedness of systems, disjoint management of urban and hinterland infrastructure is common. Current infrastructure management often focuses on regional, centralized governance, considering only the direct impacts of the climate hazards physically occurring in urban areas (Moteff and Parfomak 2004, Kim *et al* 2017, Liu and Song 2020, Bondank *et al* 2022). However, regional assets are often connected to other assets and/or infrastructures that extend beyond one geopolitical territory. Thus, co-governance of urban and hinterland infrastructures is needed to mitigate cross-boundary infrastructure disruptions. Co-governance would include shared decision-making between public and private sectors located in both hinterlands and the urban areas served by them, such that the distribution of governance is rescaled so more strategic planning can take place (Lingua 2020). A first step towards co-governance of infrastructure is to conduct a trans-regional hazard analysis like the one described in this paper to understand current and future climate hazard threats. Following a better understanding of risks to cross-boundary infrastructures, co-governance of interconnected infrastructures should then emphasize collaborative system design, maintenance, and investment in infrastructure assets.

The work herein is intended to provide perspective on the relationships, dynamics, and potential vulnerabilities of cities, their hinterlands, and climate hazards. As such, the findings are not specific to any particular place with the intention of generalizability. Differences in geographical location, climate, infrastructure design, and governance structures may limit the generalizability of the findings. Conducting a context-specific study would yield distinct outcomes, reflecting the unique environmental, infrastructural, and administrative characteristics of the area. Future work may involve a comparative study of impact pathways across regions, countries, or continents, as adaptation options should be specific to the context and embrace local knowledge through co-production.

5. Conclusion

Infrastructures are physically and non-physically interconnected transregionally, which in turn exposes urban infrastructures to far away climate hazard risks. The methodology presented in this paper demonstrates a bottom–up approach for managing hinterland hazard risks to urban infrastructure function. This begins with specifying the urban infrastructures of interest, the regions it spans and the hinterland assets on which urban infrastructure function is dependent, and potential disruptions from hinterland hazards or disruptions to infrastructures. This process was demonstrated by outlining how fire, smoke, precipitation, flooding, and PFDF occurring in hinterlands have historically impacted the CINs of transportation, electricity generation and transportation, communication, fuel supply, water distribution, stormwater drainage, and food supply.

It is important to recognize that the actual impacts possible in a particular region are dependent on specifics of the local topography, governance, and infrastructure dependencies and interdependencies. Context-specific studies should be conducted to identify regional threats to cross-boundary systems that may vary from the generalized methodology presented. Location-based studies would allow for cross-boundary planning for responses to regional primary hazards, secondary hazards, and environmental qualities that have differing impacts to hinterland and city infrastructure by location. While these cross-boundary systems are dynamic and it is difficult to predict how they may be impacted in the future, especially since the threats that hinterland hazards present today could be altered with a changing climate (Intergovernmental Panel on Climate Change 2022), managers can begin to prepare the systems for the future by first understanding the current threats and interconnections in a manner similar to the methodology described in this paper. Conducting an in-depth, transregional hazard analysis yields critical information that helps identify risks to urban infrastructure function from climate hazards. This information can then be used to support co-governance of cross-boundary infrastructures to improve resilience.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

The authors would like to acknowledge financial support from the Alfred P Sloan Foundation (G-2022-19398), the National Science Foundation Directorate for Engineering (1931324 and 1934933), the National Institute of Standards and Technology (70NANB22H056), and the US Department of Defense (CR23-7759).

ORCID iDs

Madison Horgan https://orcid.org/0000-0002-2359-7642
Rui Li https://orcid.org/0000-0001-8385-763X
Alysha Helmrich https://orcid.org/0000-0002-3753-8811
Abbie Dirks https://orcid.org/0000-0003-4590-468X
Mikhail Chester https://orcid.org/0000-0002-9354-2102

References

AghaKouchak A, Chiang F, Huning L S, Love C A, Mallakpour I, Mazdiyasni O, Moftakhari H, Papalexiou S M, Ragno E and Sadegh M 2020 Climate extremes and compound hazards in a warming world *Annu. Rev. Earth Planet. Sci.* **48** 519–48

Akpoveta V O, Osakwe S A, Ize-Iyamu O K, Medjor W O and Egharevba F 2014 Post flooding effect on soil quality in Nigeria: the Asaba, Onitsha experience *Open J. Soil Sci.* **2014** 72–80

Anderson S, Barford C and Barford P 2020 Five alarms: assessing the vulnerability of US cellular communication infrastructure to wildfires *IMC'20: Proc. ACM Internet Measurement Conf.* (https://doi.org/10.1145/3419394.3423663)

Bakirci M 2010 Negative impacts of forest fires on ecological balance and environmental sustainability: case of Turkey *J. Geogr.* **5** 15–32

Barkham R and Whelan J 2022 North America data center trends H_2 2021 *Global Commercial Real Estate Services*

Behrer A P and Wang S 2022 *Current Benefits of Wildfire Smoke for Yields in the US Midwest May Dissipate by 2050* (World Bank Group) (https://doi.org/10.1596/1813-9450-9953)

Bera S, Melo R and Guru B 2021 Assessment of exposed elements in a changing built environment by using an integrated model of debris flow initiation and runout (Kalimpong region, Himalaya) *Bull. Eng. Geol. Environ.* **80** 7131–52

Bergqvist R and Egels-Zandén N 2012 Green port dues—the case of hinterland transport *Res. Trans. Bus. Manage.* **5** 85–91

Bešinović N 2020 Resilience in railway transport systems: a literature review and research agenda *Transp. Rev.* **40** 457–78

Bicknell J, Dodman D and Satterthwaite D (eds) 2009 *Adapting Cities to Climate Change: Understanding and Addressing the Development Challenges* 1st edn (Routledge) (available at: www.routledge.com/Adapting-Cities-to-Climate-Change-Understanding-and-Addressing-the-Development/Bicknell-Dodman-Satterthwaite/p/book/9781844077465)

Bigger J E, Willingham M G, Krimgold F and Mili L 2009 Consequences of critical infrastructure interdependencies: lessons from the 2004 hurricane season in Florida *Int. J. Crit. Infrastruct.* **5** 199–219

Biging G S, Radke J D and Lee J H 2012 *Impacts of Predicted Sea-Level Rise and Extreme Storm Events on the Transportation Infrastructure in the San Francisco Bay Region* (available at: https://escholarship.org/uc/item/5wv9f40k)

Billen G, Garnier J and Barles S 2012 History of the urban environmental imprint: introduction to a multidisciplinary approach to the long-term relationships between Western cities and their hinterland *Regen. Environ. Change* **12** 249–53

Bladon K D, Emelko M B, Silins U and Stone M 2014 Wildfire and the future of water supply *Environ. Sci. Technol.* **48** 8936–43

Bollinger L A and Dijkema G P J 2016 Evaluating infrastructure resilience to extreme weather—the case of the Dutch electricity transmission network *Eur. J. Transp. Infrastruct. Res.* **16**

Bondank E N, Chester M V, Michne A, Ahmad N, Ruddell B L and Johnson N G 2022 Anticipating water distribution service outages from increasing temperatures *Environ. Res.* **2** 045002

Brunner L G, Peer R A M, Zorn C, Paulik R and Logan T M 2024 Understanding cascading risks through real-world interdependent urban infrastructure *Reliab. Eng. Syst. Saf.* **241** 109653

Buckle P, Marsh G L and Smale S 2020 Reframing risk, hazards, disasters, and daily life: a report of research into local appreciation of risks and threats *Aust. J. Emerg. Manage.* **18** 81–87

Burrington I 2016 *Networks of New York: An Illustrated Field Guide to Urban Architecture* (Melville House)

Busby J W, Baker K, Bazilian M D, Gilbert A Q, Grubert E, Rai V, Rhodes J D, Shidore S, Smith C A and Webber M E 2021 Cascading risks: understanding the 2021 winter blackout in Texas *Energy Res. Soc. Sci.* **77** 102106

Cahoon S, Chen S-L, Brooks B and Smith G 2015 The impact of climate change on Australian ports and supply chains: the emergence of adaptation strategies *Climate Change and Adaptation Planning for Ports* ed A K Y Ng, A Becker, S Cahoon, S-L Chen, P Earl and Z Yang (Routledge)

California Water Science Center 2018 *Post-Fire Flooding and Debris Flow. United States Geological Survey* (available at: www.usgs.gov/centers/california-water-science-center/science/post-fire-flooding-and-debris-flow)

Calzadilla A, Rehdanz K, Betts R, Falloon P, Wiltshire A and Tol R S J 2013 Climate change impacts on global agriculture *Clim. Change* **120** 357–74

Carson D A, Carson D B and Lundström L 2021 Northern cities and urban–rural migration of university-qualified labour in Australia and Sweden: spillovers, sponges, or disconnected city–hinterland geographies? *Geogr. Res.* **59** 424–38

Casellas Connors J P, Safayet M, Rosenheim N and Watson M 2023 Assessing changes in food pantry access after extreme events *Agric. Hum. Values* **40** 619–34

Chang D, Richardot W H, Miller E L, Dodder N G, Sedlak M D, Hoh E and Sutton R 2021 Framework for nontargeted investigation of contaminants released by wildfires into stormwater runoff: case study in the northern San Francisco Bay area *Int. Environ. Assess. Manage.* **17** 1179–93

Chang S E 2016 Socioeconomic impacts of infrastructure disruptions *Oxford Research Encyclopedia of Natural Hazard Science* (https://doi.org/10.1093/ACREFORE/9780199389407.013.66)

Chang S E, McDaniels T L, Mikawoz J and Peterson K 2007 Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm *Nat. Hazards* **41** 337–58

Chester M V, Miller T R, Muñoz-Erickson T A, Helmrich A M, Iwaniec D M, McPhearson T, Cook E M, Grimm N B and Markolf S A 2023 Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene *npj Urban Sustain.* **3** 39

Chester M, Fraser A and Bartos M 2015 *Frameworks for Assessing the Vulnerability of U.S. Rail Systems to Flooding and Extreme Heat* (ASU-SSEBE-CESEM-2015-RPR-001) (Arizona State University) (available at: http://repository.asu.edu/items/29203)

Choobineh M, Ansari B and Mohagheghi S 2015 Vulnerability assessment of the power grid against progressing wildfires *Fire Saf. J.* **73** 20–28

Chowdhury F, Lant C and Dziegielewski B 2013 A century of water supply expansion for ten U.S. cities *Appl. Geogr.* **45** 58–76

Clark S S, Chester M V, Seager T P and Eisenberg D A 2019 The vulnerability of interdependent urban infrastructure systems to climate change: could Phoenix experience a Katrina of extreme heat? *Sustain. Resilient Infrastruct.* **4** 21–35

Clark S S and Chester M 2016 A hybrid approach for assessing the multi-scale impacts of urban resource use: transportation in phoenix, Arizona *J. Ind. Ecol.* **21** 1250–61

Collins K A, Lawrence T J, Stander E K, Jontos R J, Kaushal S S, Newcomer T A, Grimm N B and Cole Ekberg M L 2010 Opportunities and challenges for managing nitrogen in urban stormwater: a review and synthesis *Ecol. Eng.* **36** 1507–19

Cova T and Conger S 2004 Transportation hazards *Handbook of Transportation Engineering* ed M Kutz pp 17.1–17.24

Crivelli J 2014 *Wired Politics: Governing transnational electricity systems* (University of Zurich) (available at: www.zora.uzh.ch/id/eprint/164348/1/20142090.pdf)

D'Ayala M, Giusti R, Arosio M and Martina M 2021 A comparative literature review of the methodologies to evaluate risk of NaTech disasters and critical infrastructure affected by natural hazard EGU21–14793 EGU21 Copernicus Meetings (https://doi.org/10.5194/egusphere-egu21-14793)

Davis T 2021 *Stormwater damages lining of CAP canal near Picacho Peak* (Tucson. Com.) (available at: https://tucson.com/news/state-regional/stormwater-damages-lining-of-cap-canal-near-picacho-peak/article_09ba308c-ee67-11eb-8da4-67dd730d2c84.html)

De Graff J V 2014 Improvement in quantifying debris flow risk for post-wildfire emergency response *Geoenviron. Disasters* **1** 1–10

Derbile E K and Kasei R A 2012 Vulnerability of crop production to heavy precipitation in north-eastern Ghana *Int. J. Clim. Change Strateg. Manage.* **4** 36–53

Donaldson D L, Piper D M and Jayaweera D 2021 Temporal solar photovoltaic generation capacity reduction from wildfire smoke *IEEE Access* **9** 79841–52

Easterling W E *et al* 2007 Food, fibre and forest products *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed M L Parry, O F Canziani, J P Palutikof, P J van der Linden and C E Hanson (Cambridge University Press) pp 273–313 (available at: www.researchgate.net/publication/200471803_Food_fibre_and_forest_products)

Ekhtiar J 1996 Effect of Flooding on Fuel Storage Systems *ConVault* (available at: www.convault.com)

Federal Communications Commission 2021 *Mobile LTE Coverage Map* (Federal Communications Commission) (available at: www.fcc.gov/BroadbandData/MobileMaps/mobile-map)

Federal Emergency Management Agency (FEMA) 2023 *Community Lifelines Implementation Toolkit* (Federal Emergency Management Agency (FEMA)) (available at: www.fema.gov/emergency-managers/practitioners/lifelines-toolkit)

FEMA 2020 *Flood Risks Increase After Fires* (available at: www.fema.gov/sites/default/files/documents/fema_flood-after-fire_factsheet_nov20.pdf)

Fischer E M and Knutti R 2015 Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes *Nat. Clim. Change* **5** 560–4

Fraser A M, Chester M V and Underwood B S 2020 Wildfire risk post-fire debris flows and transportation infrastructure vulnerability *Sustain. Resilient Infrastruct.* **7** 1–13

Goldbeck N, Angeloudis P and Ochieng W 2020 Optimal supply chain resilience with consideration of failure propagation and repair logistics *Trans. Res. E* **133** 101830

Graham S 2009 *Disrupted Cities: When Infrastructure Fails* (Routledge)

Güneralp B, Seto K C and Ramachandran M 2013 Evidence of urban land teleconnections and impacts on hinterlands *Curr. Opin. Environ. Sustain.* **5** 445–51

Hansen T G 2022 Wildfire damage of geotechnical assets pp 91–103

He Y, Lindbergh S, Ju Y, Gonzalez M and Radke J 2021 Towards resilient critical infrastructures: understanding the impact of coastal flooding on the fuel transportation network in the san Francisco bay *ISPRS Int. J. Geo-Inf.* **10** 573

Hill A C and Kakenmaster W 2020 Resilient infrastructure: understanding interconnectedness and long-term risk *Optimizing Community Infrastructure* ed R Colker (Butterworth-Heinemann) ch 1, pp 5–21

Hirsch K G and Fuglem P 2006 *Canadian Wildland Fire Strategy: Background Syntheses, Analyses, and Perspectives* (Canadian Council of Forest Ministers)

Hoff R, Helmrich A, Dirks A, Kim Y, Li R and Chester M 2023 Dynamic criticality for infrastructure prioritization in complex environments *Environ. Res.* **3** 015011

Intergovernmental Panel on Climate Change ed 2022 *Food, Fibre and Other Ecosystem Products. In Climate Change 2022—Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 713–906

Intini P, Wahlqvist J, Wetterberg N and Ronchi E 2022 Modelling the impact of wildfire smoke on driving speed *Int. J. Disaster Risk Reduct.* **80** 103211

Jakob M 2021 Debris-flow hazard assessments: a practitioner's view *Environ. Eng. Geosci.* **27** 153–66

Jakob M 2022 Chapter 14—landslides in a changing climate *Landslide Hazards, Risks, and Disasters (Second Edition) ed T* Davies, N Rosser and J F Shroder (Elsevier) pp 505–79

Jamac H and Ahlgren L 2023 *Staying Afloat: Examining the Resilience of the European Inland Waterway Transportation Industry in the Face of Climate Related Disruptions: A Policy and Resilience Analysis* (University of Gothenburg School of Business, Economics and Law) (available at: https://gupea.ub.gu.se/bitstream/handle/2077/77644/LTM%202023-72.pdf?sequence=1&isAllowed=y)

Javadi M S and Javadinasab A 2011 Power purchasing agreements in modern power system *J. Am. Sci.* **7** 164–9

Jia G *et al* 2021 Land–climate interactions *IPCC* (available at: www.ipcc.ch/site/assets/uploads/sites/4/2021/07/05_Chapter-2-V6.pdf)

Kean J W, Staley D M, Lancaster J T, Rengers F K, Swanson B J, Coe J A, Hernandez J L, Sigman A J, Allstadt K E and Lindsay D N 2019 Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: opportunities and challenges for post-wildfire risk assessment *Geosphere* **15** 1140–63

Kendix M and Walls W D 2010 Estimating the impact of refinery outages on petroleum product prices *Energy Econ.* **32** 1291–8

Khakzad N 2018 Impact of wildfires on Canada's oil sands facilities *Nat. Hazards Earth Syst. Sci.* **18** 3153–66

Kim Y, Eisenberg D, Bondank E, Chester M, Mascaro G and Underwood S 2017 Safe-to-Fail Climate Change Adaptation Strategies for Phoenix Roadways under Extreme Precipitation *Int. Conf. on Sustainable Infrastructure 2017* pp 348–53

Kolden C A and Henson C 2019 A socio-ecological approach to mitigating wildfire vulnerability in the wildland urban interface: a case study from the 2017 Thomas fire *Fire* **2** 1–19

Kpienbaareh D and Luginaah I 2019 After the flames then what? Exploring the linkages between wildfires and household food security in the northern Savannah of Ghana *Int. J. Sustain. Dev. World Ecol.* **26** 612–24

Kreimer A, Arnold M and Carlin A (eds) 2003 *Building Safer Cities: The Future of Disaster Risk* (The World Bank) 10.1596/0-8213-5497-3

Kuang H, Zhang P, Han B and Ouyang P 2021 Stability analysis and control strategy for the chained propagation of delay or disruption risk in a port-hinterland service network *Math. Problems Eng.* **2021** 1–17

Lee S E, Quinn A D and Rogers C D F 2016 Advancing city sustainability via its systems of flows: the urban metabolism of Birmingham and its hinterland *Sustainability* **8** 220

Lenzen M and Peters G 2010 How city dwellers affect their resource hinterland: a spatial impact study of Australian households *Low Carbon Cities* (Routledge) (https://doi.org/10.1111/j.1530-9290.2009.00190.x)

Li R and Chester M V 2023 Vulnerability of California roadways to post-wildfire debris flows *Environ. Res.* **3** 015003

Library of Congress n.d. *Modes of Transportation* (Oil and Gas Industry: A Research Guide) (available at: https://guides.loc.gov/oil-and-gas-industry/midstream/modes) (Accessed 6 March 2023)

Lingua V 2020 Regional designing and visioning in planning rescaling: an interactive governance perspective *Shaping Regional Futures: Designing and Visioning in Governance Rescaling ed V* Lingua and V Balz (Springer International Publishing) pp 13–25

Litman T 2006 Lessons from Katrina and Rita: what major disasters can teach transportation planners *J. Transp. Eng.* **132** 11–18

Little R G 2004 The role of organizational culture and values in the performance of critical infrastructure systems *2004 IEEE Int. Conf. on Systems, Man and Cybernetics* (IEEE Cat. No. 04CH37583) vol 5 pp 4047–52

Liu J, Sample D J, Bell C and Guan Y 2014 Review and research needs of bioretention used for the treatment of urban stormwater *Water* **6** 1069–99

Liu W and Song Z 2020 Review of studies on the resilience of urban critical infrastructure networks *Reliab. Eng. Syst. Saf.* **193** 106617

Markolf S A, Hoehne C, Fraser A, Chester M V and Underwood B S 2019 Transportation resilience to climate change and extreme weather events—beyond risk and robustness *Transp. Policy* **74** 174–86

Matthewman S and Byrd H 2014 Blackouts: a sociology of electrical power failure *Social Space* pp 1–25

McCoy K, Krasko V, Santi P, Kaffine D and Rebennack S 2016 Minimizing economic impacts from post-fire debris flows in the western United States *Nat. Hazards* **83** 149–76

McPhillips L E and Matsler A M 2018 Temporal evolution of green stormwater infrastructure strategies in three us cities *Front. Built Environ.* **4** 26

Melnikov V R, Krzhizhanovskaya V V, Boukhanovsky A V and Sloot P M A 2015 Data-driven modeling of transportation systems and traffic data analysis during a major power outage in the Netherlands *Proc. Comput. Sci.* **66** 336–45

Miles S B, Jagielo N and Gallagher H 2015 Hurricane Isaac power outage impacts and restoration *J. Infrastruct. Syst.* **22** 05015005

Mo W, Hart D, Ashcraft C M, Chester M, Cucurachi S, Lu Z and Miller S A 2023 Integrating knowledge co-production with life cycle assessment *Resour. Conserv. Recycling* **188** 106650

Mohapatra A and Trinh T 2022 Early wildfire detection technologies in practice: a review *Sustainability* **14** 12270

Moteff J and Parfomak P 2004 *Critical Infrastructure and Key Assets: Definition and Identification* (CRS Report for Congress)

Natural Hazards Center U. of C. B. 2014 Natural hazards center *Problems Related to the Oil and Gas Industry During a Flood Disaster* (available at: https://hazards.colorado.edu/quick-response-report/problems-related-to-the-oil-and-gas-industry-during-a-flood-disaster)

OECD 2020 *Food Supply Chains and COVID-19: Impacts and Policy Lessons* (OECD) (https://doi.org/10.1787/71b57aea-en)

Oh J, Fernando E G and Lytton R L 2007 Evaluation of damage potential for pavements due to overweight truck traffic *J. Transp. Eng.* **133** 308–17

Ontario-U.S. Power Outage-Impacts on Critical Infrastructure 2006 Incident analysis IA06-002 (Public Safety and Emergency Preparedness)

Padmanabhan R, Schulman A, Levin D and Spring N 2019 Residential links under the weather *SIGCOMM 2019—Proc. 2019 Conf. ACM Special Interest Group on Data Communication* pp 145–58

Palin P J *et al* 2018 Supply Chain resilience and the 2017 hurricane season A collection of case studies about hurricanes Harvey, Irma, and Maria and their impact on supply chain resilience
Patil A D, Haack J, Braun M and de Meer H 2020 Modeling interconnected ICT and power systems for resilience analysis *Energy Inf.* **3** 1–20
Peker M A 2021 Evaluation of concrete pavers affected by Manavgat wildfires *J. Sustain. Constr. Mater. Technol.* **6** 168–72
Peters K A 2010 Creating a sustainable urban agriculture revolution *J. Environ. Law Litig.* **25** 203 (available at: https://heinonline.org/HOL/Page?handle=hein.journals/jenvll25&id=205&div=&collection=)
Petrova E 2022 Investigation of accidents in the infrastructure triggered by debris flows in Russia *Nat. Hazards* **114** 3293–308
Proctor C R, Lee J, Yu D, Shah A D and Whelton A J 2020 Wildfire caused widespread drinking water distribution network contamination *AWWA Water Sci.* **2** e1183
Pyke C, Warren M P, Johnson T, LaGro J, Scharfenberg J, Groth P, Freed R, Schroeer W and Main E 2011 Assessment of low impact development for managing stormwater with changing precipitation due to climate change *Landscape Urban Plan.* **103** 166–73
Radeloff V C *et al* 2018 Rapid growth of the US wildland-urban interface raises wildfire risk *Proc. Natl Acad. Sci.* **115** 3314–9
Reder A, Iturbide M, Herrera S, Rianna G, Mercogliano P and Gutiérrez J 2018 Assessing variations of extreme indices inducing weather-hazards on critical infrastructures over Europe—the INTACT framework *Clim. Change* **148** 123–38
Rodrigue J-P 2017 Transportation, disruptions and resilience, the geography of transport systems *The Geography of Transport Systems* (Routledge) pp 456 (available at: https://transportgeography.org/contents/chapter9/transportation-and-disasters/)
Ruhl J B 2019 Governing cascade failures in complex social-ecological-technological systems: framing context, strategies, and challenges (SSRN Scholarly Paper 3471945) (available at: https://papers.ssrn.com/abstract=3471945)
Saeed Q A and Nazaripouya H 2022 Impact of wildfires on power systems *2022 IEEE Int. Conf. on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* pp 1–5
Said-Moorhouse L 2022 *Scientists say temperatures are getting "hotter faster" than their tools can calculate* (CNN) (available at: www.cnn.com/2022/07/28/uk/uk-heat-wave-climate-role-gbr-intl/index.html)
Schwartz J Y, Oakley N S and Alessio P 2021 Assessment of a post-fire debris flow impacting El Capitan Watershed, Santa Barbara County, California, U.S.A *Environ. Eng. Geosci.* **27** 423–37
Schweikert A E and Deinert M R 2021 Simple method for identifying interdependencies in service delivery in critical infrastructure networks *Appl. Netw. Sci.* **6** 44
Serre D and Heinzlef C 2018 Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks *Int. J. Disaster Risk Reduct.* **30** 235–43
Sfetsos A *et al* 2021 Assessing the effects of forest fires on interconnected critical infrastructures under climate change. Evidence from South France *Infrastructures* **6** 16
Shahbazi A 1992 The impact of energy shortages on the timeliness of agricultural operations *Agric. Ecosyst. Environ.* **38** 167–78
Sham C H, Tuccillo M E and Rooke J 2013 Effects of wildfire on drinking water utilities and best practices for wildfire risk reduction and mitigation (4482; Water Research Foundation Project)
Singh H and Papalexopoulos A 1999 Competitive procurement of ancillary services by an independent system operator *IEEE Trans. Power Syst.* **14** 498–504
Soll D 2012 City, region, and in between: New York City's water supply and the insights of regional history *J. Urban Hist.* **38** 294–318
Sowby R B and Porter B W 2023 Water supply and firefighting: early lessons from the 2023 Maui fires *Water* **16** 600
Spearing L A and Faust K M 2020 Cascading system impacts of the 2018 Camp Fire in California: the interdependent provision of infrastructure services to displaced populations *Int. J. Disaster Risk Reduct.* **50** 101822
Stein E D, Brown J S, Hogue T S, Burke M P and Kinoshita A 2012 Stormwater contaminant loading following southern California wildfires *Environ. Toxicol. Chem.* **31** 2625–38
Storper M and Walker R 1989 *The Capitalist Imperative: Territory, Technology, and Industrial Growth* (Basil Blackwell)
Sun Z, Liu Y, Qi Q, Liu W, Li D and Chai J 2022 Risk assessment of coal mine flood disasters based on projection pursuit clustering model *Sustainability* **14** 11131
Tøndel I A, Foros J, Kilskar S S, Hokstad P and Jaatun M G 2018 Interdependencies and reliability in the combined ICT and power system: an overview of current research *Appl. Comput. Inf.* **14** 17–27
Tran N H, Reinhard M, Khan E, Chen H, Nguyen V T, Li Y, Goh S G, Nguyen Q B, Saeidi N and Gin K Y-H 2019 Emerging contaminants in wastewater, stormwater runoff, and surface water: application as chemical markers for diffuse sources *Sci. Total Environ.* **676** 252–67
U.S. Department of Transportation 2014 *Fact Sheet: Natural Force Damage* (Pipeline and Hazardous Material Safety Administration (PHMSA)) (available at: https://primis.phmsa.dot.gov/comm/FactSheets/FSNaturalForce.htm?nocache=940)
UCTE 2008 Transmission Development Plan p 107
UNEP 2016 *Loss and Damage: The Role of Ecosystem Services* (United Nations Environment Programme)
USGCRP 2023 *Fifth National Climate Assessment* (U.S. Global Change Research Program) 10.7930/NCA5.2023.RiB
Valentin V and Stormont J 2019 Evaluating post-wildfire flood impacts on transportation infrastructure for mitigation planning (SPTC15.1–50-F) (Southern Plains Transportation Center) (available at: https://rosap.ntl.bts.gov/view/dot/55580)
van Ruiten K, Bles T and Kiel J 2016 EU-INTACT-case studies: impact of extreme weather on critical infrastructure *E3S Web of Conf.* vol 7 p 07001
Verschuur J, Pant R, Koks E and Hall J 2022 A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards *Maritime Econ. Logist.* **24** 489–506
Vilathgamuwa M, Mishra Y, Yigitcanlar T, Bhaskar A and Wilson C 2022 Mobile-energy-as-a-service (MEaaS): sustainable electromobility via integrated energy–transport–urban infrastructure *Sustainability* **14** 2796
Westerling A L 2016 Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring *Phil. Trans. R. Soc.* B **371** 20150178
Wetterberg N, Ronchi E and Wahlqvist J 2021 Individual driving behaviour in wildfire smoke *Fire Technol.* **57** 1041–61
Wilkinson P J and Cole D G 2010 The role of radio science in disaster management *Radio Sci. Bull.* **2010** 335
Wisetjindawat W, Burke M I and Fujita M 2017 Analysing impacts of natural disasters on logistics activities: flood risks and petroleum fuels in Queensland, Australia *Transp. Res. Proc.* **25** 1198–212
Zimmerman R and Faris C 2010 New York City panel on climate change 2010 report chapter 4: infrastructure impacts and adaptation challenges *Annals of the New York Academy of Sciences* (New York Academy of Sciences) pp 63–85
Zimmerman R, Zhu Q and Dimitri C 2016 Promoting resilience for food, energy, and water interdependencies *J. Environ. Stud. Sci.* **6** 50–61